The environmental effects of mangrove clearance in Belize, Central America

Malcolm R. Murray

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DEPARTMENT *of* GEOGRAPHY
The University of Edinburgh

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Abstract

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This work examines changes occurring in areas of mangrove forest following their partial clearance. The field sites considered are located around Belize City, in Belize, Central America.

Examining the pattern of global mangrove clearance, Belize is found to differ from most other countries, in that mangrove clearance is being driven by the current market requirement for housing, rather than industrial or agricultural demands. There is little local demand for mangrove related products (notwithstanding that many of the fish and crustaceans that use the mangrove forest as a nursery ground or habitat are commercially exploited). Analysis of recent clearance applications shows that mangrove forest clearance is rapidly accelerating around the established urban centres.

A study of the physical process of mangrove clearance in Belize identifies its effect upon forest environmental processes. These are grouped into four - changes stemming from alterations to the litter input; changes due to a reduction in the vegetation cover; changes driven by surface water and drainage modification; and finally changes relating to the geology and physical alteration to the ground surface. These are used to form a series of predictive hypotheses considering the expected changes in a range of soil, water and other environmental properties following forest clearance.

The significance of such changes is shown by considering the stress tolerance and avoidance strategies of mangroves. Published tolerance ranges and responses to critical levels of flooding, salinity, temperature, insolation, tidal action, sedimentation, wind, soil acidity, anaerobic state and the presence or absence of soil nutrients are reviewed, summarised in a series of flow diagrams.

A field site sampling strategy is devised and three sites of different ages and stages in the clearance process are selected. These provide an insight into both the spatial and temporal aspects of change. A range of soil, water and other environmental properties are measured at these sites using both areal and transect sampling schemes. The resulting data are analysed using 4D visualisation techniques, comparative statistical testing (Mann Whitney-U tests and one way ANOVA), gradient analysis (ordination) techniques and semivariogram analysis. These show that significant differences, particularly in litter-influenced variables, do exist between sites located in the forest and those in the newly cleared areas. Clearance tends to reduce sample heterogeneity. The observed differences change over time, with artificial drainage and its effect upon soil redox conditions found to be particularly significant. Changes manifest themselves at different scales over space. Spatial differences show a distinct grouping, into variables measured in the soil and those suspended in water. The latter show a far greater homogeneity over short distances. The existence of a possible "transition zone" running along the cut edge between the cleared area and the remaining forest is investigated. Its shape and width is found to be highly variable-specific.

Quantifying the changes that occur in the forest soil and water properties in areas next to cleared sites, this work concludes by calling for a re-evaluation of Belize's existing mangrove forest protective legislation. Edge effects have been found at distances of up to 50m into the forest which suggests that the present statutory buffer width needs to be revised upwards if it is to provide a sustainable protective barrier along Belize's coasts and waterways.

Declaration

This work, presented for the degree of Doctor of Philosophy, conforms to the University of Edinburgh's current research degree regulations. It has been composed by me and unless indicated otherwise, the work (the text, maps and figures) presented here are original and my own. The data presented are from samples collected in Belize in 1992 and 1994 and their subsequent analysis.

Where material has been drawn from the work of others it is duly acknowledged in the text, and the appropriate reference details listed at the end of this work.

30th September 1996.

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Data dissemination

In recognition of their help, copies of this thesis will be sent to the libraries of the University College Belize and the Belize Center for Environmental Studies. A summary of the research findings will be sent to the Chief Forest Officer in the Forest Department, Ministry of Natural Resources, Belize. In time, some of the findings will be published, and material made available from this work via the Department's World-Wide Web (internet) server (URL http://www.geo.ed.ac.uk/).

Glossary

adsorption Adsorption is the process where "foreign" atoms or molecules become attached to the surface of a compound. This attraction occurs because atoms at the edge of a compound have relatively "free" energy compared with those in the centre. Attaching foreign molecules to the surface of a compound lowers the free energy, lessening the difference (Sharp, 1990).

aerobic Requiring free (gaseous or dissolved) oxygen (Abercrombie *et al.*, 1990).

anaerobic (Of organisms) the ability to live in the absence of free (gaseous or dissolved) oxygen. (Of processes) occurring in the absence of such oxygen. Anaerobic respiration is the enzyme-mediated process by which cells (or organisms) liberate energy by oxidation of substances but without involving molecular oxygen (Abercrombie *et al.*, 1990).

anoxic Deficient or absence of free (gaseous or dissolved) oxygen (Abercrombie *et al.*, 1990).

buffer This word is used in two senses in this work. When applied to measures of soil acidity or alkalinity, it means a resistance to change in pH. When applied to forests, a buffer is a strip of forest separating two areas experiencing different conditions, again, in effect, resisting change.

cation exchange The interchange between a cation (positively charged ion) in solution and another cation on the surface of any surface-active material such as clay or organic matter (Brady, 1984).

decomposition The sum of three processes: leaching, saprophytic decay and fragmentation (Robertson *et al.* 1992).

deflation The erosion of soil by the wind.

desiccation The process of drying, of dehydration, i.e. involving the removal of water.

ecosystem A term which encompasses a community of organisms which interact with one another, plus the environment they inhabit and thus interact with. The abiotic components such as mineral ions and the climatic regime are therefore included as part of the ecosystem (Abercrombie *et al.*, 1990).

ecotone The transition between two (or more) diverse communities. Often this zone is very elongated, with considerable length, but is far narrower than adjoining communities (Abercrombie *et al.*, 1990).

empolderment The creation of polders - low-lying areas of land which have been artificially reclaimed from lakes or the sea (Goudie *et al.*, 1994).

e.p.s. Equivalent particle size. Used in determination of the size of soil particles, particularly clays, which are plate shaped rather then spherical. Clay particles of size 2 mm e.p.s. act in a similar manner to truly spherical particles of diameter 2 mm (Rowell, 1994).

facultative The ability to live under altered conditions, or to behave adaptively under markedly changed circumstances (Abercrombie *et al.*, 1990).

fixation [1] For elemental nitrogen: The process by which gaseous elemental nitrogen is chemically combined with hydrogen to form ammonia.
[2] For other elements: the process, or processes in a soil by which certain chemical elements essential for plant growth are converted from a soluble or exchangeable form to a much less soluble or to a nonexchangeable form (Brady, 1984).

flocculate To aggregate or clump together individual, tiny soil particles, especially fine clay, into small clumps or floccules. Opposite of *deflocculate* or *disperse* (Brady, 1984).

halophytic Plants able to tolerate and grow in very salty soil typical of shores of tidal estuaries, saltmarshes and alkali desert flats (Abercrombie *et al.*, 1990).

immobilisation The conversion of an element from the inorganic to the organic form in microbial tissues or in plant tissues. This has the effect of rendering the element not readily available to other organisms or to plants (Brady, 1984).

labile Groups attached to complexes and molecules which can be easily replaced. This makes them likely to participate in fast reactions (Sharp, 1990). Labile substances easily undergo transformation and are readily available to plants.

leaching The removal of materials in solution from the soil by perculating waters (Brady, 1994).

littoral The area comprising the shore and adjoining shallow waters, commonly limited to 6-10m in lakes and 200m depth in the sea (Abercrombie *et al.*, 1990).

measurement scale A way of classifying datasets according to the units of measurement. Many statistical tests are only valid for certain scales of measurement. Four scales are commonly recognised. The lowest is the *nominal* scale, which refers to a binary (yes/no, present/absent) record at each site. Typical variables measured on a nominal scale are the presence or absence of features such as mottles, or shell fragments in a soil core. Measurements made using an *ordinal* scale can be placed in order (ranked). An example of this is measures of the abundance of roots, using 4 user-defined classes. *Interval* scales are continuous and individuals can be allocated a precise position. Calculations such as addition and subtraction become meaningful when using an interval scale. An example of an interval measurement in the fieldwork is temperature in degrees Celsius. The highest level of measurement, the *ratio* scale is very similar, but differs in that it has a real zero value (such as temperature measured in Kelvin, or calcium content of a soil). The ratio of any two values on the ratio scale is independent of the unit of measurement, allowing multiplication and division to be applied to the data too (Ebdon, 1985).

mineralisation The conversion of an element from an organic form to an inorganic state, that occurs as a result of microbial decomposition (Brady, 1984).

obligate Indicating some type of restriction in an organism's way of life, from which it cannot depart and survive (Abercrombie *et al.*, 1990).

oxidation A chemical process in which the charge on an ion is made more positive (typically through electron loss), e.g. $Fe^{2+} - e^{-} \rightarrow Fe^{3+}$ (Sharp, 1990).

photosynthesis The light dependent manufacture of organic from inorganic molecules, which occurs in chloroplasts and the cells of blue-green algae and some bacteria, in the presence of one or more types of light trapping pigment (Abercrombie *et al.*, 1990).

propagule A dispersive structure, such as a seed, fruit or spore, released from the parent organism (Abercrombie *et al.*, 1990).

reduction A chemical process in which the charge on an ion is made more negative (typically through electron gain), e.g. $Fe^{3+} + e^{-} \rightarrow Fe^{2+}$ (Sharp, 1990).

respiration The release of energy from organic compounds (especially carbohydrates and fats) by enzyme action (Abercrombie *et al.*, 1990).

rhizosphere That portion of the soil in the immediate vicinity of plant roots. In this zone the abundance and composition of the microbial population are influenced by the presence of roots (Brady, 1984).

riparian Meaning occurring on the bank of a body of water, especially a river.

senescence The period between maturity and death of a plant, or plant part. In the case of leaves and fruit this usually ends in abscission (the controlled shedding of a plant part). It is characterised by an accumulation of waste metabolic products in the tissue (Toothill, 1984).

sesquioxides A term for a compound with a ratio of three oxygen atoms to two of the cationic element, such as ferric oxide - Fe_2O_3 (Sharp, 1990).

statistical power This is a way of comparing the ability of a particular statistical technique to accept or reject a false null hypothesis. Tests that are termed "powerful" have a high probability of rejecting the null hypothesis when it is false. (Jongman *et al.*, 1987).

vascular plants which contain conducting tissue (xylem and phloem). They differ from bryophytes and other non-vascular plants in that they possess stomata (Toothill, 1984).

vivipary This term has several meanings in botany. It is used in this work when referring to the premature germination of seeds *in situ* on the maternal plant, before they have been released (Toothill, 1984).

volatilisation Loss of a substance to the atmosphere, by sublimation into its gaseous state.

Units of measurement

Where possible, S.I. units have been used throughout this work. The tables below allow the conversion of these units to larger or smaller metric units, and into imperial measures.

Distance

cm	centimetre	100 cm	=	1 m	1 cm	=	0. 393 "	1 "	=	2.54 cm
m	metre				1 m	=	3.28 '	1 '	=	0.305 m
km	kilometre	1 km	=	1000 m	1 km	=	0.621 miles	1 mile	=	1.609 km

Volume

ml	millilitre	1000 ml	=	1 l	1 ml	=	0.06 cu. in.	1 cu. in.	=	16.39 ml
l	litre				1 l	=	2.1 US pints	1 US pint	=	0.47 l

Mass

ng	nanogram	1000 ng	=	1 µg						
µg	microgram	1000 µg	=	1 mg						
mg	milligram	1000 mg	=	1 g						
kg	kilogram	1000 kg	=	1 t	1 kg	=	2.20 lbs	1 lb	=	0.45 kg
t	tonne				1 t	=	0.907 imp. tons	1 imp. ton	=	1.102 t

Area

m^2	sq. metres	10000 m^2	=	1 ha	1 m^2	=	10.764 sq. ft.	1 sq. ft.	=	0.093 m^2
ha	hectare	100 ha	=	1 km^2	1 ha	=	2.474 acres	1 acre	=	0.405 ha
km^2	sq. km				1 km^2	=	0.386 sq. miles.	1 sq. mile	=	2.590 km^2

Temperature

°C	degrees Celsius

Luminous intensity

cd	candela

Light intensity is sometimes expressed in lux (lx) where 1 lx = 1 cd ·sr m^{-2}. 1 lx = 0.0929 foot-candles. The lux and thus by implication, the candela have both been criticised when applied to studies of plants, because these measures are based on the sensitivity of the human eye (Salisbury & Ross, 1992).

Electric potential

V	volt

Charge

$cmol_c\ kg^{-1}$	centimole of charge per kilogram.	1 meq 100 g^{-1}	=	1 $cmol_c\ kg^{-1}$

This value has been corrected to produce a value independent of the exchangeable ion present, i.e. it has been corrected for valency (Rowell, 1994).

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1 Introducing the research topic and approaches

Introduction

This work aims to identify the effects of mangrove forest clearance and drainage, using three field sites in Belize, Central America. The research is underpinned by three basic ecological concepts: the factors that affect plant distribution, theories of vegetation climax and succession, and edge effects. A pluralist, realist research methodology is used to aid the construction of hypotheses, fieldwork strategies and the interpretation of the data gathered. This introductory chapter explains these concepts and the structure of the chapters that follow.

1.1 Aims of the thesis

The research considers the effects of forest clearance and drainage in Belize, Central America, focusing upon mangroves, a salt-tolerant tropical forest found predominantly in coastal areas.

It has two principal aims:

1. To examine how mangrove clearance and drainage affect a range of soil, water and other environmental[1] properties. This will be achieved by measuring these properties in both selectively cleared sites and in the remaining mangrove forest, allowing the following three issues to be addressed:

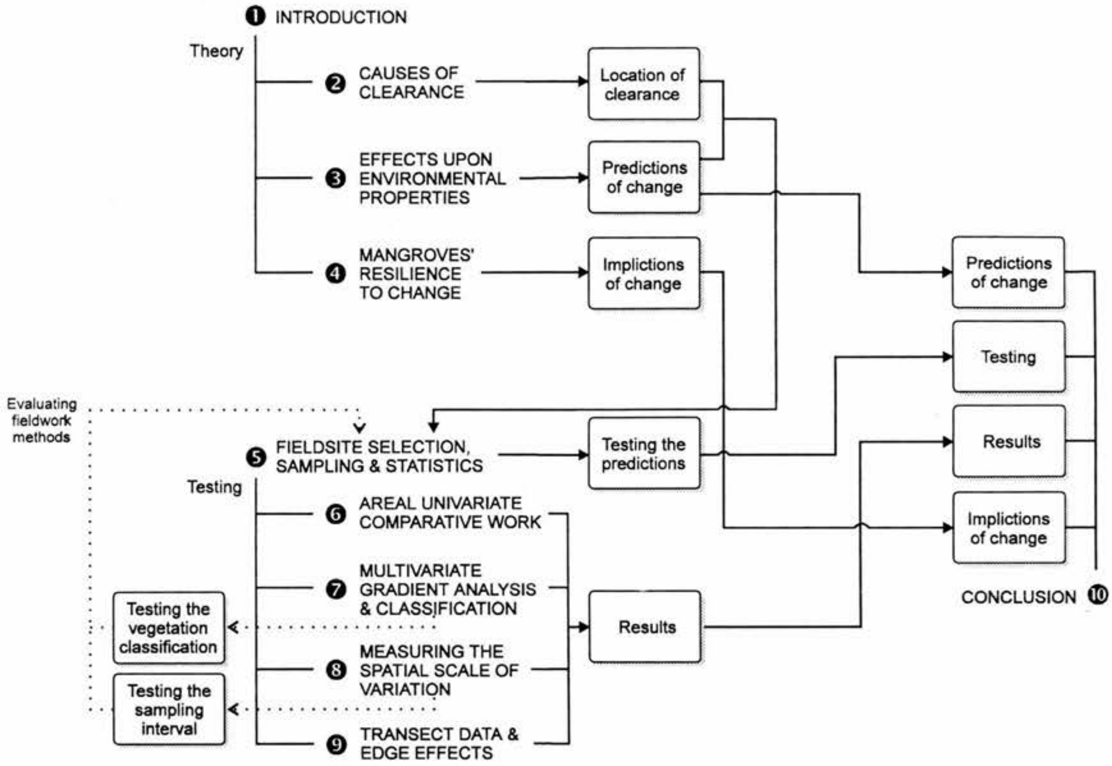
- Ascertaining whether these two areas - the forest and the cleared zone - are statistically different.
- Investigating the nature of this difference: identifying which variables are important indicators of change.
- Revealing how this pattern of change is manifested over both time and three dimensional space.

2. To measure the degree of penetration of any changes into the remaining forest - an investigation of edge effects.

[1] The word "environment" is used in this work to refer to the external influences (physical, chemical and/or biotic) which act to modify and determine the conditions surrounding organisms (be they plants, animals or fungi). Thus this study of the *environmental* effects of mangrove clearance seeks to pinpoint and explain physical, chemical and biotic changes in the mangrove ecosystem which arise as a result of forest clearance.

To meet these aims, the thesis has been split into three parts, the introductory chapters, the fieldwork chapters and the conclusion, shown below in Figure 1.1.

Figure 1.1 A schematic view of the thesis structure



This figure shows the chapters (indicated by numbered circles) arranged to highlight the linkages between them as the argument develops. Chapter 1 introduces the work, chapters 2, 3 and 4 provide the necessary information to understand the nature of the problem and develop hypotheses. Chapter 5 sets out the fieldwork strategy and the next four chapters contain the results of these tests. Chapter 10 pulls all this together in a conclusion. Dotted lines in the figure indicate test results that can be used to evaluate the methods selected in earlier chapters.

The introductory chapters investigate the causes of mangrove clearance, the effects of these activities upon the environment and the resilience of mangroves to such alterations. The fieldwork chapters begin by considering possible sampling strategies and selecting suitable field sites. Four chapters of results then follow, considering in turn spatial patterns in the data, multivariate trends (gradient analysis), the importance of spatial dependency (detected by semivariance analysis) and finally penetration effects revealed by transect sampling. The results and arguments from these chapters are then brought together to form the conclusion.

1.2 The choice of topic

As a group of strangely shaped tropical forest trees growing "into the sea", mangroves attract immediate attention. Examining their function more closely reveals that they play an important role in many ecological systems. Located at the interface between terrestrial and marine biomes, they support a diverse community of flora and fauna, providing a habitat and nursery for many commercially important species of fish and crustaceans. Mangroves play a central part in the detritus-based ecosystems of tropical coasts, as the first link in the *mangrove - sea grass - coral reef* sequence. They manage to grow, trapping energy and nutrients in their leaves, despite high salinity and anaerobic organic substrate conditions. Their roots help to stabilise the coastal sediments, protecting the littoral from buffering by waves and tropical storms. This acts to preserve the coastline and prevents offshore areas from being choked by run-off charged with terrestrial sediments. Mangrove leaves and timber offer both a home and a food source for many birds and animals, and are also widely used around the world by local people for food, fuel, medicines and in construction (Field, 1995).

1.3 The choice of field area

Belize was chosen as the fieldwork location for several reasons. Staff and students from the University of Edinburgh's Department of Geography have been working with the people of Belize for almost thirty years, in a variety of roles, from large ecological research projects to individual undergraduates working towards their dissertations. This has resulted in an established network of local contacts and a large collection of relevant publications, both local and international. This high profile and the availability of relevant material within the Department initially brought Belize to my attention.

From an ecological point of view, Belize is attractive because it has extensive areas of relatively undisturbed mangrove forest close to others where clearance is rapidly accelerating, providing ample sites for a comparative project such as this. The ease of access into the country, the fact that English is its first language, the friendliness of the local people and its relatively small size, all added to its attraction as a potential field site. Figure 1.2 is a map of Belize that shows the position of all the locations discussed in this work.

1.4 Theoretical perspectives

In examining the effects of mangrove clearance, three ecological concepts are developed which revolve around a consideration of the three primary factors affecting plant distribution: competition, disturbance and stress. This approach is complemented by a review of the debate on climax vegetation and the applicability of "edge effect" theories to penetration effects occurring in the remaining forest, all of which are explored below.

1.4.1 Factors affecting plant distribution

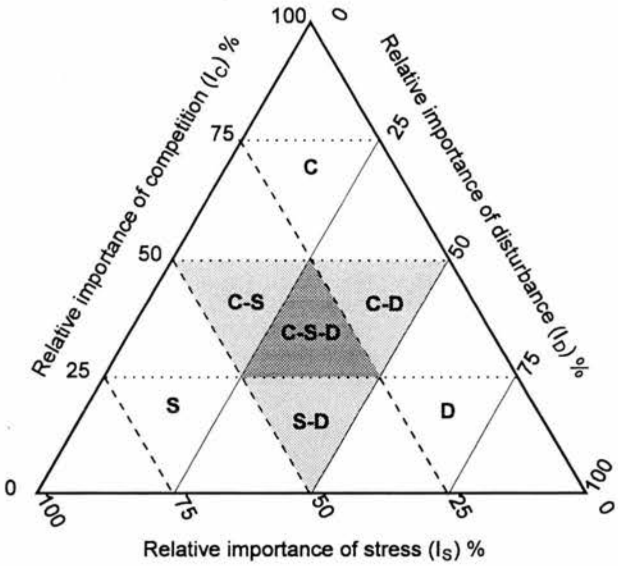
Kershaw & Looney (1985) have shown that researchers interested in plant community and population ecology have long been concerned with the factors controlling plant distribution. Suggested mechanisms include differences in seed dormancy and their responses to changes in soil properties (e.g. Watt, 1919; Harper, 1977); patterns of individual species' seedling establishment, thinning and growth (e.g. Black, 1955; Harper & McNaughton, 1962); the action of depletion and survivorship

Figure 1.2 Location Map - Belize

Based on maps published in Harsthorn et al. (1984) with additional information taken from the ITM 1:350,000 Series Sheet 230 (1993-1995 Edition).

curves in natural populations, (e.g. Sarukhán & Harper, 1973); differences in genetic control upon plant forms (e.g. Black, 1960); the pattern of seed production (e.g. MacArthur & Wilson's 1967 application of *r*- and *K*- selection strategies) and total system interaction (Grime, 1979, 1984). It is this last, synthesising approach that appears to be the most appropriate for the present research. Grime (1979) proposes a triangular-model comprising three factors that affect plant distribution: competition, stress and disturbance. This model is shown below in Figure 1.3.

Figure 1.3 A triangular ordination of three factors influencing plant distribution



Based on Grime (1979)

The central tenet of this approach is that the intensity of plant competition declines under increased levels of disturbance or stress. The resulting equilibrium between competition, stress and disturbance is proposed as a major determinant of vegetational structure and composition. Applied to mangroves, stresses from the anaerobic, reducing soil conditions, high insolation and salinity (discussed in more detail in chapter four) act to restrict the pool of potential competing plant species, pushing the equilibrium point towards the bottom left of the diagram. Selective clearance of the mangrove results in significant disturbance, (discussed in chapters two and three) which should push the equilibrium point to the right, potentially allowing greater plant competition. The effects of mangrove clearance upon this equilibrium point are a major focus of this piece of research.

1.4.2 Vegetation climax and succession

Odum (1953) defines the term "climax" as the final or stable vegetation community in a successional series; it is self-perpetuating and in equilibrium with the physical habitat. Two perceptions of climax vegetation have developed in ecology, the *monoclimax* view which draws largely on the work of Clements (1916) which sees climate as the single determining factor and the *polyclimax* view which accepts that there may be many other factors which control vegetation communities in an area. Both of these approaches are still subject to the earlier criticisms of Cowles (1901) who noted that the definition of a climax vegetation type is dependent upon the timescale used. Mangrove forest has been considered as either a pioneer or climax vegetation type, dependent on the precise community defined (Watson, 1928; Davis, 1940; and Chapman, 1944). Lugo & Snedaker (1974) have identified six types of mangrove communities, from fringing forest to inland dwarf forest, distinguished by changes in the tidal flushing and terrestrial drainage of the site. Woodroffe (1983) has shown that on Grand Cayman, a *Rhizophora* dominated community has existed there for the last 2000 years, and it is felt that the view of mangroves as a polyclimax species can be supported by such observations.

The range of plant species attempting to reinhabit cleared areas will depend upon whether such sites are amenable to traditional processes of succession, or whether the harsh soil and water conditions found in such areas act to severely restrict the range of possible colonists. Answering this question requires a more detailed consideration of the process of succession.

The classical six stage model of succession was proposed by Clements (1916):

1. Nudation: the initiation of the succession made possible because of a major disturbance to the environment.
2. Migration of available species (the migrules) to fill the vacant ecological niches.
3. Ecesis: the subsequent ability of the migrules to germinate, grow and reproduce successfully.
4. Competition.
5. Reaction.
6. Final stabilisation.

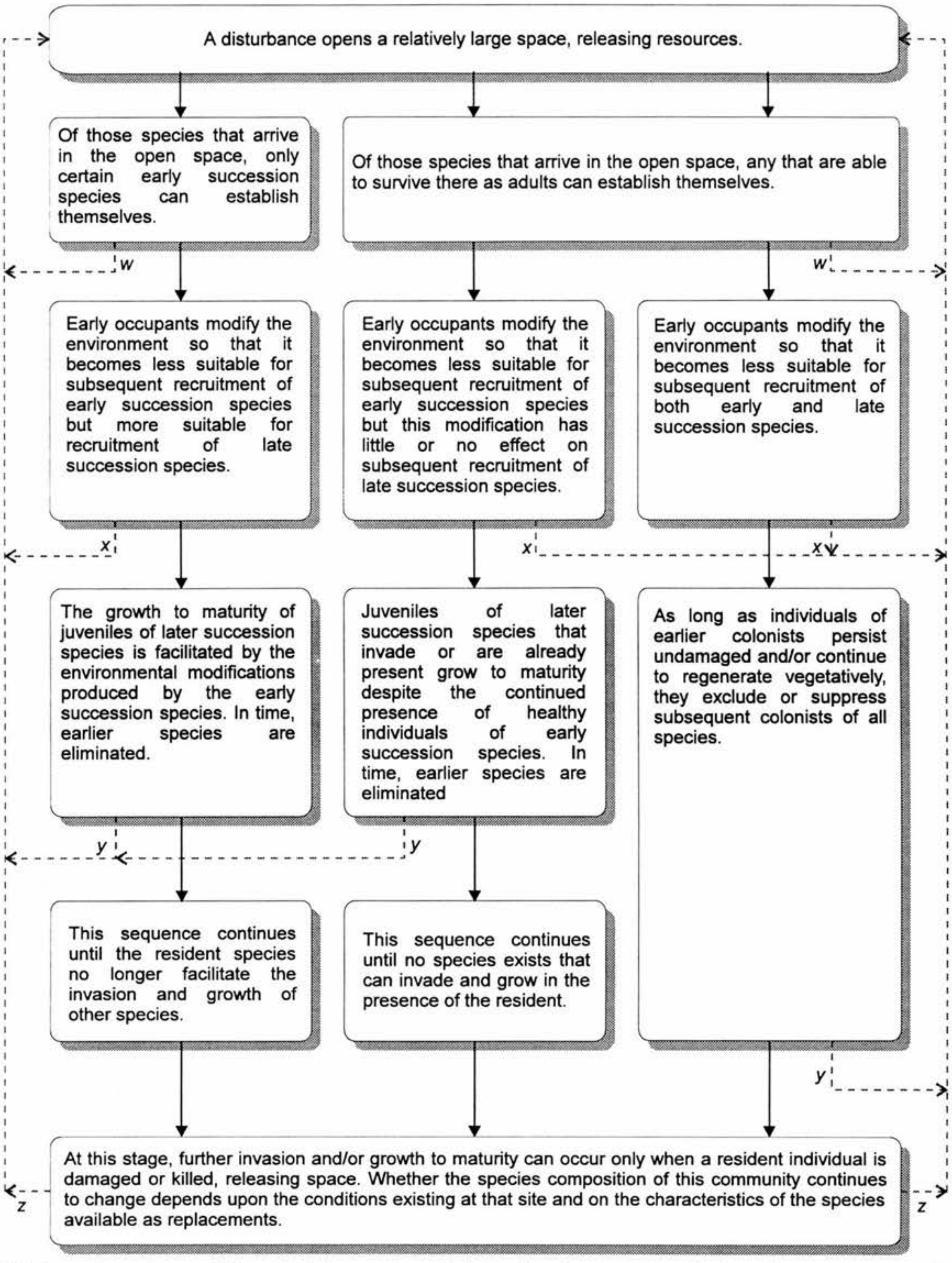
Reproduced from Kershaw & Looney (1985).

This model has been criticised as being excessively deterministic by workers such as Egler (1954) and Colinvaux (1973). Connell & Slatyer (1977) identify two alternative conceptualisations: the tolerance model and the inhibition model. These models differ in three respects:

1. The range of plant species which are able to establish themselves at the disturbed sites.
2. Whether early occupants modify the environment to favour or suppress further colonisation of the disturbed areas by late succession species.
3. The long term population dynamics of these areas, notably whether the early colonist species persist, or are gradually replaced through the process of plant succession.

These differences are shown graphically in Figure 1.4 (overleaf).

Figure 1.4 Three alternative models of succession



This figure shows three possible mechanistic sequences which describe plant succession. The dotted lines represent possible interruptions in each process, which occur in decreasing frequency in the order w, x, y, z.

Based on Connell & Slatyer (1977).

Of these three models, the second, tolerance model, seems the most applicable to mangrove forests. As colonists equipped to withstand the harsh anaerobic soil conditions, mangroves should quickly establish themselves in a disturbed area. However the same soil conditions will serve to restrict competition from non-halophytic plant species, effectively excluding other plants, as seen in the low species diversity of Belizean mangrove forests. In Belize, the earliest mangrove colonists are likely to be *Rhizophora mangle* plants, because of their large, resilient seedlings which will give them a competitive advantage through early establishment. The smaller seeded *Avicennia germinans* and *Laguncularia racemosa* are likely to invade an area at a slower rate, initially becoming established in areas further inland than the *Rhizophora*, excluded because of its greater size, where the soil conditions, particularly the high salinity levels, impose significant stresses on other non-mangrove plant species.

Several models of mangrove succession have been developed, depending on the local mangrove species present and the hydrological and geomorphological setting. Typical of those for the Atlantic coast of North and Central America is that of Chapman (1970), whose model develops from a pioneer fringing *Rhizophora* community, to an inland *Conocarpus* dominated, freshwater community. Yet these models, whilst corresponding well with the observed zonation, can be criticised because of their failure to indicate the timescale involved in this process. In the case of Chapman's model this can be seen in the lack of adequate support for the finality of the climax *Conocarpus* zone. Tomlinson (1986) has also criticised such approaches from a practical point of view, noting that in many cases the vegetation is more readily interpreted as a mosaic, than as a series of zones.

In this work, three field sites are selected in areas of undisturbed basin mangrove forest (*sensu* Lugo & Snedaker, 1974). Given the research's short timescale, this vegetation can be considered as a community which shows stability at least in the short to medium term[2]. It is also characterised by a notable absence of competitors. This is felt to justify its conceptualisation here as a polyclimax community. Recolonisation of cleared areas of mangrove forest is expected to follow a tolerance model, spearheaded by mangrove species already present at the site. Competition from other species will be severely curtailed by the harsh soil and water conditions typical of mangrove areas. However, should the process of clearance and drainage alter these conditions, then this assumption must be queried. Whether these processes do result in soil and water change, is one of the two major questions posed by research.

1.4.3 Edge effects

The second research thrust considers whether edge effects occur in the mangrove forest adjacent to cleared areas. The term edge effect is used here to refer to the suite of changes which occur in the forest as a result of edge creation, which is deemed the causal factor. The resulting ecotone is a transition between these two communities, it is narrower than the adjoining communities, but extends

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[2] Tens to hundreds of years.

linearly along the boundary. This ecotone contains many of the organisms of the two overlapping communities and possibly additional species restricted to these transitional zones. Such increased variety and density at community junctions is an expression of the edge effect, and it is this increase in diversity which has been the focus of traditional edge effect studies in ecology (Odum, 1953).

This work applies edge effect theory to investigate the effects of human disturbance, in a similar manner to many recent studies of change along tropical forest edges (e.g. Kapos, 1989; Williams-Linera, 1990; Sizer, 1991). In the context of this work, an edge is defined as the boundary between undisturbed mangrove forest and areas of cleared land. As such it can be used to delimit the areal extent of mangrove "forest". Whilst no published studies of edge effects in mangroves have been found, there exists a wealth of literature on studies in tropical and lowland forests, the findings of which are used to guide the sampling design detailed in chapter five and also interpretation of the results in later chapters.

1.5 Philosophical and methodological approaches

Traditionally, studies of forest ecology and soils have adopted an inductive approach, in common with the other empirical disciplines within the sciences. These involve a large data gathering and measurement process, followed by a search for patterns and regularity, to produce "hypotheses". These are then verified through a process of repeated observation, which if passed, leads to them becoming "laws". Such an inductive approach has been widely criticised. The eighteenth century philosopher David Hume was the first to draw attention to the fact that there is no philosophically tenable underlying principle of induction - he questioned the ability of repeated observations (verifications) to "prove" the *truth* of a theory (cited in Russell, 1961). Others, e.g. Popper (1972), have also questioned the implied objective nature of the researcher, arguing that we cannot, as the title of Gould's 1981 paper would have it, "Let... the data speak for themselves".

An alternative "hypothetico-deductive" approach, sometimes referred to as "critical rationalism", has been developed by Popper (1972, 1974, 1976). This advocates the attempted falsification of *a priori* hypotheses through observations, leading to a conjectural view of scientific knowledge. Whilst the implied rationality of science adopted by this view has been questioned, (notably by Kuhn, 1970 and Feyerabend, 1975, 1981) this approach has been adopted in many areas of scientific research. Haines-Young & Petch (1986) have shown that such methods can be applied to physical geography.

In this work where possible, these hypothetico-deductive methods have been employed. The examination of the clearance process detailed in chapter two and of our current knowledge of mangrove forest's environmental tolerances in chapter four allows a series of hypothesised predictions of change to be developed. These are then tested critically using data obtained from selectively cleared mangrove forest sites, using a sampling strategy outlined in chapter five. Probability statements are used to test the validity of the hypothesised predictions in chapter six, by attempting to find no statistical difference between values measured in the cleared and forest areas, which would falsify these predictions.

Yet, in common with much geographical research, a pluralist approach is adopted here - with some inductive methods, for example the ordination in chapter seven. This is an attempt to provide a more holistic interpretation of the process of mangrove clearance and drainage, to complement the reductionist methods of the earlier variable-by-variable comparisons. The use of these inductive methods is seen as necessary because of our, as yet, incomplete conceptualisation and understanding of the natural systems under study.

The research also employs a range of techniques which focus upon spatial processes, such as the attempts to quantify the spatial scale at which these processes operate (chapter eight). This acknowledges recent advances in the field of geostatistics, by workers such as Webster & Oliver (1990) applying the theories of Matheron (1965, 1969, 1971) and Krige (1966).

The final chapter applies the earlier work to the issue of planning and development in Belize. Existing protective legislation requires a buffer of mangrove forest to be left along the coastal edge of developments and the edge of any adjacent water body. This chapter considers how the changes identified at the field sites stemming from clearance and drainage could affect these buffer zones. As such it attempts to address the requirement for *relevance* in research, a characteristic given great emphasis by workers of the emerging new philosophical right. This chapter uses knowledge of which variables alter in value, to quantify the degree of penetration of such changes in the remaining forest, permitting an evaluation to be made of the long term success of these buffer zones.

A wide range of statistical and analytical laboratory methods have been used in this work. Where a choice of techniques exists, the rationale behind the choice of a particular method is included within the main text of the thesis, but for clarity, the exact methods of calculation and analysis have been confined to appendices, or given as references where they are already widely used.

Chapter two begins this investigation by introducing the reader to the nature of the mangroves in Belize and the causes of mangrove clearance.

2
Causes of global and local mangrove clearance

Understanding the clearance process

The purpose of this chapter is to consider the causes, rates and methods of mangrove clearance in Belize within a local, regional and global context. This permits an interpretation of the specific situation in Belize. The subsequent chapter then develops semi-quantitative nutrient budget models and examines predictions of the effects of clearance and drainage upon the soil and surrounding vegetation.

In this section mangroves are defined before identifying the causes of their clearance at both global and local scales. The forces driving this clearance are considered, by examining the possible use of mangrove products and a range of alternative activities which could be carried out on land presently occupied by mangrove forest. A study is made of the accelerating rates of mangrove clearance in Belize and the methods employed in forest removal. This is used to identify possible field site locations and indicate which variables may change following clearance.

2.1 Defining mangrove

Historically the term "mangrove" has been used in two senses. In an ecological sense, it delimits a group of salt-tolerant (halophytic) species from a restricted range of 12 genera, (Waisel, 1972; Tomlinson, 1986). It has also been applied in a more general sense to a community of tropical trees and shrubs which are adapted to life in a wet, saline environment such as fringing sheltered tropical shores, (Schimper, 1903; McKee, 1994a).

It is this latter non-taxonomic definition of mangrove that is more prevalent today and will be adopted in this work. Terms used interchangeably when referring to the wider "mangrove community" include - mangrove ecosystem, mangrove forest, mangrove swamp, mangal and mangrove itself. (McKee, 1994a).

At the species level, Tomlinson's (1986) classification is widely adopted. He produces a three fold grouping of individuals as one of a *true mangrove*, a *minor mangrove component* or a *mangrove associate*.

Tomlinson gives five elements used to define "strict" or *true mangroves*:

1. Complete fidelity to the mangrove environment. True mangroves occur only in mangrove communities, they do not extend into terrestrial communities.
2. They play a major role in the structure of the community and are able to form pure stands.
3. They show morphological specialisation - adaptations to the harsh environment, such as aerial roots and the vivipary of the embryo.
4. A physiological mechanism for salt exclusion so that they can grow in sea water. A broad definition of salt exclusion is used here, to include salt excretion as seen in members of the *Avicenniaceae* family.
5. Taxonomic isolation - strict mangroves are separated from their relatives at least at the generic level and often at the subfamily or family level.

Minor mangrove components are those which Tomlinson states cannot "form a conspicuous element of the vegetation" (p26) and thus tend to occupy peripheral locations, rarely forming pure stands. *Mangrove associates* are the group with the weakest tie to mangrove, since they are able to thrive in terrestrial locations. In the field they can most easily be distinguished from true mangroves by their much greater diversity of leaf form, size and texture, but they also have different requirements for, and tolerances to environmental factors, such as soil pH, insolation levels, salinity and the frequency of flooding.

From this definition, Tomlinson produced a list of 34 true mangrove species, from nine genera and five families (listed in appendix one). Eighty other species, from 35 families were classified as either minor components or mangrove associates. Globally, they occupy an area estimated to be at least 170 000 km^2 (Wong & Tam, 1995) but the distribution of species is very uneven. The majority of the 34 true species occur in the Indo-West Pacific region (McNae, 1968). Neotropical mangroves are dominated by only five true mangrove species - *Rhizophora mangle*, *R. harrisonii*, *R. racemosa*, *Avicennia germinans* and *Laguncularia racemosa*, (West, 1977; Feller, 1994). The three true mangroves and one mangrove associate found in Belize[1] are listed in Table 2.1 below.

[1] For readers unfamiliar with the mangroves of Belize, photographs and descriptions of the four local mangroves can be found in appendix one.

Table 2.1 The mangroves of Belize

	True mangroves	
Common English Name	Species Name	Family
Black mangrove	*Avicennia germinans*	*Avicenniaceae*
White mangrove	*Laguncularia racemosa*	*Combretaceae*
Red mangrove	*Rhizophora mangle*	*Rhizophoraceae*

	Mangrove associates	
Common English Name	Species Name	Family
Buttonwood	*Conocarpus erectus*	*Combretaceae*

Belizean species fitting Tomlinson's "minor mangrove component" class have not been listed. This is because it is considered rather weak - it aids little in the classification of an area as either mangrove or non-mangrove, as none of the minor components need to be present for an area to be deemed mangrove. In Belize, it is only likely to be a useful distinction in areas of "mangrove mosaic" which occur at the inland boundary of mangrove distribution. As such, this class will not be employed further in the thesis.

2.2 Causes of mangrove clearance

Saenger *et al.* (1983) divide the causes of mangrove destruction into two: those due to over-exploitation of the mangrove resource by so-called *traditional* users, and secondly the destructive activities where areas covered by mangrove are exploited in a *non-sustainable* way, such as large scale clearance for aquaculture. They draw attention to the fact that the impacts of these activities occur at different scales. Figures for these activities are given in Table 2.2 below. (For example, a typical scheme of clearfelling in the mangrove may result in the removal of 10,000-500,000 ha of forest, whilst a typical waste disposal project may affect only 1-10 ha). Activities highlighted with an asterisk are those which result in actual mangrove *clearance* as opposed to what could be termed *severe disturbance* (the latter may not result in the complete loss/removal of tree cover, such as the very patchy distribution of tree mortality often resulting from an oil spill).

Table 2.2 Global causes and impacts of mangrove destruction

Activity	**Scale of impact, ha**
Clearfelling *	10,000 - 500,000
Diversion of freshwater	1,000 - 500,000
Conversion to agriculture *	100 - 100,000
Conversion to aquaculture *	100 - 10,000
Conversion to salt ponds *	100 - 1,000
Conversion to urban development *	100 - 1,000
Construction of harbours and channels *	100 - 1,000
Mining or mineral extraction *	10 - 100
Liquid waste disposal	1 - 10
Solid waste garbage disposal *	1 - 10
Spillage of oil or other hazardous chemicals	1 - 10
Exploitative traditional uses *	1

After Table 6, p33 in Saenger et al. (1983).
See text above for the significance of asterisks (added).

A third type of mangrove clearance can be called "accidental clearance". This wide class includes "natural" processes such as hurricane damage, erosion by coastal currents and suffocation by silt deposition. Human activities resulting in unintentional damage to mangroves are also included in this class, for example offshore chemical and oil spills. Such accidental clearance is considered further in Section 2.2.4.

2.2.1 Traditional uses of mangrove

Traditional usage of mangrove involves small scale, short term clearance of parts of the mangrove, where, given time, regeneration and recuperation is possible. It can be subdivided into three according to differing perceptions of the mangrove resource:

1. *Mangrove as a forest*, as a source of wood for timber and fuel.
2. *Mangrove as a habitat/hunting ground*, as a nursery for many crustaceans and fish and the harvesting of mangrove-inhabiting fauna, e.g. fish, crabs, shrimps, lizards.
3. *Mangrove as a specialist provider*, e.g. fruits and leaves for use in making medicines, as a tourist attraction and wildlife reserve.

An example of traditional usage is given in Bennett & Reynolds' 1993 study of mangroves in Sarawak, Malaysia. Mangroves are used as a source of wood for charcoal, firewood, housing materials and fishing stakes by local villagers. Their primary activity is fishing, catching fish and crustaceans which spend at least a part of their life cycle in the mangrove habitat. Nipa palm fronds (*Nypa fruticans* - a mangrove associate) are used as a roofing material and for cigarette papers. Nipa palms are also used for more species-specific activities: such as making nipa sugar and tannin. WWF Malaysia (1985), believe that the present collection levels may be sustainable indefinitely. This is in marked contrast to many of the other more commercial local activities, for example the licensed extraction of *Rhizophora* poles for pilings and scaffolding.

Site-specific usage of mangrove forest varies considerably around the globe, dependent on the range, age and type of mangrove forest species present in a particular area, the availability of alternative sources of materials (many of which may be more accessible), and also the demands of the local and regional economies. An attempt to collate the global pattern of mangrove use is given in Saenger *et al.* (1983, Table 5). They suggest that the greatest known exploitation of mangrove is occurring in South-east Asia, but as they acknowledge, a fuller interpretation of these data is hampered by a lack of accurate information. Thus we are prevented from making even very general investigations such as a possible relationship between the degree of exploitation and the number or type of species.

2.2.2 Non-sustainable usage of mangrove areas

As with the traditional uses outlined above, non-sustainable usage of mangrove varies globally, both in type and scale. However there are features common to all uses, the most obvious of which is whether the usage is a form of over-exploitation, or a replacement, of the mangrove.

Over-exploitation

This includes any activity involving harvesting of mangrove resources at a rate which is greater than the system's regenerative capability, resulting in a net loss from the system. Examples of this include large scale clearfelling for fuelwood or for charcoal-making. Such activities offer at least some potential for sustainable use, if more environmentally sensitive measures could be introduced. The simplest are modifications of existing methods - e.g. allowing longer lag periods between felling. Adegbehin & Nwaigbo (1990) suggest timber can be sustainably harvested on a 20-25 year rotation in densely stocked areas of Nigeria, 30-40 years in other parts. Alternatively they may require the adoption of different techniques of production, such as mangrove agroforestry (Weinstock, 1994).

Replacement

The second group of non-sustainable uses also involves clearance of the mangrove, but the subsequent activity physically supersedes the forest. Examples include aquaculture, where the forest is replaced with fish or shrimp ponds. Another common activity is agriculture: mangrove has been cleared across large parts of southern and south-east Asia to form rice paddies (Moormann & Pons, 1975) and to create pasture in areas where there is a shortage of flat land, such as in New Zealand, (Dingwall, 1984). Mangrove forest is also cleared to allow the construction of new industrial and/or housing developments. These processes involve the soil surface being covered with clay, rubble or even concrete before being built on, or buried by waste (as seen at the new Municipal Refuse Site on the edge of Belize City). Mining activities such as the tin extraction in Thailand, coastal sand quarrying in Puerto Rico and oil shale mining in Australia, all result in a loss of the surface soil cover (Saenger *et al.*, 1983).

Table 2.3 identifies many of the mangrove-derived products, both sustainably and non-sustainably extracted, used around the world. This listing of mangrove use complements the earlier discussion of mangrove function - as a habitat, a nursery site for many fish and crustaceans, and in providing coastal protection from waves and storms.

2.2.3 Use of mangrove products in Belize

The most comprehensive reviews to date[2] of the use of mangrove-derived products in Belize can be found in Zisman (1992) and Zisman and Munro (1992), from which much of the following is taken. In contrast with other mangrove areas of the world, little use is made of the mangrove forest in Belize except for fishing purposes and small-scale pole extraction, resulting in a negative perception of mangrove amongst the general public, something which the Belizean Forest Department has recently been trying hard to combat. Applying the categories of non-sustainable usage defined in Section 2.2.2, destruction of the mangrove is occurring for "replacement" purposes, rather than due to "over exploitation".

Table 2.3 Products of the mangrove ecosystem

Fuel	Firewood (for cooking and heating) Charcoal Alcohol	**Clothing**	Synthetic fibres (rayon) Dyes for cloth Tannins for leather preservation
Construction	Timber, scaffolding Heavy construction (bridges, dock pilings, etc.) Railway sleepers, mining pit props Boat building (hulls and masts) Beams and poles for building Flooring, panelling Thatch and matting, roof shingles Fence posts, waterpipes, chipboards, glues	**Household items**	Furniture Glue Hairdressing Oil Tool handles Rice mortar Toys Matchsticks Incense Wax Baskets
Drugs	Alcohol Cigar substitutes and cigarette papers	**Agriculture**	Fodder Green manure Manure (muds)
Food and beverages	Sugar Salt Cooking oil Vinegar Tea substitute Desert toppings Condiments from bark Sweetmeats from propagules Vegetables (propagules, leaves) Fruit Honey Fish Crustaceans Shellfish Edible birds, reptiles & mammals	**Fishing**	Poles for traps Fishing floats and fish-attracting shelters Wood for smoking fish Fish poison, tannins for net and line preservation
		Paper products	Various papers and woodpulps
		Other products	Packing boxes Wood for smoking sheet rubber Wood for burning bricks Medicines from bark, fruit and leaves Animal skin products

Based largely on Table 4, p21 in Saenger et al., 1983, data also from Soegiarto, 1984, Librero, 1984 and Jagtap et al., 1993

Early Belizean forestry reports, such as those of Hummel (1921) and an anonymous report published in 1883, take a very economic approach to the assessment of mangrove utility. As a result, they offer only rather damning appraisals, such as the frequently quoted "heavy, and of no great use" (Anon., 1883) and "...almost useless except for holding together newly accumulated soil..." (Hummel, 1921). Hummel does acknowledge that mangroves could prove "quite good for various technical purposes"

[2] These are however, really only interim reports, a more detailed analysis will be published later (Zisman, Forthcoming).

but in general large-scale economic exploitation has not occurred despite their tendency for mono-specific even-aged stands, because of :

- A lack of stands of sufficient areal extent to be economically viable for extraction.
- The generally short stature of Belizean mangroves, which again makes them less economically attractive. From the vegetation survey of Ratter & Bridgewater (1992) it can be seen that most mangroves are less than 15 m tall. Generally mangroves are shorter in the north - where the dwarf form of *Rhizophora* is common - most around 3-5 m tall, and seem to be taller in the south - some old mangrove around Deep River and Temash River (which can be found on Figure 1.2) contained *Rhizophora* specimens up to 20 m in height.
- A history of hurricane damage at many sites (see the following discussion of the tannin extraction industry). The mangroves of Belize are replete with signs of hurricane damage. Fieldwork[3] carried out in 1995 at the Turneffe Islands revealed the presence of many large old *Avicennia* and *Laguncularia* specimens, which had been snapped at a height of approximately 3-5 m above the ground. Some of these trees had obtained a diameter at breast height (dbh) of over 65 cm, significantly larger than the dbh of any live tree there today.
- The narrow tidal range experienced around Belize (c.30 cm - Kjerfve *et al.,* 1982) which creates a shallow inter-tidal zone for colonisation by mangroves.
- Problematic access, notably the swampy nature of the soils and the associated wetlands, and the impenetrable nature of *Rhizophora* prop roots.
- The existence of alternative sources from the inland forests of Belize, many of which are more suitable, e.g. oak (*Quercus* spp.) for charcoal-making and pine (*Pinus* spp.), mahogany (*Swietenia macrophylla*) and Santa Maria cedar (*Calophyllum brasiliense*) for construction purposes.

However, there have been examples of several small scale uses of mangrove in Belize in the past, which are discussed below. Most of these data originate from figures published in *Belize's Forest Department Annual Reports*. These uses are worthy of consideration because of their possible effects upon the extent and implications of future mangrove clearance.

Tannin

Hummel noted in his 1921 work that mangrove bark was used for the extraction of tannin. Certainly by the early 1950s as Zisman & Munro (1992) note, there was a flourishing tannin export industry, shipping red mangrove to Mexico. This trade came to an abrupt end in 1955 because of a sudden drop in prices, combined with the destruction of the main cutting area in Corozal by Hurricane Janet. The absence of a sustained local demand for tannin (Zisman, 1992) has prevented any resurgence in tannin extraction, and it is thought that any future exploitation of Belize's mangrove forests for tannin extraction is most unlikely, despite the very heavy exploitation of mangrove in the Mexican Yucatán.

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[3] As yet unpublished.

Fuelwood and charcoal

Modern use of mangrove as a fuelwood is minimal, confined to the small cooking fires required by those involved in fishing offshore (Zisman, 1992; personal interviews with Turneffe fishermen, 1995). Although now probably ceased due to its recent relocation, Zisman notes that before 1992 the Belize City prison used mangrove wood as a cooking fuel. It is also likely that it was once widely used locally as a cooking fuel. Large scale industrial usage of mangrove as fuelwood has always been very limited, although McShane (1991) reports that some sugar factories in Corozal had used it in the 1960s and 70s. Of the Belizean mangrove species, buttonwood (*Conocarpus erectus*) is the most suitable for charcoal production, also favoured for the smell it imparts to food whilst cooking (Munro, pers. comm.) but is inferior to charcoal derived from oak. Today, both industrial and domestic users of fuel have moved away from mangrove sources, to electricity and paraffin stoves and propane gas as these sources have become cheaper and more widely available. No large scale return to using mangrove as a fuelwood is thought likely.

Timber

Historically mangrove timber has been used in construction, *Rhizophora* timber is especially favoured for its strength, durability and insect resistance. Whilst both red mangrove and buttonwood are still used for construction in some areas, as Zisman & Munro (1992) report, most housing today uses more modern materials, particularly pre-cast concrete blocks. However, some localised small-scale extraction of mainland mangrove timber still occurs, for the construction of tourist *cabanas* on island resorts such as San Pedro (Zisman & Munro, 1992). Given the expanding nature of Belize's tourism industry, this small scale extraction of timber is likely to continue, even increase slightly. However it is expected to be confined to areas already experiencing, or very close to, tourist developments. Red mangrove poles have traditionally been used to make scaffolding uprights, but their use is on the decline, being replaced with sawn timbers from inland forests (Zisman, 1992). These timbers are now more freely available because of improvements in the availability of transport and an upgrading of the road system.

Boat construction

Reports of the use of mangrove wood in boat construction are limited. Whilst Zisman draws the reader's attention to the absence of any mention of mangrove in Craig's 1966 description of woods used for boat building, Munro, in his analysis of interviews with coastal communities around Belize (Zisman & Munro, 1992) reports that red mangrove wood had occasionally been used to fashion boat ribs. In common with other mangrove areas of the world, buttonwood has also been used for masts. With the wide availability of more suitable timbers, and boat construction shifting away from wood towards glass fibre, the amount of mangrove wood felled for boat construction today is negligible.

Fish traps and marker poles

One area where mangrove wood is still in use is in fishing related activities. Mangrove poles are used to mark the location of fishtraps, lobster pots and navigable channels. Although now very much in decline, mangrove poles were also used to create fishtraps known locally as "weirs" (Zisman, 1992). Such usage involves only very minor disturbance to the mangrove and is not thought that such limited extraction will play a significant role in any future forest clearance.

Foods and medicines

In comparison with the large number of plant materials and remedies from the interior forests of Belize, mangrove products are insignificant. Local villagers interviewed by Munro told of only a very limited usage of mangrove products. Fruit of the red mangrove had been used to make wine or add flavour in cooking, some claimed potency for wound treatment, and a red mangrove tea was used to cure diarrhoea. Zisman (pers. comm.) tells of a local market trader who used boiled up mangrove bark as a treatment for Athlete's Foot. Zisman (1992) looking for examples of potential large scale exploitation writes of a Canadian investigation of Belize as a suitable site for monosaccharide extraction from red mangrove forest. However Belize proved unsuitable due to the lack of large areas of tall trees. Although the sale of traditional "forest remedies" seems to be a growth area in Belize, it is thought that these will continue to be sourced from inland forests, and so result in very little damage to the mangroves.

Harvesting of mangrove fauna

Zisman and Munro document a long history of subsistence-level hunting in the mangrove for creatures such as the blue land crab (*Cardisoma guanhumi*), and more rarely the mangrove oyster (*Crassostrea rhizoporae*). Mangroves are also used as hunting grounds for both eggs and adult waterfowl and reptiles. Crocodiles have been hunted in these areas too in the past. The exact extent of such activities today is unknown. Crab-hunting is still commonly practised, but for local consumption, rather than on a large scale for export.

Fishing

The greatest dependency upon mangroves in Belize, comes from those involved in the near and offshore fishing industry. Many commercial species of shrimps, lobster and fish have a larval and/or nursery stage in the mangrove, (Hamilton & Snedaker, 1984). An additional source of income noted by Zisman (1992) is from "sports" fishing along mangrove creeks and around mangrove cayes. Such usage relies upon the maintenance of the mangrove as both a habitat and source of food, and so should not result in further clearance.

Mariculture/aquaculture

Whilst in many other countries, large areas of mangrove have been lost to shrimp and fishponds, in Belize the industry is still in its infancy. Because of local soil conditions and the low tidal range, most of the shrimp farms developed to date have been located *behind* the mangrove fringe, minimising their impact (Zisman, 1992). Four out of the seven shrimp farms in 1991 were not operating commercially, suggesting that conditions were not particularly suitable. However there are signs of a recent renewal of interest in shrimp farming, such as the new Taiwanese-backed experimental shrimp farm, near the *Punta del Este* development on Belize's Western Highway. Such farms are probably attempting to service the growing demand for shrimps from both locally-based tourists and for export.

Thus in Belize, the greatest use made of the mangrove today is by those involved in fishing-related activities. Those who catch fish, crabs and shrimps which live or have grown up in the mangrove ecosystem are effectively dependent upon the *preservation* of the mangrove. Although still in its infancy in Belize, aquacultural activities pose more of a threat, requiring the clearance of areas of land near the coast for pond-creation and the risk of polluting surrounding areas with pesticides. More traditional exploitative activities such as fuel and timber extraction have always been relatively small when compared with other countries, and today have declined to relatively negligible amounts. Yet as will be shown in the later discussion of mangrove destruction rates, clearance in Belize today is accelerating, suggesting that it is being driven by other demands.

2.2.4 Natural and anthropogenic causes of accidental "clearance"

As well as the purposeful clearance methods outlined above, for completion, the following three causes of disturbance to large areas of mangrove should also be considered: hurricanes, salinity and sedimentation changes and chemical spills.

Hurricanes

These are relatively common in Belize. In recent times three hurricanes, the 1931 hurricane, Hurricane Janet in 1955 and Hurricane Hattie in 1961, have resulted in the flattening of large tracts of mangrove forest. The effects of Hurricane Hattie (shown in Figure 2.1 and extensively documented by Rickards, 1962 and Stoddart, 1963) can be seen in the relative youth of much of the mangrove forest south of Belize City today. Such regrowth provides evidence that these activities in themselves are not fatal. Jimenéz and Lugo (1985) have shown that because of features such as their large propagule production, sharp zonations and even-aged stands, mangroves are adapted to a rapid cycle of growth and mortality.

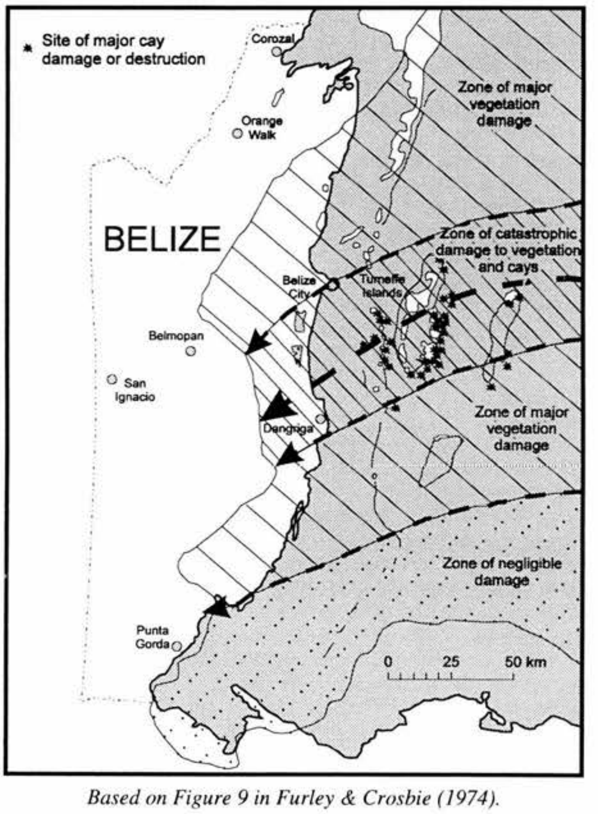
Salinity and sedimentation changes

Whilst being halophytic, mangrove species are still sensitive to salinity levels. Saenger *et al.* (1983) discuss examples from the Indus, the Nile, the Ganges and the Ord River, Australia, where human intervention (barrage creation, irrigation schemes, etc.) has resulted in a decrease in freshwater runoff downstream. This results in particular plant stress during the dry season, impeding growth, and in extreme cases, resulting in mass tree mortality, as occurred over 18 ha of *Rhizophora stylosa* forest near Cairns, Australia. In Belize as yet, there have been no large scale examples of such mangrove damage. However caution should be drawn from a few small-scale examples of wetland damage, mostly as a result of road construction. A recent example of this was at Crooked Tree Lagoon, where the construction of a causeway in 1991-2 ponded up water behind it, almost resulting in the death of trees in the lagoon before large culverts were added.

Chemical spills

The accidental introduction of large volumes of toxic substances such as hydrocarbons, pesticides and herbicides can have serious effects upon the vegetation cover. In a series of articles looking at the Galeta oil spill off Panama, Burns *et al.,* (1994a-d) consider its long term effects. As well as the immediate defoliation, limb loss and collapse of trees due to oiling, they discovered that because of the anoxic conditions in mangrove sediments, such toxins show an unexpected persistence in the substratum over time. Whilst offshore areas of Belize have been investigated by petrochemical companies, the shallow waters and coral reefs around the Belizean coast serve to ward off large volume tankers, so far sparing Belize from the effects of a major toxin spillage.

Figure 2.1 Destruction caused by Hurricane Hattie



Based on Figure 9 in Furley & Crosbie (1974).

2.3 Mangrove distribution in Central America

Before considering the rate of mangrove clearance in Belize, it is worth looking at the regional context of mangrove distribution in Central America. Precise measurement of a country's area of mangrove forest is difficult, this can be seen in the range of values given in Table 2.4. In part, this may be the result of different methods used - the refinement of remote-sensing techniques has meant that many previous estimates have had to be revised. (The latest estimate of Belize's mangrove cover is based on the *Second National Mangrove Map* satellite-derived data). Despite these differences between individual worker's estimates, the table reveals that even though Belize is one of the smallest Central American countries (by area), it has a significant amount of the remaining mangrove forest in this region, far more than may have been expected. In part,[4] the explanation for this can be seen in its low population and thus population density, by far the lowest of any Central American country[5] and thus a relatively low pressure upon the coastal zone. (However there are localised areas experiencing extreme pressure in Belize, such as Belize City, Ambergris Cay and Placentia. These will be considered further in Section 2.5.1).

There are relatively little published data detailing the proportion of mangrove already cleared, an exception is the WRI (1990) estimate that Guatemala has cleared 60% of its pre-development area of mangrove. It is thought likely that the figures for many of the other countries of Central America will also show that at least half of the original mangrove cover has been lost. The WRI (1992) report notes that the published estimates of mangrove loss in tropical countries world-wide, show an average removal of well over 50% of the pre-development area.

Table 2.4 Estimates of the area of remaining mangrove forest (sq. km) in parts of Central America

Country	Total area (sq. km)	Population 1989	Mangroves *Bossi & Cintron (1990)*	Mangroves *Snedaker (1991)*	Mangroves *WRI (1992)*	Mangroves *latest*
Mexico	1,972,547	86,400,000	14,202	6,600	14,200	
Nicaragua	129,494	3,500,000	600	600	600	
Honduras	112,088	5,100,000	1,450	1,450	1,170	
Guatemala	108,890	9,100,000	160	500	160	
Panama	78,200	2,400,000	2,975	4,860	2,980	
Costa Rica	51,100	3,000,000	350	300	350	
Belize	**22,693**	**176,000**	**750**	**770**	**780**	**772**[a]
El Salvador	21,041	5,100,000	na	450	450	

Sources: Area and Population data from PC Globe Inc.(1990); [a] *Zisman (1992).*

[4] Relating mangrove area to the total area of a country is rather crude - the length of coastline would probably be a more realistic indicator, given mangroves' littoral habitat preference, but calculation of the length of coastline is hampered by the presence of numerous offshore cayes in this region, where the coastline-land area-mangrove cover relationship may differ significantly from mainland situations.

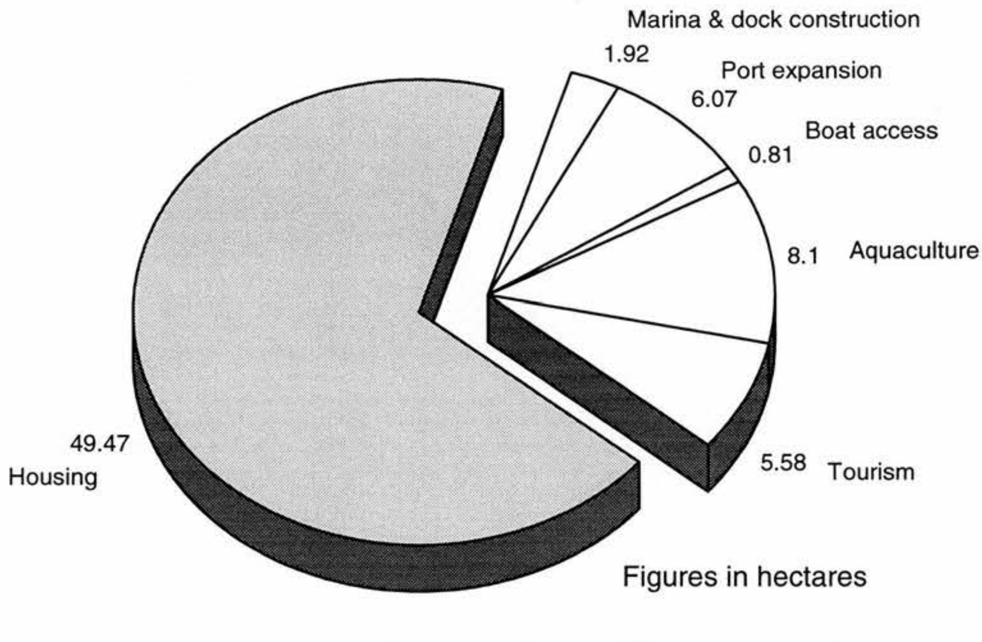
[5] Even though it has shown a marked rise, recently breaking the 200,000 barrier - the 1993 census gave a total population figure of 205,000 people (Government of Belize, 1994), reflecting the recent influx of refugees from Guatemala and El Salvador.

Belize's lower population density and more concentrated pattern of coastal development makes it likely that it still retains well over three-quarters of its pre-agricultural mangrove cover (Zisman, pers. comm.). Yet this large area of remaining mangrove is not a reason for complacency, rather it gives added impetus to the conservation argument. Belize contains mangroves *worthy* of protection - large *connected* areas of fringing, island and basin forest mangrove, backed with lagoons and saltmarshes ensuring a vital unimpeded flow of water. From a global perspective these forests are still relatively undisturbed, able to support a considerable range of floral and faunal species.

2.4 Causes of clearance in Belize

The consideration of traditional uses of mangrove above, has shown that little currently occurs in Belize. Yet clearance of mangrove forest is accelerating, showing that forest destruction is still occurring. Reasons for this clearance, which could be classified as forest replacement activity, are found in an analysis of national mangrove clearance applications shown in Figure 2.2.

Figure 2.2 Purpose of proposed clearance by area May 1989-June 1992, inclusive



Data from Forest Department of Belize/S. Zisman, pers. comm.

This pie chart shows the results of Zisman's (1993) analysis of all the permit applications to cut mangrove (a total of 71.95 ha), received by the Belizean Forest Department between 1989 and 1992, i.e. the first three years after the introduction of the *1989 Forest (Protection of Mangroves) Regulations* (See Section 3.9 for a fuller discussion of the relevant legislation). The classes shown are an amalgamation of those adopted by the Forest Department. The area of forest actually earmarked for clearance during this period is likely to be much higher than the figure shown, because of illegal clearance, by both developers and individuals. Zisman (1992) estimates that 90% of the forest clearance occurring at this time was without permission.

This study predates the enforcement activities of the Forest Department, which their creation of the post of "Mangrove manager" has allowed. It does not cover local small scale extraction of individual trees for timbers or fishing poles, for which a separate (BZ$1) annual permit is required (though both the application rate and enforcement activity have been very low to date (Zisman, pers comm.)). Whilst informative, the data are far from perfect indicators, physical clearance of the mangrove *may*[6] lag behind the permit application, meaning that the correspondence between the actual area cleared over this period and the area applied for, may be rather weak.

Despite these limitations, these data do corroborate an impression gained from personal observation of mangrove clearance around Belize - that the vast majority of clearance seems to be for the building of *housing* (nearly 70% of the area covered by permit applications). This is significant, in that the situation in Belize *differs* from that in most other countries, where the primary causes of mangrove destruction are cutting for firewood, clearing for fishponds and agriculture, and roadbuilding, (shown in Table 2.5 below).

Table 2.5 The three principal causes of mangrove clearance for some selected countries

Ranking	El Salvador	Philippines	Malaysia	Belize
1	Firewood & charcoal extraction	Fishpond creation	Road building	Housing
2	Clearing for salt-making	Extraction of fuel-wood and timber	Coconut plantations	Port expansion and commerce
3	Clearing & draining for commercial agriculture (mostly cotton and coconut palm plantations)	not given	College and housing construction	Creating tourist facilities - marinas, piers, beach frontage, etc.
Source	*Daugherty (1975)*	*Librero (1984)*	*Bennett & Reynolds (1993)*	*From Figure 2.2*

This in turn, reflects the differing structure of Belize's economy - agriculture is far less important than in many developing countries. Only 20% of the country's GNP was from agriculture in 1990, 61% was made up from the service sector, notably tourism (PC Globe Inc., 1990), an industry of increasing significance in the Yucatán Peninsula as a whole. The agricultural activity is focused inland - Belize's primary agricultural exports are sugar, citrus and bananas (Hartshorn *et al.*, 1984) - which cannot tolerate high salinity. This means that at least agriculturally speaking, most of the coastal land is suitable for little but rice. Evidence of failed previous agricultural attempts can be seen from names on old maps, such as *Cucumber Beach*, south-west of Belize City, the site of an aborted attempt in the 1960s to grow cucumbers, part of which was on an area of reclaimed wetland (Furley, pers. comm.).

[6] Although even in July 1994, clearance activity was observed near the *Punta del Este* site, for which a permit had not been obtained. Speculative clearance to "force" permits, will continue until a system of heavy fines for offenders is introduced. For an informed discussion of this, see Zisman (1993).

2.5 Mangrove clearance occurring in Belize

The national picture is highly varied, due to both the highly uneven population distribution (and so demand for housing) and variations in the mangrove-sediment systems found along the coast. The pattern of calcareous-dominated sediments in the north, giving way to organic-dominated material in the south (Furley & Minty, 1992; Ross, pers. comm.) together with variations in the pattern of rainfall may account for an increasing height of timber and a greater diversity of bromeliads, epiphytes, etc. in the mangrove as one moves south.

The present extent of mangrove has been established as 77,155 ha (772 sq. km), in the 1992 Second Series *National Mangrove Map* (published in Furley & Ratter, 1992). This used a combination of aerial photograph, Landsat TM, and Spot imagery interpretation, with extensive ground truthing via field and aerial survey. However it is far more difficult to obtain estimates of the extent of previous cover, relying on a very patchy historical aerial photo cover combined with local written and verbal records. No national reconstruction of Belize's past mangrove cover has been published[7], but a 1991 study of the Belize City area by McShane (considered below), provides a useful insight into this, the most dynamic region of clearance.

2.5.1 Notable clearance concentrations

With the new capital, Belmopan, built well inland from the main mangrove areas, the greatest residential-driven clearance is found around Belize City. The ex-capital, and still Belize's primate city, it contains over a third of the national population, (Hartshorn, 1984; Government of Belize census statistics, 1994). Its population continues to grow, fuelled by the city's continuing status as *the* commercial and economic magnet in the country. This is shown in Table 2.6 below, where Belize City continues to secure the largest single share of development concessions. Two harbour developments, one at Big Creek, creating deep water port facilities, and the other to the south of Belize City have also resulted in the removal of considerable areas of mangrove (Griffiths, pers. comm.).

Mangroves have also been cleared to allow expansion around other coastal settlements such as Dangriga, Punta Gorda and Corozal. Increasing or improving tourist facilities also seems to require mangrove clearance - creating beach frontage, boat access and clearing land for hotel and marina construction along the coast. This can be clearly seen around Ambergris Cay (McMinn, 1992), Placentia (Brately *et al.*, 1993) and on Caye Caulker (Lishman, 1994) and many of the other offshore

[7] Mangroves receive only minimal description in Standley & Record's 1936 botanical assessment of the country. Wright *et. al.'s* 1959 1:250,000 *National Vegetation Maps* do show three broad mangrove communities, but these are not detailed enough to allow reconstruction. A 1948 "First Edition" *National Vegetation Map* has recently been rediscovered in Belmopan, (Zisman, pers. comm.). It claims that at that time, 2.8% of the country (i.e. 635 sq. km) was covered by mangrove, but little confidence can be placed in this figure as it is smaller than the estimate of remaining mangrove cover today.

cayes. Clearance is also expected to accelerate around the Maskall River, as it provides easy inland boat access for tourists staying offshore at San Pedro and Ambergris Cay.

Table 2.6 District development concessions in Belize 1985-1991

District	1985	1986	1987	1988	1989	1990	1991
Corozal	0	4	1	4	4	1	0
Orange Walk	0	2	2	6	2	0	1
Belize City	4	8	12	12	24	15	12
Cayo	1	4	2	9	4	4	3
Stann Creek	1	5	7	4	6	8	3
Toledo	0	2	2	4	2	4	0
Total	6	25	26	39	42	32	19
%Total in Belize City	67	32	46	31	57	47	63

Primary data from Munro & Zisman (1992)/Ministry of Economic Development, Belmopan

2.5.2 Rate of clearance around Belize City

Figure 2.3 shows the amount of mangrove clearance which had occurred around Belize City by 1993. This map was based upon an early version of McShane's (1991) clearance study map, updated by Zisman in 1992 using aerial photographs, the initial *National Mangrove Map* and field study. McShane's work used a smaller study area than the other sources, restricted to land east of the Haulover Creek and Burdon Canal. Figure 2.3 was therefore further updated using the revised *Second National Mangrove Map* to establish the inland boundaries of the medium and dwarf mangrove units, supplemented by personal observations and oblique aerial photographs taken during the 1992 and 1994 field seasons. For reasons of continuity and because of difficulties in distinguishing between individual mangrove species in aerial photographs, this map uses the revised units of the *Second National Mangrove Map*.

They are defined as:

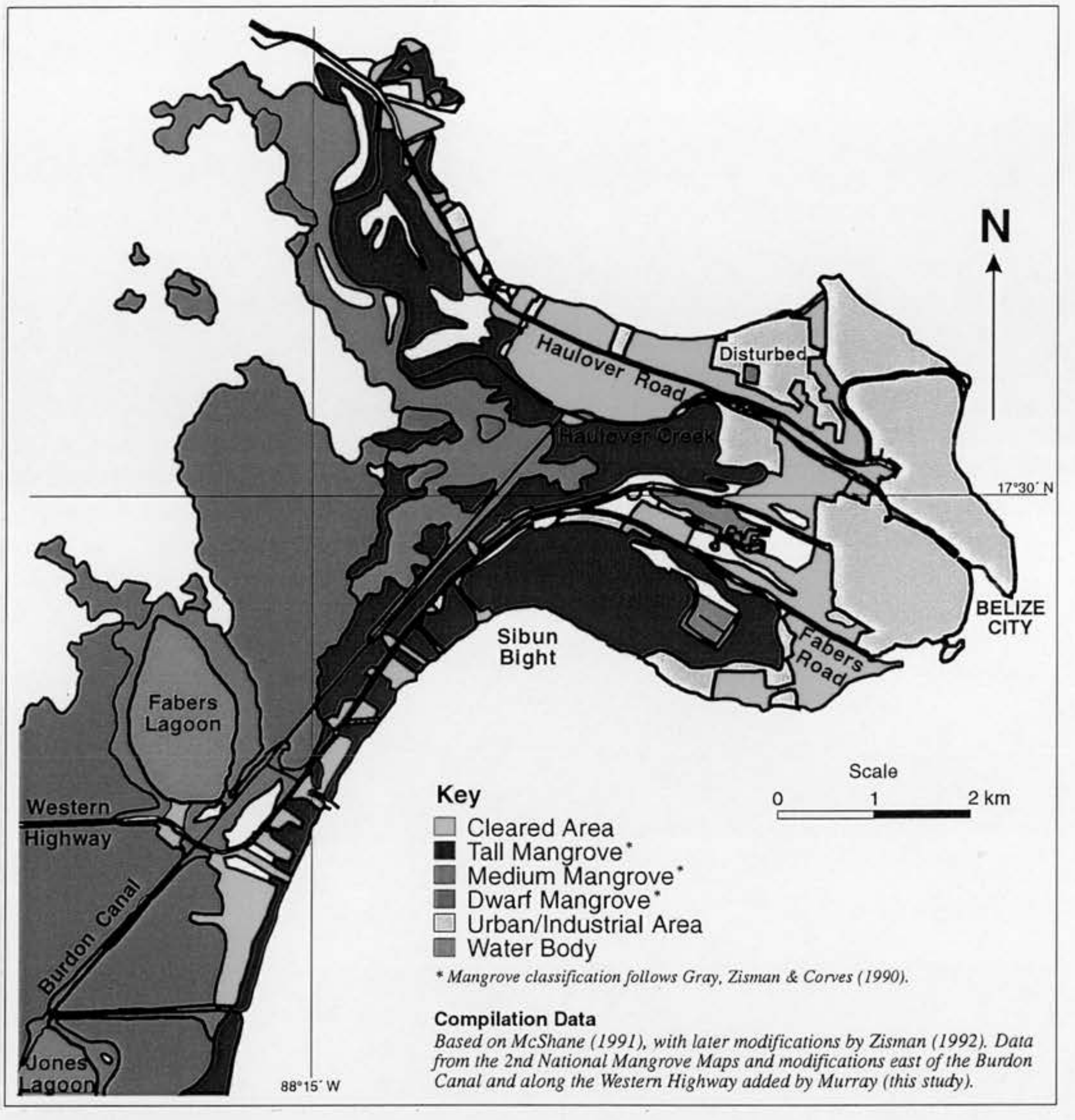
Dwarf mangrove	Approx.	below 3m tall
Medium mangrove	Approx.	3m - 8m
Tall mangrove	Approx.	greater than 7m tall.

Given in Zisman & Munro (1993).

Clearance can be seen to be concentrated around the present urban area, radiating out along the two main roads, the Haulover Road (later the Northern Highway) and the Western Highway. Since producing this map, there has been considerable further clearance along the Northern Highway.

Clearance of mangrove around Belize City is accelerating. McShane (1991) attempted to quantify this using a time-series analysis of aerial photographs combined with field reconnaissance. He estimated from the earliest available source - the 1939 aerial photograph coverage - that at this time, approximately 90-93% of the original mangrove cover remained. This figure was calculated by comparing the areal extent of mangroves at that time with an estimated complete (original) cover figure.

Figure 2.3 Mangrove clearance around Belize City, 1993



This original cover figure was generated by adding to the 1939 figure the area of coastal land covered by urban development at that time, assuming that it would have once too been mangrove. (McShane, pers. comm.). Having obtained an estimate of the initial conditions, he was able to consider changes in the rate of mangrove clearance, as shown in Table 2.7.

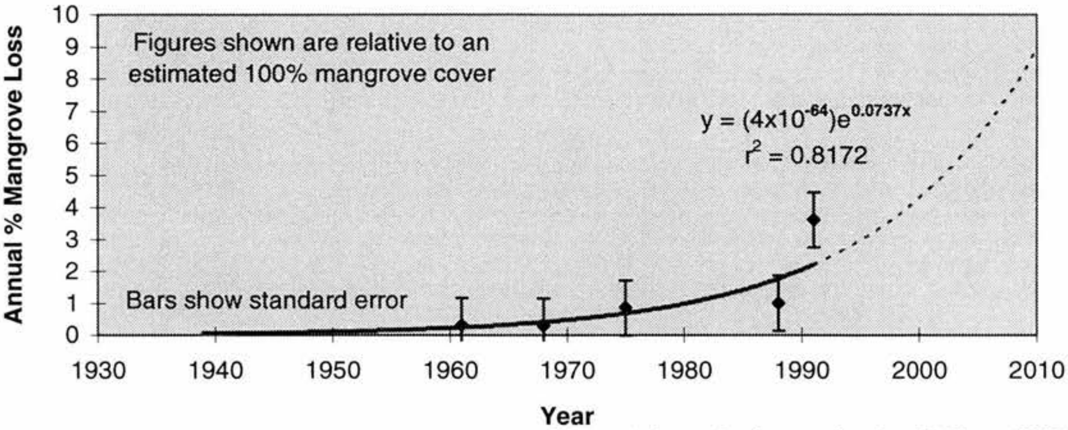
Table 2.7 Clearance of mangrove forest in the Belize City area, 1939-1991

Year	% Forest remaining	% Change	% Annual clearance
1939	90-93	unknown	unknown
1961	84	9	0.3
1968	82	2	0.28
1975	76	6	0.85
1988	63	13	1.0
1991	52	11	3.6

Source: McShane, (1991).

These data are graphed in Figure 2.4, showing a notable increase in the rate of clearance. The displayed best fit line of *exponential* increase, rather than a more *linear* rise, is due mainly to the very high 1991 figure. If this is unrepresentatively high, then these data may be a considerable over-estimate.

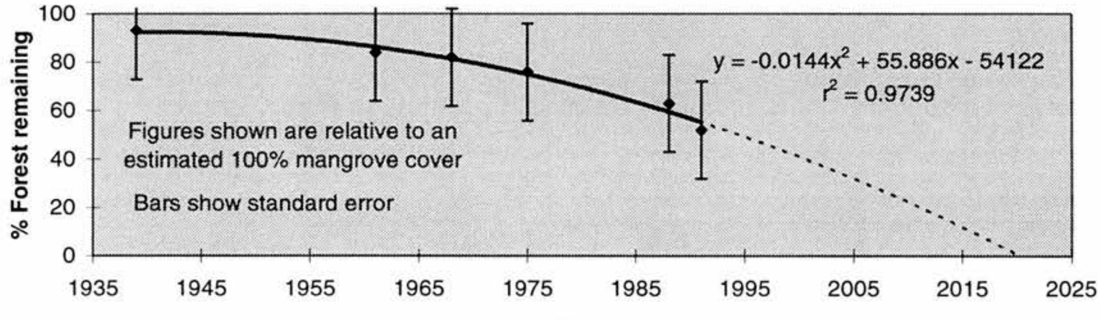
Figure 2.4 Annual percent loss in mangrove forest cover



Exponential curve fitted to raw data from McShane, (1991). Dotted line indicates the area of forward projection.

Graphing the decrease in mangrove forest cover (Figure 2.5) similarly shows an increase in the rate of change. In his original interpretation, McShane extrapolates his data, claiming that if forest clearance continued increasing, there would be effectively no mangrove left by 2006. His "total clearance" date differs slightly from that shown below (c.2020) in this re-interpretation, because a different trend line is used here, giving a better fit to the data.[8] As McShane (1991, 1993) himself acknowledges, a high degree of caution should be exercised when interpreting such a projection. Mangrove deforestation is unlikely to continue at the same rapidly accelerating rate. With the creation of Belmopan as the new administrative capital in 1971 and the recent migration of government and foreign projects there, demand for housing around Belize City may in time decay.

Figure 2.5 Decreases in Belize's mangrove forest cover, 1939-1991



Second order polynomial fitted to raw data from McShane, (1991). Dotted line indicates the area of forward projection.

[8] McShane extrapolated a linear trend line using only the data from 1989 and 1991, assuming that this would give the best estimate of future clearance. Such a line ($y = -3.67x + 7352.3$) is a poor fit of the data as a whole (particularly the data before 1988). A simple linear regression line, ($y = -0.734x + 1521.1$) fits the early data, but because of the accelerating rate of clearance, under-estimates the later rates of clearance, yielding an r^2 value of only 0.876. The second order polynomial fitted here, has a far better fit with the data ($r^2 = 0.974$).

If plans to create satellite settlements such as Ladyville succeed, then the requirement for land may be met from non-mangrove sources. The increased efforts of the Departments of Forestry and Fisheries to enforce the mangrove protection regulations, may succeed in discouraging future illegal clearance. Together with a projected increase in the costs levied for clearance[9], this may make construction in mangrove areas far less commercially attractive. Although much of the present housing stock in Belize City is in a relatively poor condition requiring major renovation or replacement, (Fairweather *et al.*, 1989), the demand for more houses is not infinite, and will depend on the future demographic trends and the national distribution of employment opportunities. More difficult to predict is the impact of aquaculture upon future mangrove clearance. This is dependent upon the success of the present, largely experimental, shrimp farms in Belize, modified by trends in both local and regional demand for shrimps, together with the future political and legislative position.

Complete clearance of the mangrove forest around Belize City should not happen. Some areas of forest, distant from both roads and urban centres, are unlikely to be developed due to a lack of demand and the low likelihood of an economic return. Many other areas of mangrove should not be cleared - protected by government legislation, as nature reserves, forest reserves, etc. The Burdon Canal Nature Reserve is the only land around Belize City currently designated either as a forest reserve or a nature reserve, but Hartshorn *et al.* (1984) have identified another area from the north of Haulover Creek to St. George's Cay as critical habitat for both West Indian Manatee (*Trichechus manatus*) and Morelet's Crocodile (*Crocodylus morleti*), both of which spend their life in and around mangroves. Further changes are expected through the implementation of Belize's Coastal Zone Management Plan (CZMP).

The trends seen are, as has already been noted, very dependent on the 1991 data for their rapid steepening. If this was a freak year then an over estimate will result. There are several reasons why doubt can be cast on the validity and representativeness of this figure. The 1991 figure, unlike the others, took advantage of the recently produced *National Mangrove Map* which was derived from Landsat TM data. This first edition of the map had some error problems, notably misclassification of areas of riparian forest as mangrove (Zisman, pers. comm.), which could lead to an under-estimated rate of clearance. The period over which the 1991 datapoint was averaged is the shortest of any in the study and so is the most vulnerable to error due to highly atypical results. The datapoint could easily be an over-estimate of the rate of clearance - 1988-1991 was a period when several very large clearance schemes were implemented - the 1989 Corozal experimental shrimp farm, clearance on Ambergris Cay for hotels, as well as large residential projects around Belize City, e.g. the *Punta del*

[9] In his final report to the Forest Planning and Management Project team as mangrove specialist, Zisman (1993) suggests a radical increase in the costs of developing mangrove. As well as raising the costs of clearance, he suggests restructuring the sliding scale of clearance costs to penalise large scale clearance projects, together with the introduction of a new payment, paid by all developers, to compensate the people of Belize for the permanent loss of mangrove benefits.

Este development (5000 planned lots on 240 ha) and *Vista del Mar* scheme (548 lots on 120 ha), possibly fuelled by the impending elections in 1989 and doubt about the re-election of the government.

It is unlikely that clearance at this rate and scale will be maintained. Already, as McShane (1993) has noted, the price of a government supported housing lot at *Vista del Mar* has had to be dropped from BZ$7000 to BZ$5000 (US$3500 to US$2500[10]) to boost sales. He further suggests that the volume of housing being built and the sales price, imply that the target market is not local. These two schemes alone provide more than the 5221 additional houses which Fairweather *et al.* (1989) predict will be required in Belize City by 1995. Although most schemes contain some government supported lots and there are areas of new low-cost housing being built - e.g. the *Fabers Road* developments and the *Bellama* project on the Northern Highway - McShane draws attention to the high prices being asked for prime sites. At over BZ$20,000 for well located coastal plots, these are outwith the financial resources of most of today's residents of Belize City. Instead he suggests that these developments are aimed primarily at only the high income Belizeans and the second home market for ex-Belizeans now living abroad. Future clearance activity will thus be influenced not only by the local economy and housing demands, but also those of countries where there are significant numbers of Belizean immigrants, notably the United States.

2.6 Methods of clearance

The effects of clearing the forest (and the resulting land-use) upon the remaining mangrove next to the developed site, is dependent on the method(s) of clearance employed. Although there is little published literature concerning differing methods of mangrove forest clearance around the world, the experiments carried out in this research, together with parallels drawn from studies of differing clearance methods in other tropical forest types, can provide an understanding of the general processes involved.

In Belize, from personal observation and conversations with local developers, contract workers and the *Forest Department Mangrove Manager* (Mr. George Hanson), the following sequence of clearance emerges:

1. Identification of land ownership (and application for a clearance permit).
2. Survey of land parcels - marking out the area to be cleared (not always carried out on small sites or areas undergoing only partial clearance).
3. Felling of timber (usually by machete, more rarely by bulldozer).
4. Timber left to dry out.
5. Drainage ditches dug (again, usually only found on large clearance schemes).

[10] The Belizean Dollar (BZ$) is tied to the US Dollar at a fixed exchange rate of BZ$2.00 equals US$1.00.

6. Fallen timber removed or rarely burnt, and/or pushed into the soil.
7. Surface levelled by hand or in larger schemes, using fixed blade bulldozers.
8. Clay-rich fill and rubble used to raise the surface of the site above that of the groundwater and tides.
9. Site levelled again.

These methods lead to complex changes in the soil which can be split into two groups - physical and chemical effects. The first physical effect is the possibility of soil compaction, because of trampling or the heavy machinery used on site. This increases bulk density and reduces soil pore-space. With the forest cover removed, the soil surface is exposed to the sun and increased wind velocities, and so may become desiccated and later deflated from the site. Chemical changes in the soil are linked to the presence or absence of water in the mangrove sediments. Before clearance, the soil is likely to be waterlogged for much of the time, giving rise to anaerobic, strongly reducing conditions. If the site is drained, then air will replace water in the soil pore spaces, resulting in the development of aerobic, oxidising conditions. This change in redox state results in changes in the ionic state of materials in the soil - sulphate to sulphide, ferric (iron III) to ferrous (iron II), manganic (manganese IV) to manganous (manganese II), nitrate to nitrogen gases, etc. (Boto, 1984). These changes can have significant effects on the soil conditions, for example an increase in soil acidity, and thus alter the plant species which it will support.

Following drainage the soil is then effectively smothered in a layer of iron-rich clay fill, quarried from inland sites alongside Belize's Western and Northern Highways. Critical to the effect this will have on soil is the presence or absence of water. If water is contained within the clay, or remains trapped in the mangrove sediment below it, then anaerobic reducing conditions will re-establish themselves. If the fill is dry, and remains so, then there is a possibility for an oxidised surface soil layer to develop above the water table. These changes and their resulting effect upon the final impact of mangrove clearance activities are detailed in the following chapter.

2.7 Summary

Global causes of mangrove clearance have been divided into two types: *traditional exploitation* of the mangrove resource, and *non-sustainable exploitation*. The nature of the activity is seen to determine the scale of clearance. This varies from the removal of individual leaves and branches for medicinal purposes, to large scale clearfelling projects affecting thousands of hectares.

Globally many products are derived from mangroves, from firewood to tea substitutes, but in Belize, little such use is made of mangrove resources. This is because of a variety of factors, including the relatively small species pool in Belizean mangroves and the existence of many alternative sources of such products from the terrestrial forests inland. Generally, the use of Belize's mangrove forests compares poorly with the large scale exploitation found in many other areas such as the Matang, Thailand (Gong & Ong, 1990).

Two reviews of historical mangrove use in Belize have been re-evaluated to estimate current and future demand for forest clearance. Apart from its traditional protective role, the greatest resource value of the mangrove today, rather than just a source of land, is based on fishing-related activities. Inshore and nearshore fishing depends upon the mangrove which acts as a habitat and nursery for many commercial species. Mangrove is also seen as a potential site for aquaculture. As yet in Belize the latter is still largely in an experimental stage, but could expand requiring the clearance and ponding of large areas of mangroves.

Within a Central American context, Belize has a large area of mangrove forest, far more than would be expected from its area or the length of its coastline. Although exact figures are unavailable, it is thought that unlike most of the neighbouring countries, Belize still retains over three-quarters of its pre-colonial mangrove forest cover (Zisman, pers. comm.) making it unusual in global terms. Belize has also been found to differ from many other countries in the forces driving this clearance. Whilst in most other parts of the world, clearance is driven by the demand for wood, or land for agriculture, Section 2.4 shows that in Belize the chief causes are boat access, harbour construction, tourist related development and most importantly, housing and commercial expansion. Belizean mangrove clearance is still at a relatively small scale, carried out by contractors and speculators attracted by the demand for land on the urban periphery. As a result of this, the distribution of clearance is very uneven, concentrated around large coastal settlements and tourist resorts.

Different methods of mangrove clearance are not widely reported in the literature, but local enquiries and personal observation has allowed a picture of clearance methods in Belize to be produced. The implications of these methods and the changes they cause in the mangrove environment are the focus of the remainder of this thesis. The effects of clearance are considered in the next chapter.

3

The effects of mangrove clearance

Exploring the effects of mangrove clearance and drainage

Having identified the causal forces of mangrove clearance, the next step is to quantify the effect of such clearance and drainage upon the environmental properties at the field sites. This chapter begins this investigation by considering how mangrove clearance affects local environmental processes. The most logical route of inquiry would be to create a fully quantified model of a mangrove's nutrient budget, but as is shown below, our knowledge of the system is insufficient to allow this. Instead, a semi-quantitative model is developed which combines known and inferred flows and storage of materials within the mangrove ecosystem. From this, a series of predictions are made concerning the expected pattern of change in physical and chemical properties which can be measured in both cleared and remaining areas of mangrove. In the discussion which follows, drainage conditions at the site are shown to be important in determining the specific outcome of these hypothesised changes in any given location.

3.1 How mangrove clearance affects environmental processes

A useful approach in studies of change is to consider the impact and effect of the induced change upon the ecological processes occurring in that area. One such method of modelling the movement of energy and materials is to develop nutrient cycles. There have been several attempts to create energy-budget models for the mangrove e.g. Miller's (1972) model of bioclimate, leaf temperature and primary production in red mangrove canopies. These focus upon the flow of materials, elucidating relationships and directions, expressing the models in an algebraic, mathematical flow diagram or in a form similar to an electrical circuit-diagram. Whilst illustrative, they tend to focus upon above-ground energy movements and so fail to quantify the soil links and water budgets necessary for a complete nutrient budget model. Other studies, such as Gong & Ong (1990) have quantified the partitioning of biomass in mangroves, measuring the distribution of a range of nutrients in different parts of the plants, both above and below the soil surface, but again, fail to combine this with similar measurements for mangrove soils. A notable exception to this is the model of carbon flow and storage produced by Lugo & Snedaker (1975) for the Rookery Bay Forest, Florida. This recognises the role of soil and peat in the model as carbon stores, but the flow of carbon through these remains unquantified. The development of a quantified mangrove nutrient budget requires the detailed measurement of a wide range of physical and chemical properties (e.g. litterfall, decomposition, evapotranspiration and photosynthesis rates, soil, water and biomass chemical composition). As yet, no complete single-site study has been carried out in Belize, or indeed in any other mangrove area[1]. Whilst published data exist for individual parts of the nutrient budget, combining them is made difficult because of the many sources of variation in the system, operating at a multitude of scales, both in space and time. Proctor (1987) produced a very detailed discussion of potential sources of error present in attempts to quantify nutrient cycling in tropical rainforests, stemming from differences in analytical techniques, sample sizes and definition of the sample population used. His findings are equally applicable to studies in mangrove forest areas.

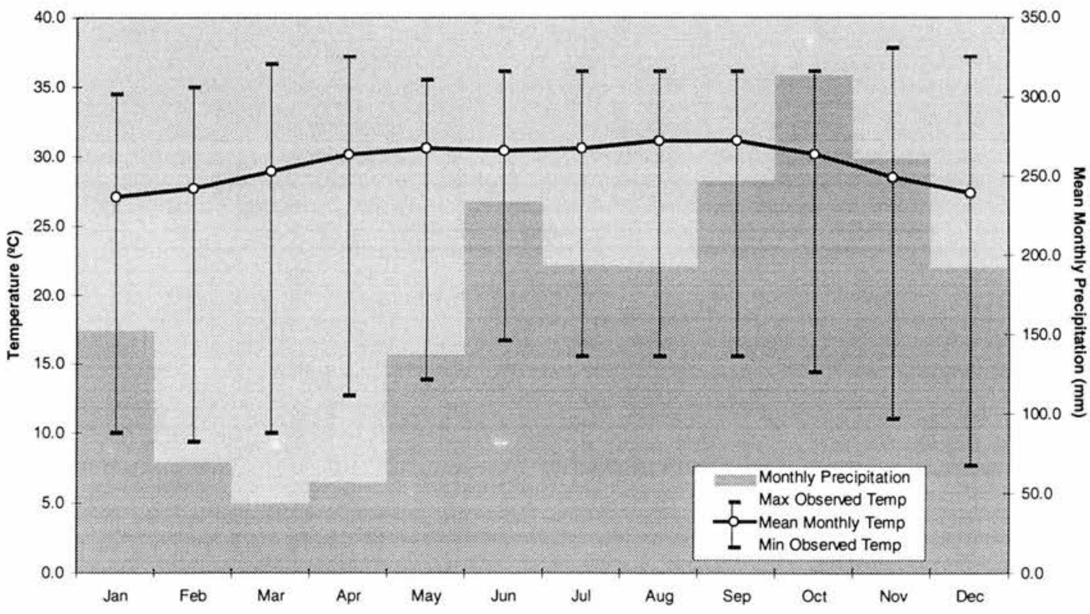
3.2 Obstacles to developing a complete, quantified nutrient budget for mangroves

Five sources of variation hindering quantification of a mangrove nutrient budget are considered below: seasonality, diurnal effects, tides, spatial variations and mangrove age.

3.2.1 Seasonality

The primary driving force behind variation in mangrove properties is the seasonal nature of the climate, resulting in variations in solar energy, precipitation and temperature inputs over a year.

Figure 3.1 Averaged monthly temperature and precipitation statistics for Belize City



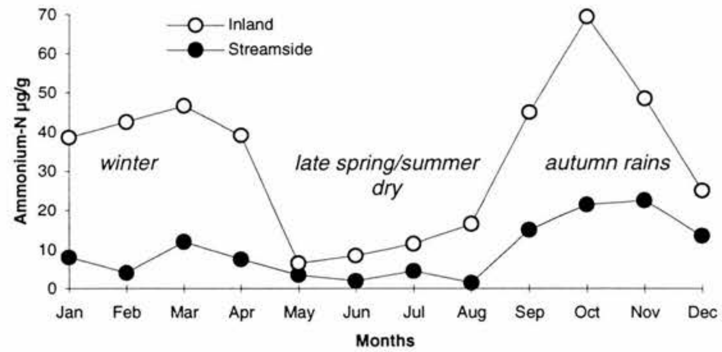
Source: From Walker (1973). Data collected at the Public Hospital, Belize City. Data are taken from a total of 55 years of records between 1894 and 1970. Temperature maxima and minima are the extreme recorded values over this period.

[1] The most complete attempt to date is by the Australian Institute of Marine Sciences at Missionary Bay, Hinchbrook Island, Australia, e.g. Alongi *et al.* (1992) and Robertson *et al.* (1992).

Figure 3.1 shows the seasonal pattern in average monthly temperature and precipitation data for the field site location, Belize City. The wet season peak in monthly precipitation occurs in October. This variation is known to affect the rate of many processes operating in the mangrove.

Shown below are the seasonal variations in two processes - soil ammonium-N levels in a salt marsh (Figure 3.2) and primary production of an Indian mangrove forest (Figure 3.3). Delaune *et al.* (1976) note that saltmarsh soil ammonium-N levels are low in spring and summer, and higher in autumn and winter.

Figure 3.2 Seasonal variation in soil ammonium-N in a Louisiana salt marsh

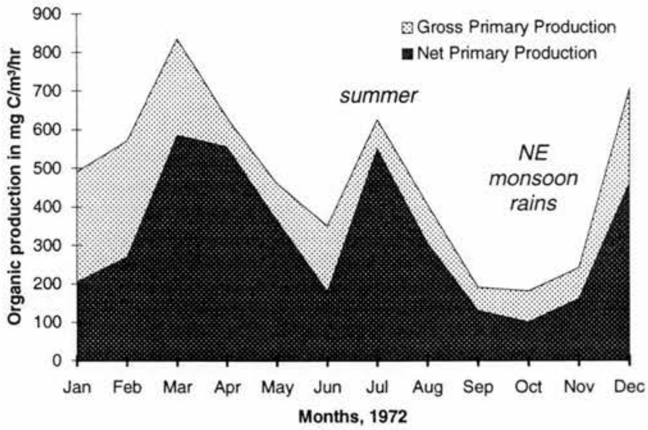


Source: Modified from Boto (1984), based on Delaune et al. (1976).

In summer, the high soil temperatures favour bacterial activity, resulting in rapid soil organic matter decomposition and ammonium-N mineralisation. This season is however, also the time of greatest plant growth, which requires ammonium-N uptake. Figure 3.2 shows there to be a net depression in soil ammonium-N values during the summer. This means that the rate of ammonium-N uptake by plants at this time exceeds the rate of bacterial mineralisation. In autumn and winter, although the lower soil temperatures will reduce bacterial activity, the decline in plant productivity is greater, resulting in a net increase in the amount of ammonium-N in the soil. A similar seasonal pattern of ammonium-N levels can be expected in mangrove soils.

Krishnamurthy *et al.* (1975) provide a very extreme example of seasonality, showing that the productivity levels of an Indian mangrove forest can be related to seasonal variations in nutrient availability and utilisation. The troughs in primary productivity coincide with peaks in nutrient levels in June and a silicate peak in October (the latter is probably a result of the high terrestrial runoff associated with monsoon activity at this time). The fact that peaks in nutrient availability coincide with troughs in primary production is interpreted by Krishnamurthy *et al.* as indicative of a lack of nutrient utilisation by phytoplankton and nanoplankton at these times.

Figure 3.3 Seasonal patterns in primary production, Pichavaram Mangrove Forest, South Arcot, Tamil Nadu, India



Source: Modified from Krishnamurthy et al. (1975)

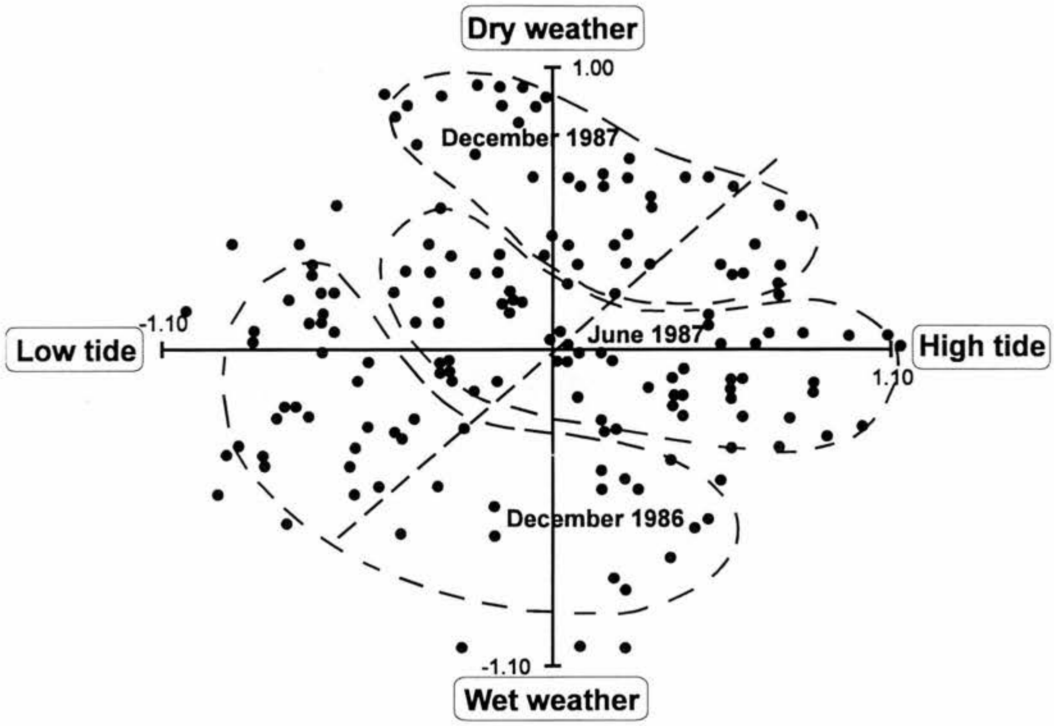
3.2.2 Daily (diurnal) variations

In the published data, evidence of diurnal variations in mangrove properties are legion. For example, variations in mangrove water dissolved oxygen content, canopy carbon dioxide concentration and exchange, and light intensity have been measured by Lugo & Snedaker (1975). Daily patterns in transpiration rate, canopy carbon dioxide concentration and exchange, xylem tension, air temperature and relative humidity were reported by Smith *et al.* (1989). In a similar manner to the seasonal trends reported above, most of these diurnal changes can be linked to changes in solar input throughout the day. Other differences may be the result of weather conditions on the day of sampling (see Figure 3.4 below).

3.2.3 Tidal variations

Ovalle *et al.* (1990) show how properties such as the dissolved oxygen content, salinity, pH, chlorine, silica, phosphate, ammonium and nitrate levels of a mangrove creek are affected by the ebb and flood of nearby tides. Figure 3.4 below shows the results of a Principal components analysis (PCA) of properties measured at their field site on three different occasions. The authors claim that the two derived principal component axes can be seen to divide the observations by date according to the state of the tide and the weather conditions at the time of measurement, showing a differential along the axis marked by the broken line angled at 45° to the axes. Whilst this explanation is open to different interpretations, notably whether the three identified clusters are sufficiently distinct to lend support to their claimed sources of variation, it is still significant that they attribute one of the principal axes to tidal factors. The poor clustering of the data suggests that there may well be factors operating at different temporal and spatial scales, not considered in their work, such as those discussed in this section.

Figure 3.4 PCA revealing tidal and meteorological variation in mangrove creek properties



Source: Modified from Figure 4 in Ovalle et al. (1990). Solid circles represent individual samples.

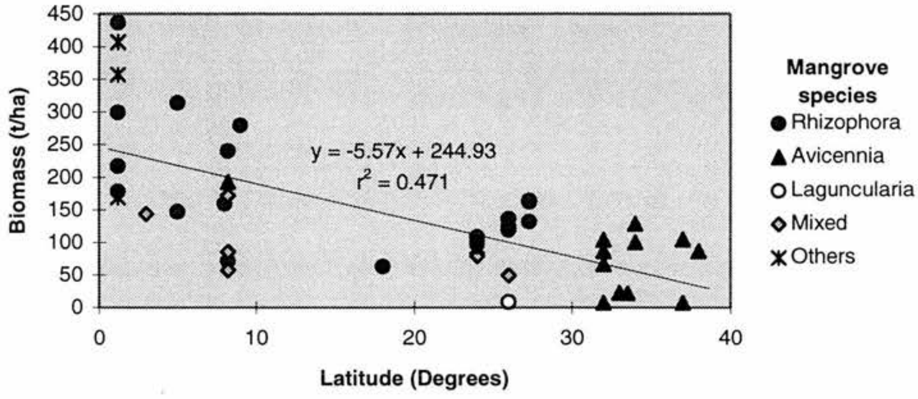
3.2.4 Spatial variations

The location chosen for the measurement of soil properties in the field can influence the values obtained. A micro-scale example of this effect is the work of McKee (1993). In a study of Florida mangroves, she shows that the location of sampling sites relative to the distribution of adult tree roots has a significant effect in determining the value of soil redox potential (Eh) and sulphide concentration. This work replicated the findings of an earlier study at Twin Cays, Belize, (McKee *et al.* 1988) where a significant negative correlation ($r = -0.65$, $r^2 = 0.42$) was found between pneumatophore density and sulphide concentration. This has been attributed to the leakage and/or export of oxygen into the rhizosphere from black mangrove pneumatophores and red mangrove prop roots changing the soil redox potential and the effect of this localised oxygenation upon the bacterial population, (Scholander *et al.,* 1955; Nickerson & Thibodeau, 1985; McKee *et al.*, 1988; McKee, 1993).

This has considerable implications for sampling design and means that published results must be interpreted with care: "differences" in reported soil properties from various workers, may be as much a function of the choice of sample sites within each study area, as a reflection of actual differences between the study locations. Equally, variations in data from a single site arising from ignoring spatial patterns (such as root distribution), may be sufficiently high to mask actual differences in representative values between this and other sites. This is particularly problematic, as few published data sets are accompanied with detailed sample site locational information.

The choice of location is equally significant at the macro-scale. For example Saenger & Snedaker (1993) show that the distribution of organic matter between plant roots, above ground biomass and litter, (partitioning) amongst mangroves differs around the globe. Figure 3.5 taken from their work shows that mangrove forest above ground biomass is not constant across different latitudes, even for the same species of mangrove. Rather, biomass decreases as the latitude of the field site increases. In the same study, they show that litterfall and tree height also decrease with latitude.

Figure 3.5 Variations in mangrove above ground biomass with latitude



Drawn from data published in Table 1 of Saenger & Snedaker (1993) n = 43. Mangrove species occurring in Belize have been highlighted. The regression line shown is that Saenger & Snedaker fitted to the combined mangrove species dataset.

3.2.5 Mangrove age

Atkinson *et al.* (1967) studied the concentration of ions in mangrove leaf pairs of differing ages. They found that in *Rhizophora mucronata* leaves, sodium and chloride concentration increases with age (although chloride levels remain constant in relation to leaf water content) but potassium levels decrease. This contrasts with the behaviour of leaves from *Avicennia annulata*, which show decreasing levels of sodium, chloride and potassium with leaf age. This difference between the two species is thought to be due to the ability of *A. annulata* to excrete salt through epidermal salt glands, not present in *R. mucronata* (Atkinson *et al.*, 1967). The concentration of salts and toxins in leaves will also increase prior to senescence, showing a further effect of leaf age upon elemental composition.

Smith *et al.* (1989) working in Venezuela, found that although leaf age had no significant effect upon leaf succulence for *Avicennia germinans*, succulence was generally greater in older leaves of *Conocarpus erectus*. Succulence is significant in that it affects leaf salt concentrations and thus sap osmotic pressure. They extrapolate their results to other mangrove tree species on the basis of the anatomical method for increasing succulence (notably whether this is by mesophyll development in the centre of the leaf, cell enlargement or cell division). *Laguncularia* species are expected to show greater succulence in older leaves, but *Rhizophora* species are not, assuming equal soil salinity conditions.

On a larger scale, Gong & Ong (1990) working in a managed forest reserve in the Matang, Malaysia measured how much the biomass, nutrient and organic matter content of mangrove stands increases with age. Selected results are shown below in Table 3.1:

Table 3.1 Total biomass, nutrient & organic matter content (tonnes) in stands of different ages

Age	Biomass	N	P	K	Ca	Mg	Na	OM
1-10y	1264400	6819	349	1615	3401	3851	10785	1179072
11-20	2540400	13700	701	3244	6834	7738	21670	2368961
21-30	3804800	20519	1050	4859	10235	11589	32455	3548033

Source: Simplified from Table 3 in Gong & Ong (1990). Data were collected from a whole forest of 40800 ha. They report that phosphorus values may need correction: multiplied by a factor of 3.3, but this does not alter the trend in higher phosphorus values found in timber of increasing age. "OM" is organic matter.

The major control on mangrove stand age around Belize City is likely to be the frequency of hurricane impact. The last hurricane to hit Belize City was Hurricane Hattie in 1961 which means that the mangroves in this area are likely to be approximately thirty-five years old.

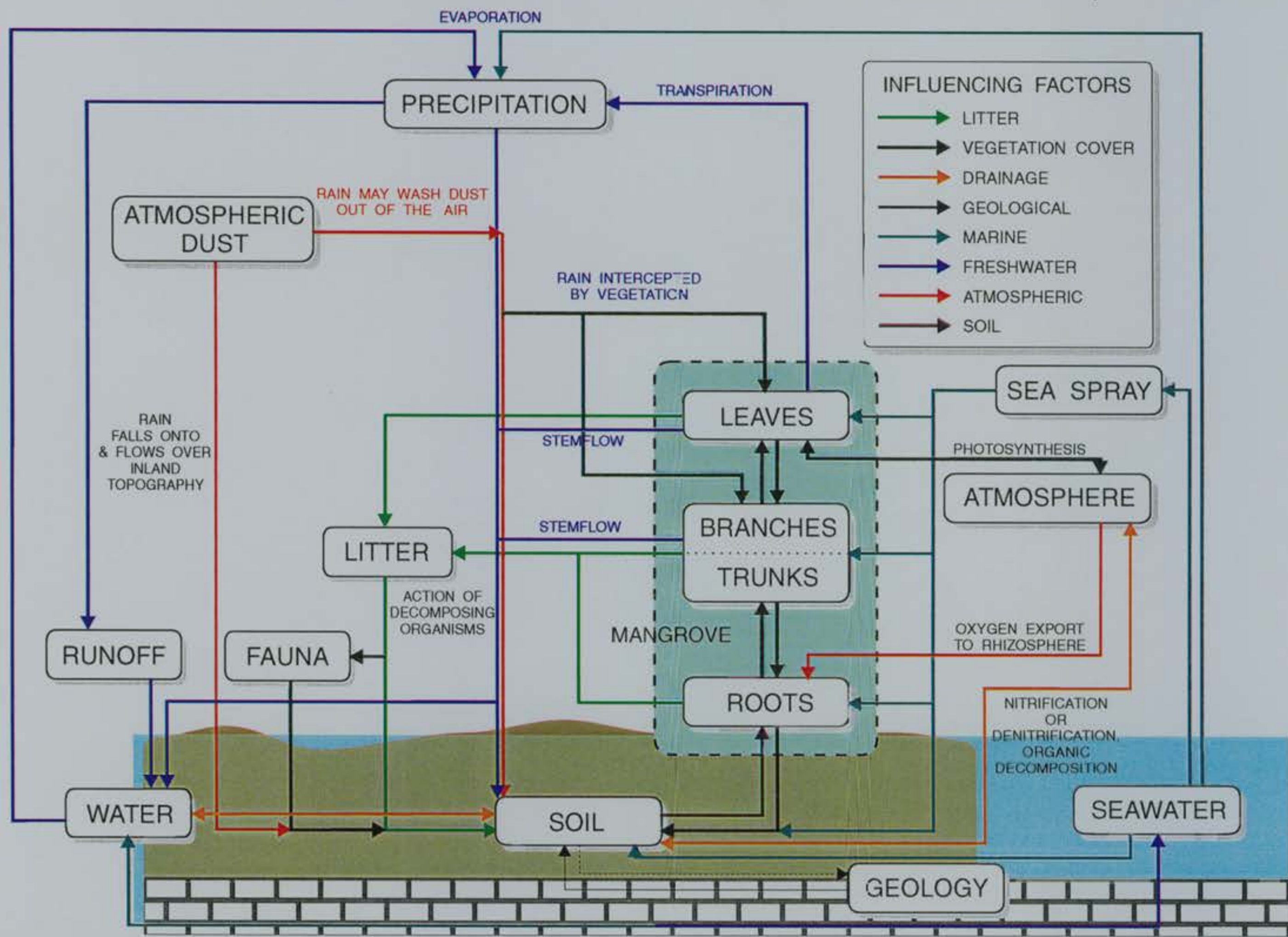
In summary it can be seen that it is very difficult to produce a quantified nutrient budget by combining data from different sources because of the variation inherent in the data. Measured values can vary according to the mangrove species present, the age profile of the stand, the latitude of the site, the locations chosen for sampling within a site, the time of day, the state of the tides and the time of year when sampling. Often published data are not accompanied by sufficient details regarding sample support, location and time of measurement to enable "correction" of the data, if indeed such a correction factor has yet been calculated. This conclusion should not be entirely unexpected, it accords with the findings of Proctor (1987) who showed that even when considering nutrient cycling in the far more studied biome of tropical rainforests, there was inadequate quantification of the process to justify producing a numerical model:

> "much more research is necessary before useful generalisations are possible."
>
> Proctor (1987, p135).

3.3 Producing a semi-quantitative nutrient flow model

In the absence of adequate quantitative nutrient cycling data, it was decided to pursue an alternative, more qualitative approach. The first stage of this - modelling the flow and storage of materials in a mangrove forest - is shown in Figure 3.6. Mangroves (represented as a green rectangle) are shown divided into three *compartments* - "leaves", "branches & trunks" and "roots". This division facilitates a discussion of the flow and storage of nutrients in the mangrove. Whilst such a three class compartmentalisation is relatively crude when compared with other workers - Silva *et al.* (1990) used seven classes and Golley (1969) defined 9 classes - by avoiding further differentiation (into prop roots, flowers, pneumatophores, etc.) it allows the compartmentalisation to be applied to all the mangrove species found in Belize.

Figure 3.6 An abstract model of nutrient flow and reserves in the mangrove, with paths coloured by the relevant influencing factors



Note for diagrammatic purposes, the role of insolation has been indicated only indirectly, through processes such as photosynthesis and evaporation. Two influencing factors - atmospheric and soil - not discussed in the text are shown in this figure to complete the feedback loops.

Figure 3.6 uses different coloured arrows to separate the many paths of nutrient movement. It is an attempt to show how differences in nutrient input and export can affect the processes of accumulation, conversion (decomposition) and combination, occurring in the mangrove. The main inputs into the system are seen as forest litterfall, precipitation, atmospheric dust, saltspray and water-transported materials. Exported materials are removed by the tides, by leaching or consumed by organisms. Different combinations and levels of these movements will affect the processes acting in the environment over a range of spatial and temporal scales. Four groups of ecological processes are relevant to this study of mangroves:

1. Soil processes of nutrient decomposition, accumulation, immobilisation and/or release.
2. Plant respiration and growth processes (especially those affected by light or shade).
3. Geological processes stemming from bedrock weathering and sediment deposition.
4. Drainage processes, which reflect the balance of fresh and saltwater inputs and exports (determining salinity levels) and the relative rates of precipitation, evaporation and transpiration (which dictates the height of the water table in any given region).

In the pictorial representation of Figure 3.6, greater emphasis has been given to displaying the inputs and exports, than the processes, which are discussed in more detail below. This study will focus on two of these groups of processes, those thought to be the most likely to experience the greatest short-term change: the soil and drainage processes. Geological processes typically act over a far longer timescale, making changes difficult to detect over the full three year field period. Studies of clearance induced changes in mangrove plant respiration and growth are needed, but require an intensive dedicated monitoring programme, and as such are outwith the scope of this piece of research.

Forest clearance distorts the rate and volume of litterfall input in both the deforested area and the remaining mangrove. Litter is a major source of nutrient input to the soil and waters of the mangrove, so it also receives detailed investigation below.

The role of water in the mangrove is complicated. Freshwater can enter the mangrove system directly through precipitation falling on the ground, be intercepted by the canopy becoming stem flow, or travel overland as runoff, throughflow or streamflow. Saltwater enters as a result of tidal inundation, groundwater flow and as salt spray. Many of these routes also bring nutrients into the ecosystem, such as the significant salt and sulphate input provided by seawater (Boto, 1982). Variations in the water level in mangroves exert a major control on organic matter decomposition and nutrient mineralisation processes, affecting both the standing vegetation and faunal populations. Finally water can act to remove materials from the ecosystem, both to its benefit, e.g. the flushing action of the tides which helps to reduce the level of toxic substances (such as sulphides) in the soil, and its detriment, removing nutrient sources (such as surface litter and dissolved particulate organic matter).

The dynamic impact of clearance upon this process can be seen by considering how local nutrient flow and storage changes over time. Table 3.2 below predicts changes in the flow and storage of nutrients in the three mangrove compartments, the surrounding soil and the waters of the cleared area occurring during the process of clearance and drainage (described more fully in Section 5.3.2). Ticks in the table represent compartments still actively participating in the movement and storage of materials. Before clearance, nutrients are flowing through, or are stored in all compartments of the undisturbed forest (6 ticks). Clearance results in the release of nutrients from the leaves as they turn into litter, thus removing leaves from the process. Later, as the stumps and roots of felled trees die off, they too decay, releasing nutrients and are removed from further nutrient cycling and storage activities. Eventually in a cleared and drained area, nutrients are limited to reserves in the soil.

Table 3.2 Changes in nutrient flow and storage in the cleared area

	Leaves	Branches & Trunks	Roots	Litter	Soil	Water
Undisturbed	✓	✓	✓	✓	✓	✓
Immediate post-clearance		(✓)	✓	✓	✓	✓
Longer post-clearance					✓	✓
Post drainage					✓	

Table 3.2 indicates that changes in litterfall inputs could have important effects on nutrient availability. This is considered first in the discussion which follows, which draws on the published studies of mangrove litterfall and decomposition. The rate and nature of the soil processes, notably decomposition and nutrient immobilisation will determine the amount and form (availability) of nutrients to plants and soil fauna. The amount of the three key plant-nutrients, carbon, nitrogen and phosphorus, are considered in detail below. Because drainage can accelerate or inhibit soil nutrient availability this process is also examined. Together, these studies allow the development of models which can predict changes in the value of individual measurable soil, water and other environmental properties over time. The specific predictions direct the fieldwork towards the measurement of particular variables at the different field sites.

3.4 The role of litter fall in nutrient release

The three litter sources in the mangrove are (by volume) leaves, branches and trunks and thirdly the roots of the mangroves, many of which extend above ground (Golley, 1969; Walsh, 1974). The litter can fall upon the ground and be directly combined into the soil, broken down by the action of micro-organisms and weathering processes, or first intercepted by fauna such as the many crabs found in the mangrove. Decomposition rates in the flooded soils of undisturbed mangroves are relatively slow (Tusneem & Patrick, 1971) and so over time the litterfall creates a thick layer of peaty soil. Felling the standing vegetation will result in a very large single litter input to the field sites. This is expected to have the greatest impact upon the ecological processes which depend on litter input. It should also have a lesser impact on the rate of many other processes because the loss of shade and plant cover will change soil temperature and water availability.

If the fallen timber is removed from the mangrove there will be a large scale export of leaf and stem nutrient stores from the system. The nutrients likely to be affected can be determined from Table 3.3, which shows the distribution of nutrients in the leaves, stem and roots of the red mangrove.

Table 3.3 Mean concentration (mg kg^{-1}) of selected elements in Rhizophora mangle vegetative parts

Element	Leaves	Stem	Roots
Aluminium	30 (5.9%)	35 (20.0%)	130 (74.1%)
Carbon	463,000 (25.3%)	447,000 (43.4%)	426,000 (41.3%)
Calcium	13,800 (22.1%)	10,300 (48.4%)	6,300 (29.5%)
Chloride	39,000 (13.7%)	23,600 (24.3%)	60,200 (61.9%)
Iron	52.9 (1.6%)	37.3 (3.2%)	110 (95.2%)
Hydrogen	53,000 (14.4%)	55,000 (44.0%)	52,000 (41.5%)
Magnesium	4,100 (24.3%)	1,300 (23.2%)	3,000 (52.5%)
Manganese	2,980 (36.9%)	1,180 (43.0%)	550 (20.1%)
Nitrogen	4,000 (5.2%)	17,000 (64.5%)	8,000 (30.3%)
Phosphorus	1500 (25.9%)	817 (40.4%)	685 (33.7%)
Potassium	17,800 (40.1%)	3,400 (22.4%)	5,700 (37.5%)
Sodium	19,600 (10.8%)	16,300 (26.6%)	38,500 (62.5%)
Sulphur	2,900 (18.2%)	1,200 (21.2%)	3,300 (60.6%)

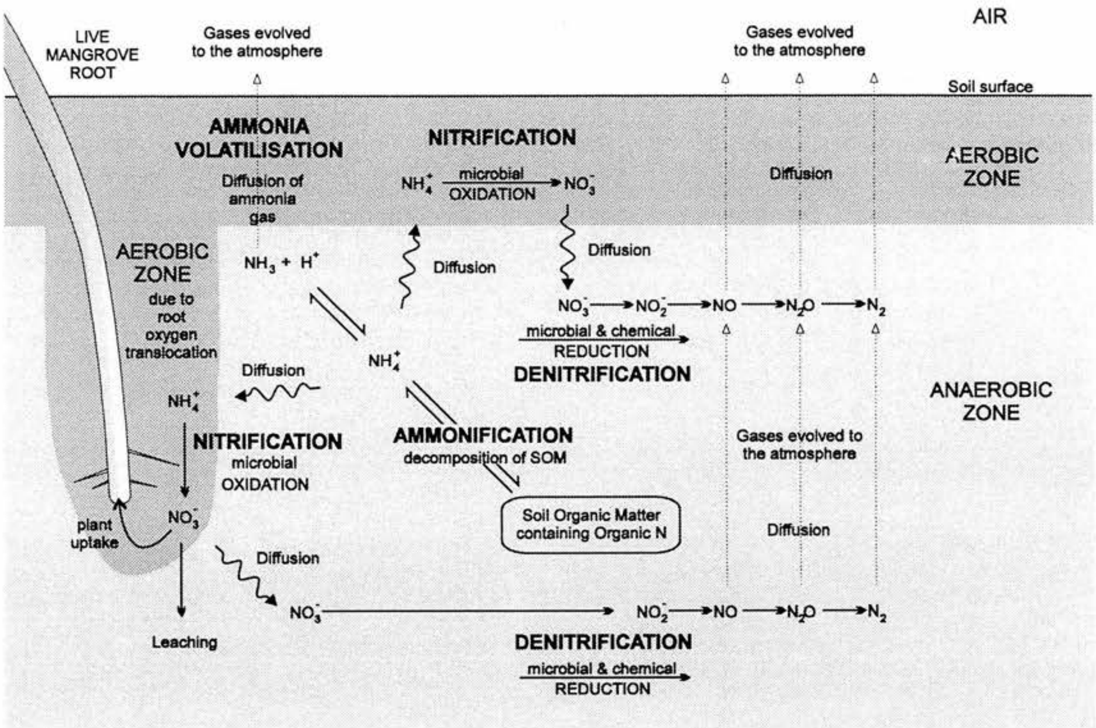
Figures in parentheses sum to 100% in each row and show the percentage distribution of the total amount of an element by mangrove part. About 75% of the fresh weight of plants was found to be water. The mangroves were grown in glasshouses in Sri Lanka. Data in this table are selected from those given in Table 2, Jayasekera (1991).

Such forest removal would result in the loss of the majority of plant-held stores of carbon, calcium, hydrogen, manganese, nitrogen, phosphorus and potassium. However in Belize, it is far more common for the fallen timber to be left at the site, sometimes compacted into the soil surface using heavy machinery (personal observation). More rarely, some of this fallen timber is burnt, the effects of which are considered further in Section 3.7. By leaving the timber *in situ*, the nutrients contained in these stores will be made available to plants and animals over time.

3.4.1 The rate of nutrient release from litter sources

In the fallen litter lying over the soil and to a lesser extent in any relatively well-drained surface regions of the soil, the most rapidly released elements will be those that are readily soluble. The solubility of elements is in general, dependent upon their valency, so monovalent ions such as sodium and potassium will be released before divalent ions such as calcium and magnesium, which will in turn be released before trivalent ions such as aluminium. In plant material, carbon, oxygen, hydrogen, nitrogen, phosphorus and sulphur are bound up in organic molecules (Rowell, 1994). They are released more slowly through the decomposing action of animals and micro-organisms. Organic forms of nitrogen, phosphorus and sulphur will be released through mineralisation and converted into their inorganic forms, ammonium-N, phosphate-P and sulphate-S. The inorganic nitrogen may then be reduced to nitrite (nitrification) in aerobic regions of the soil and further reduced in anaerobic zones to yield gaseous nitrogen compounds (likely to be predominantly nitrous oxide) by the denitrifying actions of soil microbes (Boto, 1984). The balance between nitrification and denitrification processes for flooded soils is shown in Figure 3.7.

Figure 3.7 Nitrification and denitrification in flooded soils



This diagram shows the fate of nitrogen in mangrove soils. Organic-N from soil organic matter can be mineralised, to give ammonium-N. Some of this ammonium-N may be lost to the system through ammonia volatilisation. Alternatively, via diffusion processes ammonium-N can travel into aerobic regions near the soil surface and around mangrove roots. Here the ammonium-N is oxidised by autotrophic bacteria to nitrate-N. This can then diffuse back to anaerobic regions, where the reducing action of soil microbes and some chemical processes, convert it first into nitrite-N and then gaseous forms of nitrogen. These gases travel up through the soil and escape into the atmosphere.

Note: this is not a complete model of the nitrogen cycle. Direct nitrogen fixation, and assimilatory processes such as the possible reduction of nitrate-N to ammonium-N, or the immobilisation of soil ammonium-N which may occur in nitrogen poor, carbon rich soils, have not been shown.

Based upon illustrations in Boto (1982) and Ross (1989).

Carbon and oxygen will be taken up through the respiration of bacteria, fungi and soil macrofauna, resulting in the release of water and carbon dioxide. After the initial loss of dissolved organic matter, the release of carbon stored in leaves and stems is slow. The first form of such refractory carbon to be released will be that in the form of sugars, followed by carbon in fats and waxes and finally the long chain forms such as cellulose and lignin (Ross, 1989).

3.4.2 The release of nutrients from below ground sources

Root death following clearance, which in mangroves is most likely in *Rhizophora* plants because they do not coppice and show the poorest ability to regenerate damaged limbs (Hamilton & Snedaker, 1984; Gill & Tomlinson, 1971), will result in the gradual release of below ground nutrient stores.

Their release is expected to follow a similar pattern to that of the above ground biomass, although nutrient release will be far slower. The increased likelihood of limited oxygen availability below the surface may also favour reductive decomposition process over oxidative ones, when the air spaces in the dead roots are flooded.

The rate of decomposition of plant material, such as roots, which remains buried in the sediment is markedly lower than that for material above or at the aerobic sediment-water interface, (Albright, 1976). In general, anaerobic decomposition processes have been found to be much slower (Tusneem & Patrick, 1971) which has led Boto (1982, p243) to suggest that under normal conditions these processes "probably contribute little to nutrient recycling". Certainly the very slow decomposition rate of mangrove material was confirmed by personal observations at Turneffe Atoll in 1995. Here, the remains of *Rhizophora mangle* prop roots could be clearly identified in submerged sediments surrounding cayes which had lost their mangrove cover during Hurricane Hattie in 1961.

Forest cutting will therefore result in the multi-stage release of large amounts of nutrients from above ground vegetative sources and possibly lesser amounts from below ground plant stores, released at a far slower rate. These nutrients may be taken up by the vegetation remaining in the adjoining forest, stored in the soil and waters or lost to the mangrove through leaching by rainwater, tidal flushing (export) and the evolution of gases by processes such as denitrification.

Physical erosion of the sediment from the exposed unvegetated surface will result in further nutrient loss, as soil nutrients are bound to the sediment particles. This process will be greatest in sand rich, permeable soils (Boto, 1982) subject to tidal action (Wolanski, 1995). Mechanical and chemical processes occurring in the mangrove waters may act to break up flocculated aggregates formed in freshwater, increasing the turbidity of the water and the volume of material removed. This will serve to increase nutrient export. Biological processes are also important in determining the nutrient loading of waters. In his study of Australian mangroves, Wolanski (1995) found many suspended particles were bound together by algae and mucus, or were in pellets formed by the feeding activities of benthic detrivores. Such pellets were frequently washed out to sea by the action of the tides, resulting in nutrient export from the mangrove.

3.5 Mangrove soil processes

The soils of the mangrove act as a major nutrient store, supplying the standing vegetation. Nutrients are removed by plant roots and used to create the vegetative mass of the plant. Over time, through leaf senescence, litterfall and eventual plant death, many of these nutrients locked up in the vegetation are returned to the soil, where decomposition processes act to make them available for floral and faunal uptake once more.

There have been many studies of decomposition rates in the mangrove (such as those of Albright, 1976; Cundell *et al.*, 1979; Goulter & Allaway, 1979; Odum & Heald, 1975; Robertson & Daniel, 1989a). Most of these focus upon the most easily measurable components, notably leaf litter. Robertson *et al.* (1992) note four conclusions prevalent in these studies:

1. In common with other vascular plants, mangrove detritus decomposes more slowly than detritus from non-vascular plants (e.g. seaweeds and algae) because of the presence of components such as ligninocellulose which are resistant to decay.
2. The rate of decomposition varies with tree species. Of the mangroves, litter from *Avicennia* species decomposes most rapidly. This has been attributed to its higher nitrogen content which makes it more attractive to consumers and the low concentrations of substances which inhibit microbial colonisation and activity, such as polyphenolic compounds.
3. For litter on the soil surface, during the first few months of decomposition the nitrogen content either remains very near the original figure or may even increase slightly, because of the addition of bacterial exudates, rich in nitrogen.
4. Decomposition of mangrove detritus proceeds in phases:
   (i) Loss of labile, water soluble compounds.
   (ii) Microbial colonisation and utilisation.
   (iii) Mechanical fragmentation (which is often enhanced by crab activity).

Many of these studies assume aerobic (surface) conditions. The effect of anaerobic soil conditions upon the decomposition process is considered in more detail below; in general it acts to greatly reduce the rate of breakdown.

The release rate of three plant nutrients - carbon, nitrogen and phosphorus are particularly relevant to this work and are considered below:

3.5.1 Carbon release

During the first 10-14 days, most of the changes in the mass of decomposing leaves has been found to be due to carbon loss, (Rice & Tenore, 1981; Robertson, 1988). This is primarily in the form of dissolved organic matter, and is a result of leaching not microbial activity. This source of carbon can remain available to the soil at a later date only if it can be incorporated into bacterial and fungal masses. Further leaching losses have been found to be highly dependent upon the action of bacterial and fungal communities (Fell & Masters, 1980). Approximately 30-60% of the organic matter in mangrove leaves is in a form which can be readily leached, the remainder consists of structural polymers, which breakdown far more slowly during decomposition (Robertson *et al.*, 1992). The exact proportion of this labile form of carbon varies with species, Robertson (1988) reports that *Avicennia* species have a higher labile fraction compared with *Rhizophora* species. Benner & Hodson (1985) measured the rate of decay of *Rhizophora* litter using isotope labelling. They found that the rate of decay of the more refractory lignocellulose fraction of leaf detritus was of an order of magnitude lower than the leachable fraction. Furthermore, the polysaccharide component of the lignocellulose was mineralised at a rate twice that of the lignin component suggesting that, over time, the proportion of lignin in the remaining litter would increase. In a later study, Benner *et al.* (1991) have found that microbial mineralisation losses are lower than those from leaching. They estimate that leaching losses from *Rhizophora* account for approximately 46% of the polysaccharide and 74% of the lignin loss. The importance of microbial activity in carbon turnover is affected by site-specific factors such as the degree of tidal flushing and the presence or absence of leaf-consuming fauna, notably crabs (Twilley *et al.*, 1986; Robertson & Daniel 1989b).

Robertson & Daniel (1989a) expanded such studies to include woody components. They found that trunk wood decomposed far more rapidly in mangroves than in temperate and tropical terrestrial forests, but that after a period of 15 years, 20% of the original carbon still remained in the fallen trunks. They found a rapid drop in wood C:N ratios in the first year of decomposition (from c.1400 to c.190) but a very small change in the C:N ratio thereafter. Branch wood was found to decompose faster than trunks. Much of the decomposition of the wood was attributed to the action of wood-boring molluscs, which are a common feature in the decaying timbers of the 1992 field site (this study). Decomposition resulting from direct microbial action also occurs, but microbial decay of the lignocellulose component is very slow, particularly if the timber is partly submerged, resulting in anaerobic conditions (Benner & Hodson, 1985; Robertson & Daniel, 1989a).

Robertson & Daniel (1989b) combined decomposition rate data with estimates of the mass of fallen dead wood in a mature Australian *Rhizophora* forest. They found that detritus from wood breakdown contributed as much to the overall carbon flux as the leaf litter consuming activities of crabs. Their data show that for younger forests, the carbon contribution of wood to food chains is far lower.

There are very few published studies of mangrove root decomposition, making an assessment of their contribution to carbon flux difficult. Albright (1976) found that the decomposition rate of roots from the mangrove *Avicennia marina* varied with depth. Roots exposed at the surface lost 52% of their original mass during the 154 days of his study, whilst those buried in the mud experiencing anaerobic decay lost only 30% of their original mass. Van der Valk & Attiwill (1984) showed that the rate of decomposition also varied with root size. Roots 1-2 cm in diameter lost 60% of their initial weight in a study of 270 days, compared with only 15% for smaller, fibrous roots. This will result in species differences in the decay of roots. *Rhizophora* species have a shallow network of fine roots extending from their far larger aerial roots, whilst *Avicennia* species have an elaborate below-ground cable network of many coarse, medium and fine roots.

In summary, carbon is broken down in a series of stages, analogous to but distinctly different from more typically terrestrial forests. The effect of aeration and the time elapsed since clearance seem to be the key factors in determining the of soil organic matter decomposition rate.

3.5.2 Nitrogen release

Robertson (1988) examined nitrogen release from decomposing mangrove litter using a series of experiments with leaf litter bags. During the first 40-71 days, the amount of nitrogen in leaves from *Rhizophora stylosa* trees either remained constant or increased slightly. After this period, the amount of nitrogen (measured as %N by mass) decreased, but at the end of the experiment (348 days) around 80% of the original mass of nitrogen remained in the leaves. Leaves from *Avicennia marina* lost nitrogen continually. Nitrogen loss for leaves from both species was increased if the bags were submerged in tidal creeks rather than buried in forest soils. This shows that it is not anaerobic conditions *per se* that inhibit bacterial decomposition of litter. Rather, the higher decomposition rate found in samples in tidal creeks, suggests that the flushing action of the water may remove reduced soil compounds which are inhibiting further decomposition in the mangrove soil. Bacterial nitrogen was found to contribute only a tiny fraction of the leaf nitrogen content, which accords with the findings of other vascular plant decomposition studies (e.g. Rice & Hanson, 1984). Robertson (1988) attributed the initial rise in *Rhizophora* leaf nitrogen mass to the bacterial production of mucopolysaccharide exudates and the incorporation of these into humic compounds.

The study of Robertson & Daniel (1989a) is unique in its consideration of nitrogen dynamics during the decomposition of fallen timber as opposed to leaf litter. Their study shows that the nitrogen content of fallen timber (twigs, branches and tree trunks) can increase over time due to bacterial activity. Working in mixed *Rhizophora* forests in Australia, the nitrogen content of freshly fallen trunks was found to be only 0.05% by dry weight. Rapid nitrogen immobilisation during the first 2½ months led to a concentration of nitrogen in the timber and a five-fold increase in total nitrogen values. Over the remainder of the study period (15½ years), the nitrogen concentration increased only slightly, with the percentage of original nitrogen remaining in the timber gradually declining to a final figure of c. 250%. The nitrogen concentration in small branches (initially 0.37% by dry weight) increased only gradually during the first 1½ years of decomposition, rising to a final figure of 0.54% after 15 months. Unlike the larger trunks, the total nitrogen content of branches decreased slowly throughout this period and was only c.80% of the original after 15 months. They found that most of this processed wood remains within the forest, conserving mangrove nitrogen stocks. This confirms the findings of other studies (e.g. Stanley *et al.*, 1987; Alongi, 1988, 1989) which have shown that the bacterial fixation rate in mangroves is far greater than denitrification losses. In summary, these studies show that the nitrogen content of litter is generally conserved by soil bacterial activity.

3.5.3 Phosphorus release

The release of phosphorus from decomposing mangrove litter has received far less attention than that of carbon or nitrogen. Albright (1976) found that phosphorus decomposition rates are higher in leaves than roots, and even lower in pneumatophores. This suggests that phosphorus mineralisation is inhibited under anaerobic conditions[2]. Sumitra-Vijayaraghavan *et al.* (1980) and Steinke *et al.* (1983) have found that the phosphorus content of a range of mangrove leaves (including leaves from both *Avicennia* and *Rhizophora* species) declined during the first 4-6 weeks of decomposition. Subsequently, phosphorus levels remained the same or began to increase slightly (up to 24 weeks) suggesting that immobilisation of phosphorus was occurring.

In general, the ability of mangrove soils to immobilise phosphorus rapidly means that even large litter inputs are unlikely to result in a significant increase in the level of soil phosphorus.

All the studies considered above have been carried out in relatively undisturbed mangrove forests. Yet the rate and indeed nature of the decompositional processes under investigation are known to change under differing regimes of tidal inundation, sediment type, rainfall, climatic-disturbance and topography (Alongi *et al.*, 1992). In the present study, looking at the effects of mangrove clearance and drainage, aspects of the decomposition process may be altered. Such changes form the focus of the following section.

3.6 Water movement

Two aspects of water are relevant to this work. These are firstly, the predominant direction of water movement within a soil profile, and secondly the water level in relation to the soil surface. These are considered separately below, then combined in a general discussion of the effects of forced (i.e. artificial) drainage.

3.6.1 The direction of water movement

The dominant direction of water movement has long been recognised as an important characteristic of soils (Brady, 1984). This stems from two factors. Water acts as an efficient transport mechanism for many substances, by solution and/or suspension of materials. Secondly, water can occupy the pore spaces of a soil, affecting both its physical properties (such as cohesion and strength) and chemical properties (notably redox potential).

Downward water movement occurs when the water table is well below the soil surface. It results in eluviation, the removal of soil material. These leached materials are often deposited (from suspension) or precipitated (from solution) in a region of accumulation known as the illuvial horizon. This results

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[2] The effect of drainage upon phosphorus levels is considered in more detail later in Section 3.6.5.

in the evolution of very distinct soils such as the ultisols and spodic oxisol groups, with marked eluviated and illuviated horizons. Studies of mangroves around Belize (e.g. Furley *et al.*, 1993) have not found such horizons, suggesting that in mangrove soils, vertical displacement of water is not a significant soil-shaping process.

Flooded soils may show little movement of water within the profile, particularly if, as in the case of mangroves, some of this water is saline, creating density differences. Because the pore spaces in these soils are filled with water rather than air, anaerobic soil conditions predominate, which results in the reduction of soil compounds such as the oxides and hydroxides of iron and manganese. This produces a characteristic grey matrix and orange-brown coloured mottling (oxidised patches) in the soil, often referred to as gley features (Rowell, 1994). Such features are very common in mangrove soils.

Fluctuations in the water level, variations in the direction of water movement, soil porosity and permeability result in soils experiencing both oxidising and reducing conditions. This can lead to the loss of nutrients from surface regions of the soil. The mobility of ions within the soil varies with redox potential and pH as these factors determine the valency of the ions (which can alter their solubility) and whether immobilisation and organic bonding (chelation) of the metals will occur (Engler & Patrick, 1975; Sims & Patrick, 1978). Van Breemen (1976) has shown that under aerobic conditions changes in the oxidative state of sulphur can severely lower soil pH. Iron and manganese are mobilised under very reducing (anaerobic) conditions, because the divalent forms (ferric and manganic) are more soluble than the trivalent oxidised forms (Ross, 1989). Whether the oxidised or reduced species are present in a soil is a function of its redox potential. A major control on soil redox potential is whether the soil is saturated or not. This is considered below.

3.6.2 Water levels in relation to the soil surface

The height of the water table (which affects the direction of water movement) in mangrove sites reflects the balance between evaporation, transpiration and inflow. Removing the forest cover will expose a greater area of soil (or standing water) to direct sunlight, increasing evaporative loss. However, plants themselves extract water from the soils through the process of transpiration, so their removal creates the potential for an increase in the height of the water table. In any study of the effects of deforestation, whether the result is a net increase or decrease in water levels depends on the balance between these two factors.

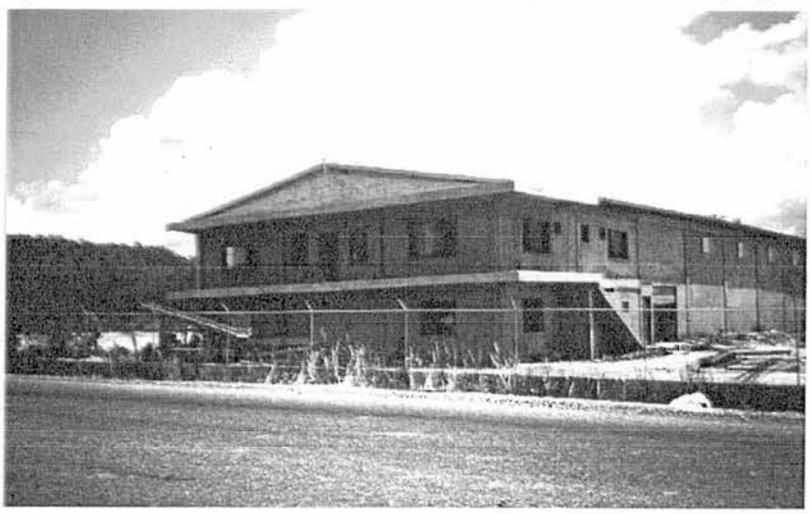
In studies of mangroves, the situation is further complicated by two additional factors: external water inputs and tidal forcing of the non-saline groundwaters. Mangroves receive freshwater inputs from terrestrial rivers and runoff, and saltwater inputs from the sea. In deforested, low-lying coastal sites, any potential changes in the water levels resulting from differences in the evaporation-transpiration balance may be masked by the over-riding effects of these other inputs, notably the local sea level.

For plants, the most important water characteristic is the availability of freshwater. Being less dense, fresh water floats above salt water, and many studies of the hydrology of mangrove covered areas, particularly islands, have found fresh water lenses at sites above the mean high water mark (e.g. Prins, 1986; Miller & Mackenzie, 1988). However, the three chosen field sites[3] are all at very low elevations, particularly the Burnt site, which in 1992 was covered in standing water. This will result in a mixing of the fresh and saltwater layers, effectively negating any such effects at the field sites considered in this research.

3.6.3 The effect of drainage

Forced drainage of the site by developers is designed to change the characteristics of these ex-mangrove soils by lowering the water table. It should increase the oxygen content of soils and promote the vertical movement of water down the soil profile. Such activities are likely to accelerate nutrient loss through leaching. The exposed, unvegetated soil surface will dry out, leaving it prone to physical erosive processes, with sediment particles removed by wind and rain. The high organic content of mangrove soils make them prone to physical problems such as subsidence, the effects of which are clearly visible in the tilted warehouses built too hastily along the Northern Highway just outside Belize City, as shown in Figure 3.8.

Figure 3.8 Recent construction on a cleared mangrove site showing signs of subsidence



The convergence of the road and the warehouse balcony seen at the left hand side of this picture is more than just a trick of perspective. The corner of this building has sunk into the ground, which is made up of poorly consolidated fill.

Photograph taken in August 1991.

Mangrove ecosystems have long been considered nutrient limited, particularly with respect to nitrogen and phosphorus (Hicks & Burns, 1975; Lugo *et al.*, 1976; Onuf *et al.* 1977, Clough *et al.*, 1983). The impact which artificial drainage will have upon levels of these two important plant macronutrients is considered below.

[3] Details of the location of the fieldsites are given in chapter five.

3.6.4 Drainage effects upon soil nitrogen levels and availability

The susceptibility of soil ammonium-N (the major inorganic form of nitrogen in anaerobic soils) varies according to the age of exposed soils. In long-exposed and thus more heavily leached soils, sodium levels will be low, and further freshwater leaching of the soil is unlikely to deplete the ammonium-N reserves significantly. This is because ammonium-N tends to be fixed on the cation exchange sites, which act to bind it in the soil (Boto, 1982). However, when soils are first drained, these exchange sites are likely to be swamped by sodium cations, meaning that ammonium-N has to occupy interstitial phases (Clough *et al.*, 1983). If the soil permeability is high enough to allow freshwater or tidal water to flow freely through the soil, then losses of ammonium-N by solution may be high. In addition, nitrification may occur (which will be promoted by artificial drainage, increasing the area of aerobic sections of the soil), resulting in severe leaching losses of the highly soluble nitrate-N. Such inorganic nitrogen losses are far lower in undisturbed mangrove soils because the redox potential seldom exceeds +100 mV, resulting in soil conditions unfavourable to the production of nitrate, and the high clay and silt content impedes water movement through the soil (Clough *et al.*, 1983).

A loss of soil inorganic nitrogen is significant because studies such as that of Nedwell (1975) have shown that increased ammonium-N availability increases primary productivity in mangroves, suggesting that mangroves are ammonium-N limited. There are however, a few exceptions to this perception of mangroves as being nitrogen limited. Riveramonroy *et al.* (1995) studying fringing mangroves around a Mexican lagoon found them to be acting as a sink for organic nitrogen and a source of dissolved and particulate nitrogen. This is probably due to a very low energy tidal regime, and shows that site specific effects are still very important in studies of mangrove nutrient movements.

Soil dehydration, often accompanied by an increase in porewater salinity has been found to have a detrimental effect on the nitrogen fixing activity of below ground bacteria (Sheridan, 1992). However, the earlier deforestation of the field sites may at least partially compensate for this a decrease in fixation as a result of soil dehydration. Kimball & Teas (1975) have found that in the mangroves of Southern Florida soil surface nitrogen fixation rates were enhanced by increases in ground level insolation, attributing this to the actions of blue-green algae and photosynthetic bacteria at the soil surface.

Although not strictly a direct result of water movement, disturbance to the site is likely to see a fall in the resident population of grapsid crabs, which is considered here because of its affect upon soil conditions. Studies of the effects of crab burrowing in Australia (Smith *et al.*, 1991) have found that a decrease in crab activity lead to a significant increase in soil sulphide and ammonium concentrations. This was interpreted as showing how crab burrows play an important role in aerating mangrove soils.

Thus, if the ecological role of the Belizean crabs is similar to that of those in Australia[4], then a reduction in crab numbers should be accompanied by increasingly anaerobic conditions in undrained sediments.

3.6.5 Drainage effects upon soil phosphorus levels and availability

Rich in organic material, undisturbed mangrove soils contain relatively large amounts of organic phosphorus. Hesse (1962, 1963) found that 75-85% of the total phosphorus in mangrove sediments in Sierra Leone and Nigeria was in the organic form. Organic phosphorus is thought to occur as complexes with humic and fulvic acids (Boto, 1982). The inorganic forms are those incorporated within hydrated iron and aluminium colloidal sesquioxides and in alkaline soils, bound with calcium (Hesse, 1962; Attiwill and Clough, 1978). Phosphorus has been shown to be more mobile in anaerobic than aerobic soils (Patrick *et al.*, 1973) under conditions of low redox potential, particularly at acidic pH values. The reason for this is the importance of reductive processes, seen in the five mechanisms identified by Patrick & Mahapatra (1968) which are involved in phosphorus release:

1. Reduction of insoluble ferric phosphate to the more soluble ferrous phosphate.

Reduction of the hydrated ferric oxide coating found on clay and silt particles, which results in the release of occluded (precipitated) phosphate.The action of organic anions displacing phosphate from ferric and aluminium phosphates.

4. Hydrolysis of ferric and aluminium phosphates.
5. Anion exchange (replacement of phosphates) between clay and organic ions.

These diverse mechanisms result in a very complex pattern of phosphorus availability in mangrove soils. Clough *et al.* (1983) suggest that a state of thermal disequilibrium exists between the three forms of phosphate: soluble interstitial phosphate, readily exchangeable phosphate and the far less soluble organic and mineral forms. This disequilibrium is further disturbed by the uptake of inorganic and to a lesser extent organic forms of phosphate by plants and changes in the amounts of interstitial and exchangeable phosphates because of tidal exchange and drainage. Draining the soil should therefore result in a decrease in the availability of phosphorus to plants because of the development of oxidising conditions. There may also be a net loss of phosphorus by leaching from surface regions of the soil. This loss of phosphorus may be significant enough to affect plant growth. In a study of Australian mangroves, Boto & Wellington (1984) found that in elevated (and thus well drained) sites the vegetation was phosphorus limited. In such situations the soil underlying the mangrove vegetation is showing characteristics typical of well drained inland soils across the humid tropics.

[4] Something which the authors themselves acknowledge requires far more detailed research, as their studies of grapsid craps in the Caribbean and Central America have produced conflicting results concerning the importance of these crabs in litter recycling.

3.6.6 Drainage effects upon soil acidity

The creation of aerobic soil conditions has been seen to favour the oxidation of soil compounds, as discussed above. Studies of mangrove empolderment and shrimp pond creation have shown that in some areas, site drainage risks the development of acid sulphate soils. This is because of the formation of sulphuric acid as a result of the oxidation of pyrite deposits, (Hesse, 1961a, 1961b; Jordan, 1964; Bloomfield & Coulter, 1973; Carlson & Yarbro, 1988). King *et al.* (1992) have found that soils in Belize rich in jarosite[5] are prone to acid sulphate development. The resulting soil sulphates may be partly neutralised by alkaline soil compounds such as carbonates. Any remaining acid can attack the clay minerals, which may result in the release of aluminium compounds into solution, substances known to be toxic to plants and soil micro-organisms, unless lime is added to the soil (Burbridge, 1990).

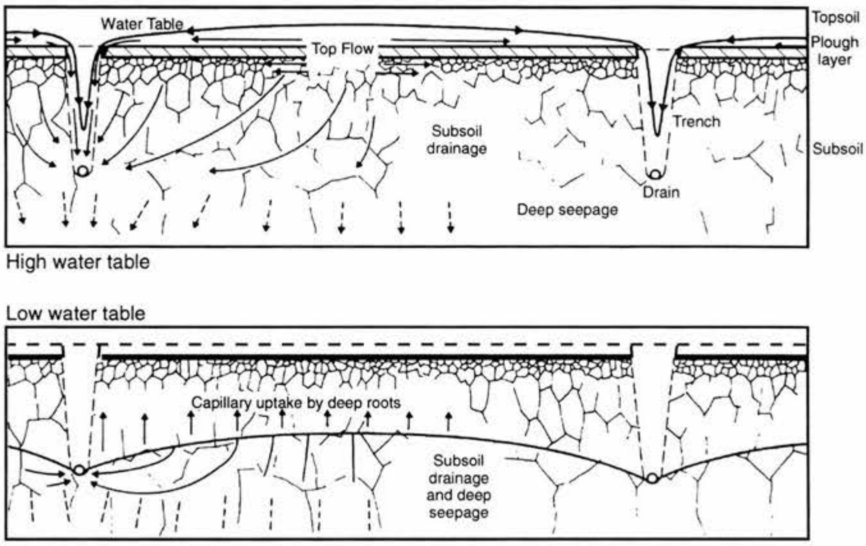
Tidal flushing of mangrove soils has been found to cause dissolved organic carbon export from the leachates and the removal of humic and fulvic acids from the mangrove peat (Boto, 1982). Felling the timber (and possible burning) will increase the volume of carbon, but draining the site (and possibly sea-wall construction) should reduce such losses by restricting the penetration of saltwater.

3.6.7 Moderation of drainage effects

The magnitude of these drainage effects are all dependent on the permeability of the soil and the efficiency of the water removal process. Permeability is dependent on soil texture. Soils with a high content of coarse sediment fractions such as sands and gravels contain many inter-connected spaces and so drain well, soils rich in the very fine mineral fractions, particularly clay suffer from impeded drainage due to a low porosity. Texture also affects the efficiency of water movement through the soil by capillary action. The organic rich peat found at the surface of the field sites is underlain by a thick layer of relatively impermeable marine silts and clays which is expected to impede throughflow. Removal of the water from the field sites will be hampered by their low elevation. Many lie very close to mean sea level which will result in a very low gravitational drainage effect, and explains the widespread activity of fill-dumping upon developing sites in order to increase their elevation. The resulting soil water conditions at the three field sites considered in this work are expected to be nearer to the "high water table" than the "low water table" conditions in the work of Lawrence (1981) which are reproduced in Figure 3.9 below:

[5] $KFe_3(SO_4)_2(OH)_6$ - formed from the aeration of soils containing sulphide and pyrite minerals.

Figure 3.9 The effect of artificial drainage on subsurface water flow paths



These two figures show how differences in the height of the water table affects the efficiency of drainage measures because of root capillary effects. In areas with a high water table (such as the cleared mangrove sites) despite the digging of deep ditches, water remains close to, or at the surface except in areas immediately adjacent to the drains.

After Lawrence (1981).

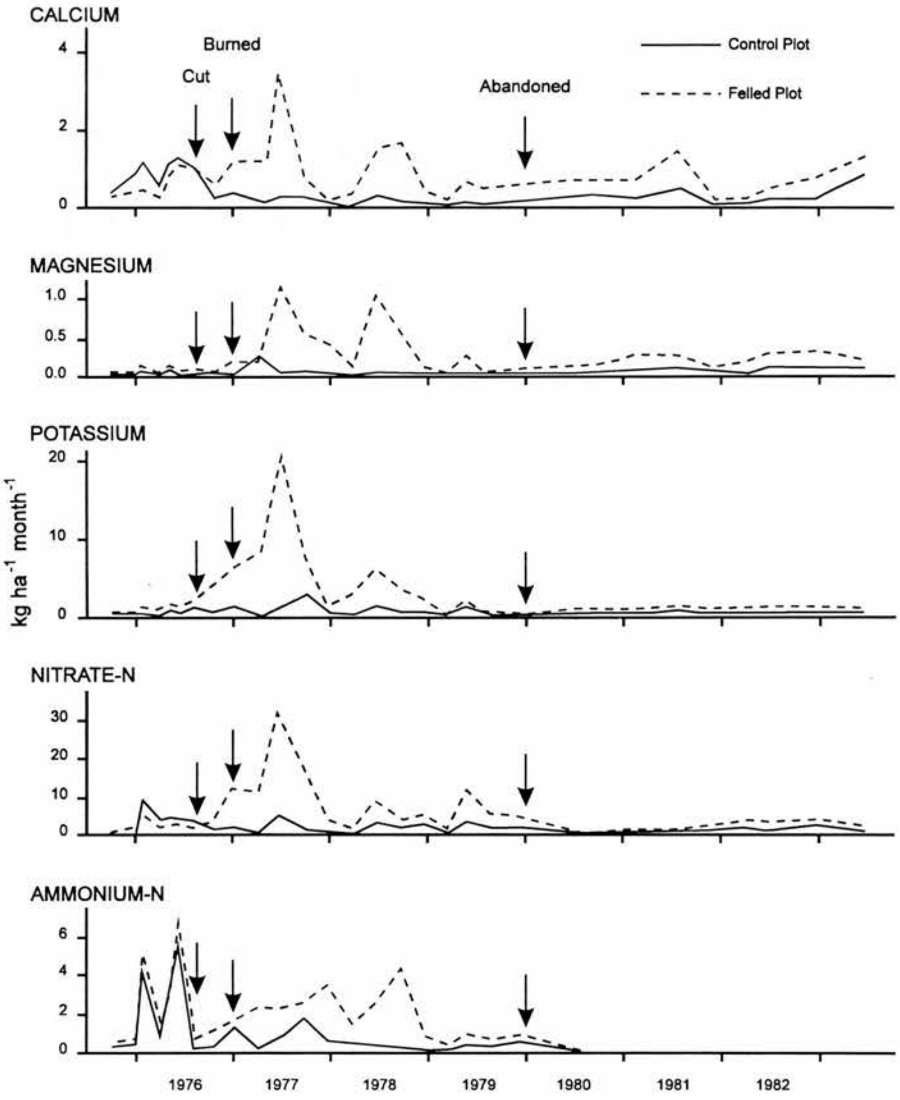
This means that the drainage-induced effects found at the three field sites are unlikely to be as extreme as some of the cases cited above.

3.7 Complications introduced by burning the field site

There is a lack of published work upon the effects of burning mangrove timber upon nutrient availability, but parallels can be drawn from research carried out in cleared areas of tropical rainforest. The two figures considered below are taken from a study of nutrient cycling and productivity in a cleared and burnt plot of Amazonian rain forest in Venezuela (Jordan, 1987). The clearance process employed is very similar to that used to remove much of the mangrove cover in Belize, except for the use of mechanical felling techniques, required because of the larger diameter of the standing timber. The forest understory was removed manually using machetes, then the large standing timber was mechanically felled. The fallen timber was left to dry for about four months and then burned (Jordan, 1987). However, the Venezuelan site differs from those considered in the present work, in that five months after clearance it was planted for agriculture. This will result in a decrease in leaching losses at this time, due to the establishment of vegetation cover, but an increase in the uptake of nutrients by the standing crops.

Figure 3.10 presents the results of Jordan's analysis of the leachate water at the study site, compared with leachate water from an undisturbed control plot. This shows a marked increase in the loss of calcium, magnesium, potassium and nitrate-N following clearance of the experimental plot and a further increase after burning. Ammonium-N levels show a high value around the time of clearance, but this is matched by an equal trend in the control plot, seen repeated (although at lower magnitude) in the undisturbed site in 1977 and 1978 suggesting this is a seasonal pattern.

Figure 3.10 Monthly rates of nutrient leaching in the two plots



Based on Figure 2.2 in Jordan (1987).

The felling and burning of the forest should have released large quantities of inorganic nitrogen, but such a rise is not seen in the ammonium-N levels of the leachate at the experimental plot. Jordan (1987) interprets this as a sign that the numbers of nitrifying bacteria at the site increased, rapidly converting the ammonium-N to nitrate-N. This explanation seems highly plausible, as it explains both the low leachate ammonium-N levels (nitrified before it could be leached) and the marked rise in leachate nitrate-N. Jordan found no increase in phosphate-P in the leachate over the course of the experiment, which he attributes to rapid fixation by iron and aluminium compounds in the mineral soil.

Figure 3.11 isolates more clearly the effect of burning upon the nutrient stocks. Calcium and magnesium are released from the fallen timber, resulting in an increase in the exchangeable levels of these nutrients in the soil. The amount of soil nitrogen in the soil post-burning is considerably lower than the volume previously locked up in the vegetation. This suggests that during the burn, nitrogen is lost to the forest by volatilisation. Exchangeable potassium levels in the soil also show an increase immediately following the burn, but quickly diminish, which is attributed to leaching loss of this highly soluble nutrient. Changes in phosphorus levels are not shown, because throughout Jordan's experiment most of the phosphorus remained immobile, fixed in the soil. In undisturbed forest, 84% of the total phosphorus was in the soil, only about 2% of which was available to plants, in soluble or exchangeable forms. Burning resulted only in an minor increase of soluble phosphate, to a level equivalent to just under 4% of the total phosphorus in the ecosystem.

Longer term monitoring of the plots revealed that soil nutrient levels remained relatively high after clearance and burning as long as a cover of decomposing organic matter remained on the soil surface. Their observations, showing that relatively high soil fertility is maintained agree with the findings of other researchers working in tropical forests, e.g. Nye & Greenland (1964) and Sanchez *et al.* (1983). However, the loss of the soil surface mat of humus and roots because of soil erosion following plot abandonment, can be seen in Figure 3.11 to coincide with a large drop in soil nutrients (up until this point the root mat had remained relatively undamaged, despite the clearance and fire). The magnitude of this loss is too great to be explained simply by the measured leaching losses at this time.

Relating these findings to the mangrove, the importance of maintaining a root mat is highly significant. Due to their coastal location, the surface root mat in mangroves may be rapidly removed by both wind and water erosion. Repeated burning which is known to have been practised on the Burnt Site[6] (Hanson, pers. comm.) and the lack of secondary vegetation development meant that the organic mat had completely disappeared from this site in 1994, only two and a half years after clearance. It has been replaced with a thin algal covering.

In such situations, nutrient losses in the mangrove following clearance and burning are likely to be more rapid than those reported above in Figure 3.11, assuming unimpeded drainage conditions. This accelerated loss in soil nutrients is expected to be greatest for levels of calcium, potassium, nitrogen and magnesium. In soils where anaerobic conditions predominate, then the decomposition of material is likely to occur at a far slower rate. Nutrient loss through leaching of soluble components will be greatly reduced, as dissolved nutrients remain within the mangrove ecosystem.

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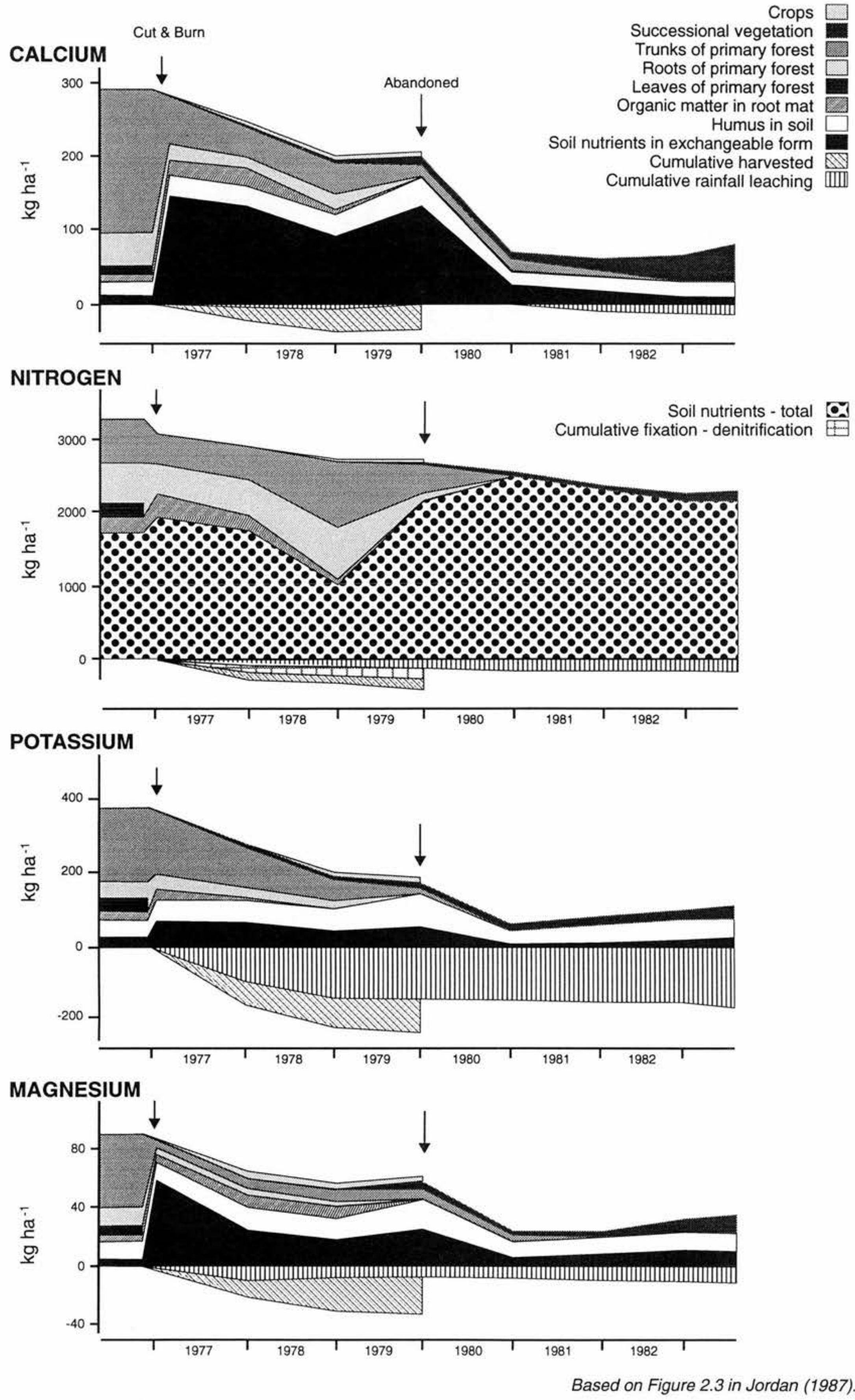
[6] The field sites are described in Section 5.

Figure 3.11 Stock and cumulative nutrient losses



Based on Figure 2.3 in Jordan (1987).

3.8 Predictions of change following mangrove clearance and drainage

Figure 3.6 can be used to produce a series of research hypotheses (predictions of change), stemming from differences in the inputs and exports from the system following clearance and drainage, combined with modifications to the ecological processes acting in the mangrove. These predictions are given in Figure 3.12.

The composition of mangrove soils from around the world has been reviewed by Walsh (1974) and a recent study (Furley & Minty, 1992; Furley et al., 1993) provides a picture of the variation along the coast of Belize. In common with other ecosystems, the availability of two elements is of greatest significance to plant growth: nitrogen and phosphorus. In studies of Florida mangroves, the nitrogen requirements of the plants were found to be met by populations of nitrogen-fixing bacteria (Zuberer & Silver, 1978), although some studies, notably those in Australia question whether this phenomenon applies world-wide (Hutchings & Saenger, 1987). Phosphate inputs to the mangrove are primarily from freshwater. Many studies of mangrove soils have found a low phosphorus concentration (e.g. Boto, 1983) and in common with other ecosystems of the tropics, it is thought that in many cases, phosphorus availability is the limit to growth (Beadle, 1954; Hutchings & Saenger, 1987). This situation is compounded by tidal flushing of mangroves, which results in losses of nitrate and phosphate to the sea (Walsh, 1967; Lugo et al., 1976). Numerical models of mangrove communities in south Florida has found them to be highly sensitive to nutrient availability, with mangrove biomass showing a steady decline if nutrient inputs cease (Lugo et al., 1976). Enrichment studies (e.g. Onuf et al., 1977) show that for many mangroves, their growth is currently limited by the supply of available nutrients.

Decomposition of the vegetation felled during clearance will release nutrients to the soil. From Table 3.3 it is possible to estimate the likely nutrient inputs that the vegetation will provide: large amounts of elements such as carbon, nitrogen, potassium and sodium, and smaller amounts of elements such as magnesium, phosphorus, sulphur and iron. The exact composition of the plant material will depend upon the time of felling, as plants tend to increase ammonium-N uptake during times of growth and phosphorus uptake during reproductive activity. The decay of this material will produce a peak in the levels of the highly soluble cations such as potassium, calcium and magnesium, with phosphorus, sulphur, carbon and nitrogen released more slowly through mineralisation.

In both the cleared areas and remaining forest, the felling of the mangrove effectively acts as a one-off increase in the litter input, resulting in a short-term rise in the level of exchangeable nutrients in the soil. The rate of release of these exchangeable nutrients will increase if burning of the fallen material occurs. In time nutrient levels in the soil will decline in the cleared area as nutrients are lost through leaching, dilution and wind transport, immobilised in the soil by micro-organisms and taken up by the roots of plants from the nearby forest. In the adjacent areas of remaining mangrove forest, nutrient levels will be maintained by regular litter input and the protective action of the vegetation cover.

The discussion of soil processes above, allows the prediction of the soil's macronutrient levels following forest clearance, possible burning and drainage. The scenarios developed below show the expected level of soil nutrients over a timescale which can be divided into four relatively discrete periods:

1. Before clearance.
2. Immediately after clearance, (if burning occurs, it is assumed to occur in this period).
3. Some time after clearance, when although no further human disturbance to the site has occurred, nutrient levels in the soil are expected to decline because of the absence of further litter inputs.
4. After drainage of the site.

The changing pattern of soil conditions and nutrient levels are presented as seven diagrams in Figure 3.12. Individually considering every measurable variable shown in the earlier nutrient flow model (Figure 3.6), would result in needless repetition. Instead, the discussion focuses first upon a few individual key nutrients, then considers the remaining variables together, grouping them by two processes: drainage and litter cover/inputs. Two other processes affecting soil and water variable values, weathering of geological material and terrestrial sediment deposition are also discussed below, but the predicted pattern of change for these latter two processes is considered too small to merit graphical representation.

Such a *process* focus follows logically from nutrient flow models such Figure 3.6, and whilst being efficient in terms of describing changes from a common source (e.g. reduced litterfall), does not develop an exclusive classification. For example, changes in nutrients such as calcium and magnesium may result from alterations predicted from the discussions of several factors, such as litterfall and freshwater alluvial input. Whilst this in itself introduces some repetition, it serves to emphasise the multi-causal nature of change in the mangrove, as in other ecological systems.

3.8.1 Litter influenced variables

Mangroves produce considerable amounts of litter. Clearance should result in a sudden local input of litter during the felling process. Differences in the release rate of litter influenced nutrients over time mean that it is more informative to consider them individually rather than together as one group. The predicted changes are given in Figure 3.12.

Rapidly released soluble cations

The levels of the exchangeable cations in the soil shown in Figure 3.12(i) should rise from their initial moderate level soon after clearance, as the metal cations are released from the litter. This rapid release through decomposition will continue as long as the fallen litter remains above the soil surface, in aerobic conditions permitting free drainage of the material. Material which becomes incorporated into anaerobic regions of the soil will decay far more slowly, because of the smaller numbers of suitable bacteria. If burning of the fallen material occurs, it should increase the rate of nutrient release. However, because further litter input has been prevented, the early increased level of these labile elements in the soil and water will decline markedly over time. Sodium and potassium, the most soluble of these cations, are expected to decline most rapidly because of leaching losses. The overall loss of nutrients from the soil will increase rapidly if the root mat is lost, marked as point "e" on Figure 3.12(i), because of physical erosion of the soil surface. Drainage of the site will accelerate leaching losses of these nutrients by promoting the downward flow of water through the soil. The relative importance of drainage in reducing the level of exchangeable cations in the soil will be greatest when it occurs soon after forest clearance.

Organic carbon

A large proportion of the fallen timber is composed of carbon, which will be gradually released into the soil over time. The increase in litter because of clearance will result in a short term increase in the amount of organic material in the soil. Burning the fallen timber will result in the conversion of much of the wood into ash, and carbon which would have otherwise entered the soil will be lost through volatilisation. As the organic material is broken down by soil fauna and bacteria via respiration, soil carbon levels will decline. Figure 3.12(ii) shows this general decline in organic carbon levels, punctuated by a second, lesser peak (point "r"). This corresponds with the release of carbon from the breakdown of the refractory components - waxes, fats, lignin, cellulose, etc. which decompose more slowly. Drainage will accelerate the rate of the decomposition process by promoting oxidising conditions more favourable towards efficient microbial activity. Furthermore, the drying out of the surface region of the soil is likely to increase nutrient loss through greater physical erosion.

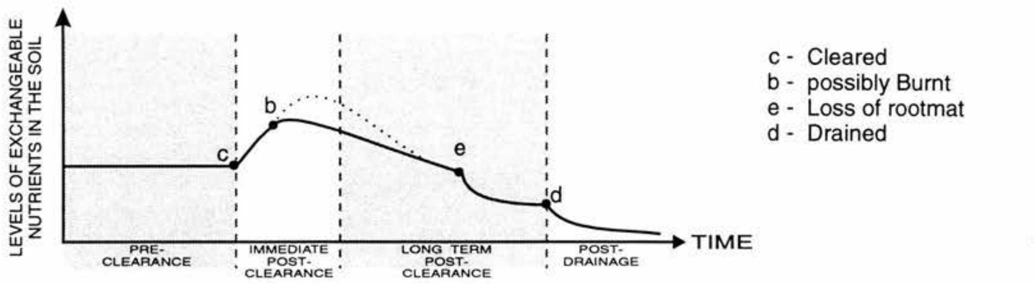
Extractable and available phosphorus

The amount of phosphorus in mangrove soil which is present in a form available to plants is very low. Although the fallen mangrove timber will contain phosphorus, as shown in Figure 3.12(iii), its release is not expected to increase significantly the levels of available phosphorus in the soil. Rather, released phosphorus will be rapidly immobilised. Drainage will promote oxidising soil conditions which has a negative effect upon phosphorus availability to plants, promoting phosphate fixation (by iron and aluminium oxides) resulting in a decline in the levels of soil available phosphorus (Ross, 1989).

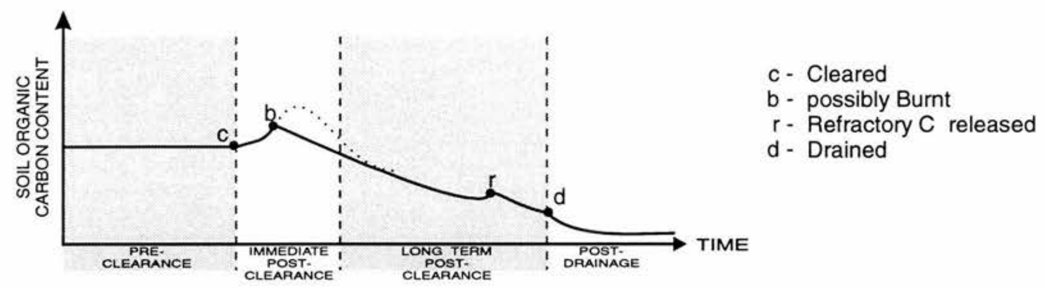
Figure 3.12 Predicted changes following clearance and drainage

Litter-influenced nutrients

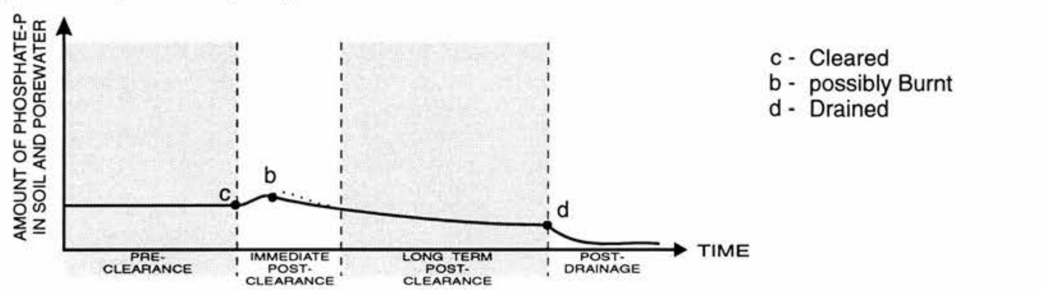
(i) Levels of exchangeable nutrients in the soil



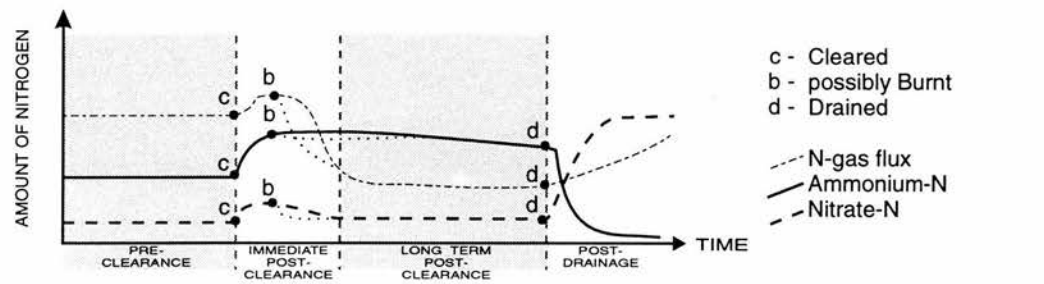
(ii) Soil organic carbon content



(iii) Soil and porewater phosphate-P concentration



(iv) Inorganic forms of nitrogen



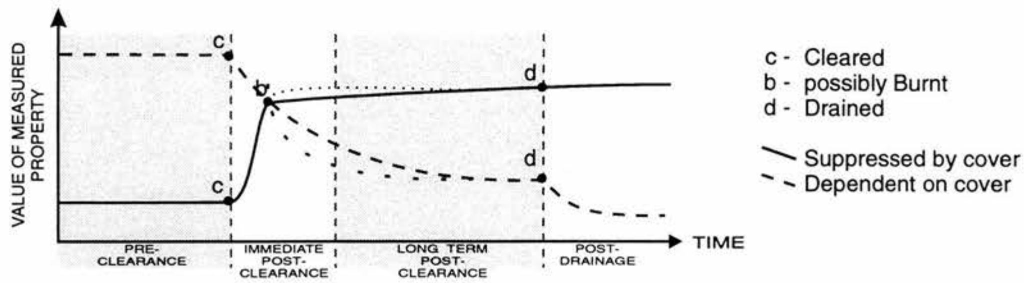
Note the fact that the properties (and thus the measurement units) along the y-axis differ for each diagram. None of the axes are numbered, as these diagrams seek to give only an indication of relative differences in the values of the properties graphed.

Doted lines indicate changes in the value of the measured property if the fallen vegetation is burnt.

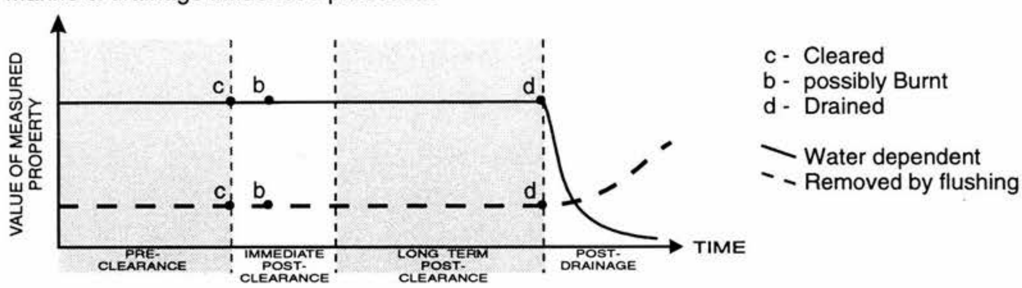
Figure 3.12 continued

Other process-influenced nutrients

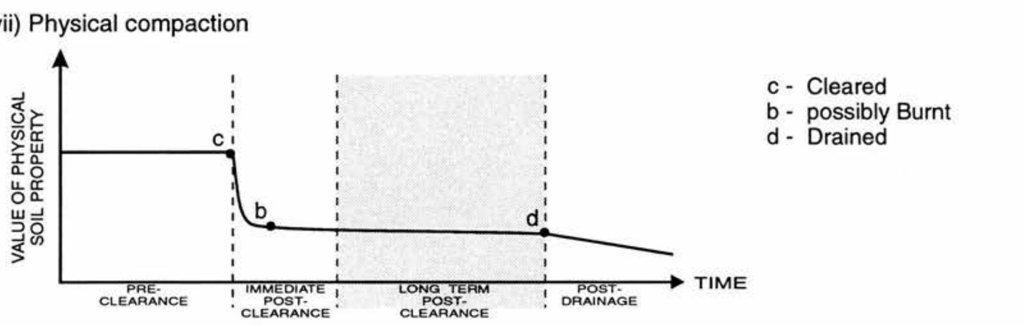
(v) Vegetation cover influenced processes



(vi) Marine & drainage influenced processes



(vii) Physical compaction



The effect of weathering of geological material and terrestrial sedimentation processes upon soil nutrient levels are considered in the text. However their effects are thought to be minimal over the timescale of this study and so graphs for these two processes are not included here.

Soil nitrogen

Mangrove forest soils contain ammonium-N as the result of mineralisation of organic nitrogen. The low redox levels and absence of oxygen curtail the activity of the bacteria responsible for nitrification (the conversion of ammonium-N to nitrate-N). When the forest is felled, the litter contains new sources of organic nitrogen, some of which may be converted by bacterial activity into ammonium-N under the favourable soil conditions (a low C:N ratio). Burning the timber is expected to decrease the magnitude of the litter nitrogen-input because of volatilisation losses. Whilst predominantly anaerobic conditions remain, soil ammonium-N levels should stay fairly high. Upon drainage, soil redox potentials will rise as the soil becomes oxidised, resulting in a rapid decrease in soil ammonium-N as it is converted to nitrate-N via nitrification.

In the anaerobic soils of the undisturbed forest, nitrate-N levels will be very low due to denitrification and volatilisation. They may increase slightly because of nitrogen release resulting from litter decomposition and nitrification, but unless the soil redox potential changes (i.e. conditions become more oxidising), denitrification will follow and the levels will quickly decline again. Site drainage will promote nitrification resulting in the oxidation of ammonium-N to nitrate-N. The magnitude of this increase will depend on the efficiency of the site drainage, determining whether the inorganic nitrogen remains as nitrate-N or is reduced by chemical processes and bacterial activity, releasing nitrogen in gaseous forms.

Nitrogenous gas flux, in the form of nitrous oxide and nitrogen gas, is the end product of denitrification. Nitrogen can also be lost from the soil as ammonia gas (ammonia volatilisation) through the disassociation of soil ammonium-N into aqueous ammonia and hydrogen ions (Ross, 1989). This latter process is greatest at high soil pH and so given the acidic conditions typical of the mangrove, nitrogen losses as a result of ammonia volatilisation are likely to be small.

The poor drainage conditions typical of mangrove soils combined with the oxygen translocation activity of mangrove roots provide adjoining regions of reducing and oxidising conditions - ideal for denitrification. The soil ammonium-N produced from the decomposition of organic matter (ammonification) can be easily converted to nitrate-N in the oxidised rhizosphere (nitrification) which in turn, can be reduced to nitrite-N and gaseous forms such as nitrous oxide (denitrification) in areas with reducing soil conditions. This should result in a large loss of nitrogeneous gases from the mangrove soil to the atmosphere by diffusion.

Figure 3.12(iv) shows that nitrogeneous gas flux is generally expected to be higher in the forest, because of the presence of live roots, exporting oxygen below the surface allowing nitrification. Clearance will increase the volume of soil organic matter, resulting in a rise in soil ammonium-N levels, and possibly accompanied by an increase in ammonia volatilisation. However, the loss of oxidising pockets in the soil resulting from the death of the standing forest will restrict nitrification and so the amount of nitrate-N available for denitrification and eventual evolution as nitrogeneous gas will fall markedly. During the dry season or after site drainage, soil water levels in the cleared area will drop, and the resultant oxidising conditions facilitate nitrification once more. The high clay content and tortuous pore spaces will mean that some reducing regions remain in the soil, resulting in denitrification and so finally an increase in the nitrogenous gas flux in the cleared zone.

All these processes are dependent on microbial activity, however, and rely on the soil conditions being favourable for micro-organism growth. There are three possible hazards to bacteria in the mangrove soils, which may act to reduce the overall loss of nitrogen: the soil salinity, hydrogen sulphide concentration and the presence of tannins in the organic matter. Salinity acts a constraint to many biological processes. Spratt & Hodson (1994) have shown that high salinity inhibits the oxidation of manganese by bacteria, and thus, it is possible that the bacteria which oxidise ammonium-N to nitrate-N are similarly affected. Rheinheimer (1972) found that hydrogen sulphide killed the bacteria responsible for marine nitrification. Clearance of the mangrove will intensify the reducing conditions, resulting in a higher proportion of soil sulphur being present as sulphide-S. The leaves of mangroves, particularly *Rhizophora* species (Robertson, 1988) contain high levels of tannin, to reduce insect herbivory and tissue damage from UV radiation. Boto *et al.* (1989) and Kimball & Teas (1975) have shown that decomposition of this material results in significant amounts of soluble tannins entering the mangrove porewater, which inhibits the growth and activity of nitrifying bacteria (Morell & Corredor, 1993).

In general, the level of litter-derived nutrients in the soil of cleared areas will show an initial increase following deforestation, then gradually decline to a level well below that of the undisturbed forest soils. Predicting the amount of inorganic nitrogen in the soil is made more complicated by changes in the form of nitrogen according to soil oxygen availability.

3.8.2 Vegetation cover influenced processes (including those affected by precipitation and insolation)

Clearing an area of mangrove forest results in the loss of the surface vegetation cover and alterations to the local micro-climatic conditions. This will result in changes increasing the value of some variables and decreasing the value of others because of differences in ground level insolation, atmospheric input and soil temperature. In Figure 3.12(v), variables whose value is predicted to increase following clearance are shown by a solid line, those expected to decrease by a broken line.

Increased

The most obvious of these is an immediate increase in ground level insolation in the cleared area. More complex is the expected change in soil moisture level, which will depend on the balance between increased precipitation input following forest loss accompanied by a reduction in vegetative transpiration and greater evaporation expected from the newly exposed soil. If the soil dries out, the redox potential will increase as the soil becomes oxidised. Changes in the forest cover may affect the activity of mangrove fauna. The number of ground feeders such as crabs may decrease, because of their greater exposure to predators. Conversely, the creation of cleared areas may attract species preferring open habitats, such as wading birds. Such changes may affect the level of nutrients from faecal sources, notably organic nitrogen and phosphorus.

Reduced

The loss of live plant cover will reduce the area's total photosynthetic output (an avenue which will not be pursued in this piece of research because of the many difficulties associated with its accurate measurement[7]) and plant uptake of soil mineral nitrogen (ammonium and nitrate). The number of live roots (which can be measured as root biomass) should decline in the cleared area because of tree death.

Whilst removing the forest cover will prevent vegetative interception of nutrients from sea spray, atmospheric dust deposition and substances dissolved in precipitation, the net effect is expected to be a decrease in the level of these nutrients in the soil following clearance. This is because the large surface area of the standing forest is a more efficient interceptor of atmospheric material than the bare soil surface, despite the loss of some of this material through direct plant uptake. Table 3.4 shows the plant nutrients available in sea water which are thus expected to show a decrease in the soil following clearance.

Table 3.4 The major constituents of the oceans

Substance	Concentration: g kg^{-1}	Concentration: millimolar	% Weight of ions
Borate	0.03	0.5	0.08
Bromide	0.07	0.4	0.20
Calcium	0.41	11.5	1.20
Chloride	19.40	558.0	55.30
Magnesium	1.30	54.5	3.70
Potassium	0.39	10.0	1.10
Sodium	10.80	483.0	30.70
Strontium	0.01	0.1	0.020
Sulphate	2.70	29.0	7.70

Source: Harvey (1966).

3.8.3 Marine and drainage processes

The level of marine influenced variables available to plants depends on two processes: salt water incursion and the deposition of salts in sea spray. If clearance and drainage results in lessening the

[7] Considered in more detail in Clough (1992).

marine influence (for example by excluding salt water using sea-walls), then the levels of these compounds in the soil and water should decrease, particularly sodium, chloride and sulphates (thus also affecting conductivity, effectively a surrogate for salinity). The predicted values of such variables are represented by the solid line on Figure 3.12(vi). However, the tidal action of the sea has a second important function in mangroves, as identified by McKee (1994a), the regular flushing acts to remove concentrations of reduced compounds. Losing this may result in a lower redox potential, lower levels of dissolved oxygen and a predominance of reduced forms of sulphur, iron, manganese, etc. Similarly, the lack of flushing may lead to stagnation, with water turbidity and the amount of suspended solids increasing and possible changes in soil colour. (The predicted changes in the values of these variables are shown by the broken line). As the sea is a significant source of water in mangrove areas, limiting its influence through site drainage and the erection of physical barriers will lower the soil moisture content. After drainage, the organic rich soil layers may be liable to physical changes such as alterations in their texture (a loss of the very fine fraction) and a tendency for subsidence.

If the water table drops, the soil redox potential will increase and become oxidising, reflecting the new, aerobic conditions. However, if there is no drainage of the site, then the loss of the forest cover and litter may mean that the soil remains permanently submerged. This would have the opposite effect, acting to maintain anaerobic conditions. Soil aerobic/anaerobic conditions influence the level of soil and water dissolved nitrates, nitrites and ammonium. In a typical flooded anaerobic mangrove soil, denitrification occurs, which yields very low soil and water nitrate and nitrite levels but higher levels of evolved gaseous nitrogen in the atmosphere; under aerobic conditions which may develop if the soil is strongly drained, soil ammonium is oxidised to give higher levels of nitrite and nitrate. These differences show how the activities of soil bacteria change according to field drainage conditions and may manifest themselves physically as differences in the colour of the soils.

Flooding tends to buffer soil pH (Boto, 1984). If the water table drops there may be an increase in soil acidity, shown in lower soil and water pH values (solid line). If the soils contain sulphide and pyrite minerals, aeration may lead to the development of the mineral jarosite which is hydrolysed to form sulphuric acid, yielding acid-sulphate soil conditions - common in parts of Africa and south-east Asia, (Hesse, 1961a). Water salinity (measured as conductivity) is expected to decrease markedly following clearance and drainage as the soluble salts are washed out of the soil through leaching processes.

3.8.4 Terrestrial (alluvial) sedimentation processes

Freshwater input into mangroves is important as a control upon salinity levels and a source of dissolved oxygen. Freshwater also contains dissolved metals useful to plants, such as calcium, magnesium and iron in concentrations dependant upon the inland course of the river. Because the composition of water is dictated off-site, it will be unaffected by clearance. Changes in the properties of freshwater-influenced soil and water variables in the field areas will only occur if water flow into the site is impeded, or if the drainage regime at the site alters. Thus a graph predicting the value of terrestrial sediment-sourced variables would be unaffected by clearance and burning of the site. A slight decrease in the value of sediment-sourced variables is possible following drainage of the site because of increased leaching losses across the site as a whole.

3.8.5 Geological processes

The geology, principally manifested as the rock type underlying the mangrove forest, will affect the physical and chemical properties of the soil. Around the field sites, the soils overlie a series of unconsolidated marine sediments. This will influence the soil particle size distribution (measurable as the proportion greater than 2 mm, less than 2 mm and as the percentage of sand, silt and clay). This in turn influences physical properties such as soil drainage and the bulk density of a layer. The composition of this material may affect soil chemistry through the levels of carbonate silicates, iron, calcium, magnesium, etc. which influence variables such as soil pH.

Upon clearance the underlying geology will remain unaltered, so many of these properties such as the soil particle size distribution are not expected to change significantly. Draining the site, by altering the hydrology may result in long term solution and transportation effects, which may result in gradual change, but not over short enough timescales to merit detailed study in this research.

3.8.6 Compaction effects

Some physical soil properties may be more rapidly altered by clearance. It is likely that the soil will show signs of compaction because of pressure exerted by people and machines during clearance. The bulk density of soils in the cleared zone should increase, with a corresponding reduction in average thickness of organic-rich horizons. This is shown in the final graph, Figure 3.12(vii).

3.8.7 Implications for the fieldwork

These graphs facilitate a comparison of variables measured in the forest and cleared zones. Those measured in the forest are assumed to have values in the same range as the pre-clearance values in Figure 3.12, those in the cleared zone will have values predicted to be higher, lower or broadly similar according to the stage of clearance and drainage experienced by the cleared zone of the field site. By measuring these variables at selectively cleared field sites of different ages, (i.e. at different stages in the clearance process), it should be possible to test the validity of these predictions.

The above consideration of environmental processes, has yielded a suite of research hypotheses predicting the expected changes in a range of soil, water and other environmental properties. Such *process*-focused investigations can be complemented by a line of inquiry stemming from a major *socio-economic* force in mangrove clearance: the legislative framework. The remainder of this chapter outlines how protective legislation in Belize has acted to preserve narrow buffer strips of mangrove forest next to areas of disturbance. It also draws attention to the absence of an accompanying justification for the specified width of this buffer zone.

By considering the socio-economic (legislative) framework, a further spatial aspect can be added to this work. The legislation defines the width of the remaining buffer zones, providing a relevant spatial scale for the present enquiry. The following research is able to offer insight into debates about the sustainability of this buffer zone by quantifying the penetration of change effects experienced in the remaining mangrove. By focusing on such "edge effects" this work can provide suitable evidence to evaluate existing and future protective legislation in Belize.

3.9 Legislation relating to mangrove clearance

Belizean legislation relating to mangrove protection has been extensively reviewed by McShane (1991) Zisman (1992, 1993) and Miller (1994), from which much of the following analysis is drawn.

Mangroves are given general protection under the Belizean *1989 Forests (Protection of Mangroves) Regulations* which state:

> Unless specifically exempted... ...no person shall alter, allow or cause to be altered any mangrove in jurisdictional waters without first obtaining a permit from the Department. This prohibition applies to both privately owned and public lands.
> *Section 3, 1989 Forests (Protection of Mangroves) Regulations.*

However, provision remains within this act for the granting of permits to allow development in mangrove areas. The act specifies charges to be levied for the cutting of mangrove - BZ$25.00 for areas less than 0.1 acres, BZ$50.00 for areas between 0.1 and 1 acre, and BZ$300.00 for areas greater than 1 acre. Such low rates will act as little deterrent to developers[8].

In his analysis of this legislation, Zisman (1992) reports it to be reasonably comprehensive but that public compliance is poor. He estimates that approximately 90% of mangrove clearance by area is occurring without permits being sought. Three reasons for this lack of compliance are given:

1. The low level of public awareness of the legislation.
2. The lack of financial resources available to the Forest Department for adequate enforcement.
3. The low level of fines.

Measures are being taken to rectify this situation - Zisman (1992) notes that the penalty for non-compliance with this legislation has been increased to a maximum of BZ$1000.00 or 12 months imprisonment. Recently, the Forest Department mounted a publicity campaign providing a series of explanatory brochures aimed at developers, explaining the legal and environmental aspects of the

[8] The level of these charges have been repeatedly condemned as too low (e.g. Miller, 1994; Zisman, 1993). Criticism of the fee levied for clearance of areas greater than an acre has been particularly fierce, claiming that it is set far too low, and that it unfairly penalises small developers - further categories with larger areas should be set, with appropriate increases in cutting costs, to deter large scale developments.

legislation (Waight, 1993). Large signs informing the public of the need to obtain permits before clearing mangrove have been placed at strategic locations along the two main roads out of Belize City - the Western and Northern Highways.

Mangroves are also protected under the *1939 66' Reserve Act* which was introduced to defend public rights of way (but may have its origins in far earlier colonial legislation, concerned with maintaining a standing supply of timber available for use by passing navy ships (Roger Wilson, pers. comm.)). This law states that a landowner's property rights extend only to a distance of 66' (c.20 m) from any water body. Theoretically this should prevent the removal of coastal mangroves, but in practice this has not happened. There are two reasons for this: land acquired before the act was excluded from this provision, and secondly, because this act is concerned with retaining *access* to areas, it does not prevent clearance of mangrove in this zone as long as public access is retained (Zisman, pers. comm.). Erosion of the coast at certain locations provides a further complication, highlighted by Miller (1994). Parts of the original 66' reserve may be washed away from the original seaward boundary mark, resulting in the loss of this right of way. In such cases the law is unclear as to whether a new reserve must be created.

Further protection for mangroves is given in the *1992 National Lands Act*. This states that on new leases of national land outside a city, town or village, a 66' wide strip bordering streams, rivers or open water should be left in its natural (undisturbed) state, unless otherwise approved by a Minister. Many local areas have passed similar legislation, specific to their own domain. McShane (1991) in discussions with a planner from the Belize City Planning Authority, reports that the Belize City Housing Department *Zoning and Development Plan* recognises the need for the maintenance of a 22 yard (i.e. 66') buffer zone of mangroves in all coastal areas and along the Haulover Creek.

Politically and ecologically, the long term success of such legislation depends upon three assumptions:

1. It needs to be consistently enforced.
2. Ideally this provision should be extended to include private as well as national land (the proportion still held nationally is declining annually as development continues).
3. It assumes that the 66' yard mangrove buffer zone is an ecologically sustainable unit.

Zisman (forthcoming) considers how the rate and location of mangrove clearance in Belize is a result of the complex political and socio-economic situation. He considers the distribution of national land, differences in access to land titles, the significance of the nationality of applicants in its effect upon the purpose of purchase and the likelihood of plot resale, etc. As such, these factors are not considered further here. Instead, it is the third point, the question of the sustainability of the 66' buffer zone which this work will address.

No ecological justification for the suitability of the 66' buffer zone could be found. Zisman, in an earlier report (Zisman & Munro, 1992) recommends that a larger buffer - 100 m of mangrove - should be left next to rivers, creeks and lagoons, and a 200 m buffer of mangrove adjacent to coasts (this higher figure is chosen to reduce coastal storm and hurricane impacts). These figures are however, still "informed guesses" (Zisman, pers. comm.). Miller (1994, p57) makes the case for a wider mangrove buffer in Belize, noting that "...strong recommendations have been made to retain at least 500 feet [c.150 m] of mangrove along primary coastline and 250 feet [c.75 m] along secondary coastline in the Belize City area".

Internationally there is no consensus of opinion either. In Indonesia the required buffer zone is far greater - Soegiarto (1984) notes that the government requires a 50-200 m wide belt of mangroves to be retained along the coast. This it is hoped will be sufficient to preserve the forest's ecological functioning and ensure natural regeneration of the mangrove. Conversely, the situation in the Philippines, (Librero, 1984) is far closer to that in Belize. *Presidential Decree 705* requires only 20 m strips of mangrove to be left along the edges of water bodies, although it also states that any mangrove swamp set aside for coastal protection purposes should not be clear-felled.

Without an international consensus, or indeed adequate justification for any of these figures, this work has highlighted the need to quantify the necessary minimum *sustainable* width of a mangrove buffer in Belize. Essentially, this work seeks to answer the question "is the legislated 66' buffer zone adequate?" Using an approach discussed further in Section 5.2.1, rather than set up a series of experimental plots of different buffer widths, the research will proceed by focusing on the depth (distance) of penetration of any changes found in mangrove forest. This will require the examination of edge effects in standing forest adjoining existing cleared areas. If within these sites, soil, water and other environmental properties are found to change in areas deep inside the remaining forest, then the validity of the existing specified buffers can be questioned.

3.10 Summary

The mangrove ecosystem has been shown to be highly dynamic. Variations in the value of soil and water properties have been found acting over a wide range of spatial and temporal scales. These variations and a paucity of comparable work which quantifies measures of nutrient movement in the mangrove currently prevent the development of a true nutrient budget for mangrove forests. Instead, a semi-quantitative model has been produced, identifying nutrient inputs and exports and the key ecological processes which act in the mangrove.

By focusing on the effects of clearance (particularly changes in the litter input) and drainage upon these processes, and thus the value of measurable soil and water properties, a series of predictive models has been produced. These models can be used to direct the fieldwork towards variables which should identify regions experiencing change because of deforestation and drainage.

The process work is accompanied by a review of legislation relating to mangrove clearance. This requires developers to leave mangrove buffer zones of a certain size along the edges of cleared sites and water bodies. At this stage, there seems to be no ecological justification for the thickness of the mangrove buffers specified in the legislation, or a consideration of the possible edge effects that may arise. Thus, the research aims have been expanded to quantify any changes in soil, water and environmental properties in the remaining forest following selected clearance, allowing an evaluation of the buffer width specified in the legislation.

Such work complements the primary research hypothesis developed earlier in Section 3.6: comparing still-forested and cleared areas to test process-based predictions of change. Interpreting the significance of measured differences requires a knowledge of two factors: the expected normal level of variation in mangrove forest values, and secondly the upper and lower tolerance limits which determine which habitats are suitable for mangrove colonisation. These are considered in the following chapter.

4

The robustness of the mangrove ecosystem

The question of resilience

This chapter considers mangroves' tolerance to flooding, salinity and insolation, plus some lesser physical, chemical and environmental factors which determine the vegetation cover in mangrove areas. It does this in three stages: firstly by detailing the plant community strategies for tolerating or avoiding stresses imposed by these factors; secondly by recording the known upper and lower tolerance limits of the different mangrove species for each major property known to be influential, and finally by considering the likely changes in these values following mangrove clearance. The findings of this chapter will be used to interpret the testing of the hypotheses developed in the previous chapter, relating to the expected nature and effects of mangrove clearance.

Mangroves manage to thrive in a very dynamic, yet potentially hostile environment. The factors considered comprise periodic flooding and storms, sedimentation and the mobile nature of the substrate, anaerobic soil conditions, high insolation levels and high salinity. These all pose severe problems which prevent or inhibit plant competition. The chapter shows that mangroves manage to grow because of a series of morphological and physiological adaptations. To a large extent the success of such adaptations (the plants capacity to tolerate biological and environmental stresses) determines the present environmental range of mangroves.

When considering the dynamics of change, both the upper and lower tolerance limits are important. If the upper (usually physiographically imposed) threshold is reached, even mangroves will not be able to grow. If the lower (commonly ecological[1]) limit is reached, true terrestrial plants may be able to grow too, and so outcompete the mangroves. Looking at the lower as well as the upper limits of mangrove tolerance is important, as mangroves are believed to tolerate, rather than require (in a physiological sense) such harsh growth conditions. They occupy their particular ecological niche because few others can, rather than because these sites are the most physiologically suitable. When

[1] There are exceptions to this perception of the lower limits being imposed mainly by ecological factors, one such is temperature. Mangroves cannot tolerate freezing, and so here, this limit is set for physiological reasons.

considering the range of tolerances, the nature and duration of the biological stresses are also important. Often it is not the average conditions, but the extremes, which determine the limits to plant tolerance and thus distribution.

4.1 Defining stress

The present research adopts a definition of stress drawn from that of Lugo & Snedaker (1974, p57) as an "action or influence which retards or restricts the normal functioning or development of living biological units". In other words, it reflects the draining of potential energy reserves that would have otherwise been available to the plant for different purposes (after Odum, 1971). This accords well with Levitt's (1972) definition of *biological stress* as being any change in the environmental conditions which may reduce or adversely affect a plant's normal functions (growth and development). Levitt gave the reduced or changed function the label *biological strain*. He divided this latter concept into elastic and plastic biological strain. *Elastic biological strains* are changes which are only temporary; if the stress is removed, the function returns to its previous level, (e.g. a temporary decrease in photosynthetic activity due to low light levels). *Plastic biological strains* are those which do not return to normal after the stress has been removed, (e.g. frost damaged tissue). However, as detailed in Salisbury & Ross (1992), the adoption of these terms, derived from equivalents in the physical sciences, has not been without its critics (e.g. Kramer, 1980; Larcher, 1987), particularly the frequent muddling of the terms stress and strain. Larcher therefore suggests a modification of Levitt's concepts -the use of *stress factor* in place of Levitt's *stress* and *stress response* for Levitt's *strain*. Larcher's modification of Levitt's terms will be adopted in this study.

Lugo & Snedaker (1974) show three ways in which stress factors can act:

1. Stresses factors can act to short-circuit a natural pathway (e.g. forcing drainage along a canal, rather than via overland sheet flow).
2. Stress factors can accelerate the rate of a natural process (e.g. increasing respiration rate in response to higher temperatures).
3. Stress factors can act to eliminate a pathway (e.g. sediment deposition preventing below ground root gaseous exchange with the overlying water).

Levitt (1972, 1980) drawing on earlier work, such as that of Shantz (1927), divides the plant's *stress response* into one of either *tolerance* or *avoidance*. Tolerance is the ability of a plant to endure a stress factor. Avoidance strategies are responses by the organism to reduce the impact of a stress factor. Salisbury & Ross (1992) give the example of desert plants avoiding the stresses dry soils impose by extending their roots downwards to reach the water table below.

Mangroves face many stress factors, due to their location. Growing in tropical latitudes leads to high temperatures and leaf insolation levels. Their littoral habitat means that they must cope with high

levels of soil and water salinity, frequent tidal inundation, flooding and the risk of hurricane damage. The anaerobic soil conditions impose severe limitations upon oxygen availability and allow the build up of potentially lethal concentrations of reduced soil compounds such as hydrogen sulphide.
Figure 4.1 shows an example of stressed mangroves observed in Belize.

Figure 4.1 Mangroves from the Punta del Este field site, showing signs of stress

The red mangroves seen in the foreground are showing signs of insolation stress - their leaves are steeply angled towards the sun. Their uniform short height (approximately 3m) is indicative of further stress retarding their growth, thought to be due to a lack of nutrients.

This view of limited nutrient availability is reinforced by the taller isolated black mangroves seen emerging from the red mangrove canopy. The black mangroves at this field site have unusually low number of leaves, are lacking in branches and have a very narrow crown, all suggesting that these plants are severely stressed.

Photograph taken by Sheila Ross, August 1994.

The mangrove species found in Belize differ in their stress tolerance and avoidance strategies. For clarity, each stress factor and the mangroves' corresponding tolerance and avoidance strategies will be considered *individually* below, but in reality many of these factors will act together, for example high temperatures combining with high leaf surface insolation levels.

4.2 Stress tolerance and avoidance strategies

The four main stress factors affecting mangroves are considered: flooding, salinity, insolation, and extremes of temperature. The discussion is directed at establishing what is termed the mangroves' "tolerance" of these stress factors, i.e. the range of values within which mangroves are able to grow and reproduce, and secondly the physiological adaptations which mangroves have developed as stress "avoidance" strategies.

4.2.1 Flooding

Mangrove soils are frequently flooded by freshwater, for example after heavy rains in upland areas, and more regularly by saltwater, due to tidal action or storm surges. The depth and duration of such flood events are highly variable. Flooding of a soil affects plants in three ways - it can mechanically damage the soil, deprive the soil of oxygen for respiration, and cause the formation of toxic reduced compounds in the soil.

Upon flooding, the pore-spaces around roots, usually filled with air, become waterlogged. Oxygen in the flooded soil is used by soil micro-organisms and in root respiration at a rate far faster than it can be replaced through diffusion,[2] resulting in the development of anaerobic soil conditions. Without the adaptations common in mangroves (aerenchyma, aerial roots, etc.), other plants face a lack of free and dissolved oxygen. This reduces root respiration and thus the plants' energy production available for nutrient uptake, transport processes and anabolic metabolism. Without oxygen, soil micro-organisms have to switch to alternative electron acceptors to allow them to decompose carbohydrates. In the absence of oxygen, the electron acceptors are used one at a time (if available), in order as the soil becomes increasingly reduced:- first nitrate, then manganic, then ferric iron, then sulphate, then carbon dioxide (Boto, 1984). These substances are reduced yielding potentially toxic reduced species. Of these, hydrogen sulphide is the most problematic in marine soils (McKee, 1994b). Very small quantities of hydrogen sulphide can prevent aerobic respiration of many plants and animals. Hydrogen sulphide levels in mangrove soils have been found to be orders of magnitude higher than those required to inhibit respiratory enzymes, (McKee, 1994b).

Mangroves have developed four strategies for flood "*avoidance*": aerenchyma, aerial roots, lenticels and oxidised rhizospheres.

1. Root aerenchyma (tissue with many large intercellular air spaces). The roots of mangroves contain abundant air spaces, allowing them to conduct oxygen from the aerial portions of the plant to the root tips (Scholander *et al.*, 1955). The presence of this imported sub-surface oxygen allows the plant to continue aerobic respiration. This results in a reduction in the oxygen demand from living cells, and allows the removal of potentially toxic volatile chemicals from the roots.
2. Mangroves have a highly developed system of aerial roots, which transport atmospheric oxygen to the roots underground. Both the prop (and drop) roots of red mangrove and the pneumatophores of the black and white mangroves have been shown to conduct oxygen to the below ground roots. (Scholander *et al.*, 1955, Thibodeau & Nickerson, 1986[3] , McKee *et al.*, 1988).
3. Lenticels (elliptical openings in the periderm (secondary tissue) which open to allow gaseous exchange) are found on mangrove stems and aerial roots. In the case of mangroves, this gaseous exchange is primarily the entry of atmospheric oxygen.
4. An oxidised rhizosphere (the soil immediately surrounding plant roots). Leakage of oxygen from the plant roots allows the oxidation of surrounding toxic soil compounds produced under anaerobic

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[2] The diffusion of oxygen in water is 10,000 times slower than in air (Ross, 1989).

[3] Scholander found oxidised regions around the roots of both red and black mangroves but Thibodeau & Nickerson only found oxidised rhizospheres in *Avicennia* species, with *Rhizophora* showing no marked difference from the surrounding soil. The work of McKee *et al.* prompted in part by Thibodeau & Nickerson's null result for *Rhizophora* found signs that local oxidation was occurring: redox potential and pore-water sulphide concentration were significantly correlated with the presence of roots of both *Avicennia* and *Rhizophora*. They concluded that Thibodeau & Nickerson's dissimilar results could be due to variation in the sediments studied or the ecological plasticity of the mangrove species at different sites.

conditions (such as hydrogen sulphide), creating an oxidised zone around the mangrove roots. (After McKee, 1994b)

Like many other plants, mangroves also have a flood *tolerance* strategy. They have metabolic pathways that can function without oxygen, i.e. anaerobic respiration. This allows them to tolerate short periods of extreme flooding (such as the total submergence of pneumatophores during a very high tide). However, because anaerobic respiration produces a far lower energy yield, it cannot be maintained in the long term.

Flood tolerance limits

Mangroves are thus able to tolerate far greater degrees of soil flooding than most other plants. They will be able to grow in soils covered by water, providing that the parts of the mangroves morphologically adapted to allow downward oxygen transport remain exposed (pneumatophores in the case of *Avicennia* and *Laguncularia*, aerial roots for *Rhizophora*). The size and form of these morphological adaptations determine the plants' floodwater depth limits. In Belize, these are approximately 20-30cm for mangroves with pneumatophores and over a metre for aerial rooting species. Mangroves can also tolerate flooding to greater depths for short periods (such as during a high tide or storm surge) because of their ability to respire anaerobically, albeit at a greater energy cost.

The greatest threat posed to mangroves by flooding is not by short-term submersion but by a longer-term increase in mean water depth. Snedaker (1995) notes that the proximal roots of mangroves with horizontal root structures (e.g. *Avicennia* species) appear confined to locations very near the sediment surface, and only the anchoring roots are able to penetrate the deeper, saturated anaerobic sediments. He suggests that this indicates that sediment conditions at greater depth do not support the growth and long-term survival of the proximal roots. An increase in water level would alter the vertical sediment physical and chemical environment, which he suggests would therefore induce stress on the mass of proximal roots through anoxia or sulphide toxicity. This hypothesis is supported by observations in Florida, where high mortality rates of the horizontal-rooted *Avicennia germinans*, but not *Rhizophora mangle*, are occurring in areas where mosquito-control impoundments have resulted in prolonged periods of increased water level.

Effects of clearance upon flooding levels and implications for the future

Clearance activity, as witnessed in Belize, will only affect the flooding regime of an area if the local hydrology or species distribution is also changed. Four points (sea wall construction, drainage, selective cutting and soil oxidation) are considered below:

1. The construction of earth embankments or concrete sea walls (as observed at sites along the Northern Highway[4]) are designed to prevent seawater flooding the site. Certainly, if of sufficient height, such constructions should significantly reduce the threat from flooding, by effectively increasing the elevation of the land. If this occurs, then mangroves may be outcompeted in these now drier soils by terrestrial plants (unless high soil salinities develop). However, if these coastal engineering measures are breached or topped, they will act to restrict the retreat of floodwaters back to the sea, thus ponding the site. If such ponding is prolonged (more than a few days), then this will have the opposite effect, pushing the balance back towards the flood tolerant mangrove species, notably *Rhizophora mangle*.
2. Part of the clearance process observed at large sites (e.g. *Punta del Este* and *Vista del Mar*), is the creation of drainage channels. These serve to lower the local water table, and thus should act to reduce the depth, and effectively the frequency of flooding. However, because of the low elevation of the coastal plain in Belize, such drainage works are highly prone to error. If the outflow to the sea is poorly designed, water during high tides can flow up the drains, flooding areas inland. The effects of such drainage measures upon the vegetation are dependent upon their resultant changes in the duration and depth of flooding at a site. As such, they are similar to those proposed for the creation of seawalls, above.
3. Selective cutting of the mangrove which also affects the tolerance of an area to flooding. In many sites along the Western Highway, although a coastal buffer of mangrove forest has been left, it is predominantly composed of *Avicennia germinans*, with the previous seaward fringe of *Rhizophora mangle* stripped away. Thus exposed, individual *Avicennia germinans* trees, because of their lesser depth of flooding tolerance, are often killed, either by suffocation due to prolonged submergence of their roots, or erosion of the surrounding substrate by wave action. Such processes are accelerated by an alarming activity - first reported by McShane (1993) - the trimming of pneumatophores to ground level. This process has also been observed at first hand at locations along the Western Highway. It effectively robs the trees of their natural tolerance to inundation, and must therefore drastically affect their ability to survive in these locations.
4. Flooding of mangrove sites, maintains anaerobic soil conditions, and high levels of reduced rather than oxidised soil compounds. If following clearance flooding ceases, aerobic soil conditions will develop due to decreased transpiration and a greater surface area now available for evaporation. This in turn will result in the oxidation of soil compounds, which can pose a new threat to plants. Hesse (1961a) has documented the development of toxic *acid-sulphate* soil conditions in empoldered mangroves in Sierra Leone, which can drastically impede plant growth. Acid sulphate soil conditions are a particularly widespread problem in many parts of South-East Asia. Acid-sulphate soils can attack concrete, if it is not pre-treated. If there are sufficient sulphide and pyrite

[4] Figure 5.1 is a map of Belize City, where such sites can be located.

compounds in Belizean mangrove sediments, then the processes of clearance and drainage could result in the development of similar acid sulphate soil conditions.

4.2.2 Salinity

Substrate salinity has been shown to have a negative effect upon many plant physiological processes such as transpiration, leaf conductance, carbon dioxide assimilation and water use efficiency (Naidoo & von Willert, 1995). Yet mangroves can grow, reproduce and complete their lifecycle in highly saline habitats. Mangroves' tolerance to salinity varies with species. In general, those possessing both salt excretion and limited salt exclusion mechanisms (such as *Avicennia* and *Laguncularia* spp.) have a greater salt tolerance than those with only salt exclusion mechanisms (e.g. *Rhizophora*).

In his study of mangroves in Vietnam, Hong (1992) found mangroves growing best in salt concentrations of 20-35‰ (grams of salt per kilogram of seawater). Higher salinities (40-80‰) reduced both the size of individual trees and the number of species. At salinity levels of 90‰ only a few *Avicennia* species were able to survive, with a very slow growth rate, suggesting that the upper salinity limit was being reached[5]. Nearer Belize, Teas (1979) reports sightings of very short, gnarled black and white mangrove in Florida, in areas with a soil salinity of 80‰. Recalculating Bowman's (1917) Florida data, Teas (1979) concludes that for *Rhizophora mangle*, the upper salinity limit is around 60-65‰, and that red mangrove seedling transpiration ceases at 65‰. This accords well with the Puerto Rican work of Cintrón *et al.* (1978) who found more dead than living *Rhizophora* where interstitial soil salinities were greater than 65‰.

An increase in soil water salinity has been found to result in reduced growth, and a decrease in the nitrogen concentration of plant roots and shoots (Naidoo, 1987). He postulates that this is due to nitrogen resources being reallocated to osmotic adjustment, thus retarding plant growth. In combination with a strongly reducing soil redox potential, salinity has been shown to have a retarding effect upon leaf net carbon assimilation (Ball and Farquhar, 1988; Ball, *et al.*, 1988). According to Munns *et al.* (1983) and Robinson & Downtown (1984) this is because the high salinity disrupts the plant's ability to take up potassium ions, resulting in low leaf potassium concentrations, which in turn retards several photosynthetic processes (Huber, 1985).

A further variable is introduced by the work of McMillan (1975a) who found that the upper limit of salinity tolerance for black and white mangrove seedlings varied with the clay content of the soil. Seedlings growing in sand died upon only a short exposure to salinities of 80-150‰. Those in a soil with a moderate clay content (5-10%) survived, but showed signs of wilting, whilst seedlings in a soil

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[5] This value of the upper salinity limit is corroborated by Teas' (1979) work on vegetation-free hypersaline lagoons which are found in the centre of some mangrove forests. In these a combination of water temperatures as high as 45°C and salinities over 100‰ resulted in mangrove death. Similarly, Gordon (1988) cites a value of 90‰ as the upper tolerance limit of mangroves in western Australia.

containing more than 17% clay continued growing. McMillan was unable to isolate the exact mechanism for this increased tolerance but, noting a depression of the soil pH in soils with a higher clay content, he suggests that this response may be due to increased cation exchange capacity. The exchange of sodium and hydrogen ions in the clays may be reducing the salinity of rhizosphere porewater. Clay deflocculation will occur as the result of adsorption of sodium ions. This will effectively reduce root contact with the salt water at once facilitating freshwater uptake and yet also reducing the uptake of salts. McMillan's hypothesis of reduced salt uptake by plants grown in clay-rich soils is lent further weight by the observation that plants growing in the clay showed far less salt excretion by their leaves than both those in sand and growing without soil.

Historically, great debate existed as to whether mangroves are *obligate* or *facultative* halophytes, that is plants which require salt for survival and reproduction, or plants which tolerate salt, but can grow and reproduce in either fresh or salt water. Bowman (1917) thought salt was needed for optimum development, whilst both Egler (1948) and Davis (1940) claimed mangroves to be facultative halophytes. Today this debate appears to have been resolved, Smith (1994, p10) for example, categorically states that mangroves "are not obligate halophytes". This resolution may be part of a broader argument, many plant physiologists such as Barbour (1970) believe that no angiosperms (flowering plants) are obligate halophytes, all known halophytic species have been observed growing or cultivated successfully in non-salty soils. In a local context, in the Rio Bravo area of north-west Belize, red mangroves have been observed growing far inland, (Furley *et al.*, pers. comm.) in an area where freshwater swamp-forest might have been expected. More generally, Teas (1979) points out that most mangroves are capable of growing well in freshwater.

However, high salinity levels are a key factor in the creation and maintenance of mangrove communities. Mangroves are highly efficient *salt regulators* (halophytes which prevent their internal salt concentrations from increasing during the growing season). Ball (1988) has shown that mangroves can exclude almost 100% of the salt. Kuenzler (1974) notes that mangroves predominate in saline areas because these conditions prevent the growth of terrestrial plant species, which would otherwise outcompete the mangroves, as can be seen in nearby non-saline habitats. This paradoxical relationship with saltwater is neatly summed up by Snedaker (1979) - mangroves need freshwater to satisfy their *physiological* requirements, but salt water to satisfy their *ecological* requirements (minimising the competition).

Mangroves have developed *tolerance* mechanisms for both major plant stress factors induced by salinity: plant water deficit and ion toxicity. Plants are able to take up water osmotically, because the concentration of water outside the root is greater than that inside. Saline soil pore-water inhibits this process by reducing the effective water concentration gradient. Without mechanisms to accommodate salinity, plants may suffer from dehydration. Salt-excluding species such as *Rhizophora* have been shown to use a non-metabolic ultrafiltration system to separate freshwater from seawater at the root surface (Scholander, 1968). This "reverse osmosis" process, powered by leaf transpiration induced pressures, allows sap salt concentrations to be about 1/70 of that of the surrounding sea-water[6]. Species which rely primarily on salt secretion methods (e.g. *Avicennia* and *Laguncularia*) dispose of excess salt using biochemically powered excretion through salt glands on the leaf surface. Atkinson *et al.* (1967) suggest that this process is enzymatic, as it is highly temperature dependent. This process results in a higher sap salt concentration than that found in salt excluders, with a typical concentration being around 1/7 the salinity of seawater (Odum, *et al.*, 1982). Within the plant, high concentrations of sodium and chloride ions can have a toxic effect, interfering with protein synthesis, inhibiting enzyme activity and altering respiration rates.

Mangroves have developed four *avoidance* strategies for coping with salinity: exclusion, excretion, succulence and abscission. These are considered below, highlighting the strategies employed by the mangroves found in Belize:

1. Exclusion of salts by the plant roots (the primary mechanism employed by *Rhizophora mangle*, to a much lesser extent it is also adopted by *Avicennia germinans* and *Laguncularia racemosa*).
2. Excretion of salts from salt glands in the leaves (*A. germinans*, *L. racemosa*).
3. Succulence - dilution of salts achieved through increasing tissue water content (*L. racemosa, Conocarpus erectus*).
4. Abscission - elimination of salt-saturated organs (this method is used by *R. mangle* to dispose of excess salt).

After Teas (1979) and McKee (1994b)

They have also developed three *tolerance* strategies for highly saline conditions: compartmentalisation, synthesis and conservative water use.

1. Compartmentalisation of salts in the vacuole, removes the toxic ions from the metabolically active regions of the cell.
2. Synthesis of organic solutes balances inorganic ions in the solute.
3. Highly conservative water use strategies, minimise the plant's need for water uptake.

Mangroves also show the following three morphological and physiological adaptations to salinity:

1. Stomata on the lower leaf surface - decreasing plant water loss.
2. Thickened cuticle on the leaf surface - decreasing water loss.
3. Salt glands in the leaf epidermis.

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[6] Although this is still approximately ten times more saline than sap found in normal terrestrial plants (Scholander *et al.*, 1962). The average salinity of ocean water is approximately 35‰, but varies with latitude. In the waters around Belize (c. 17°50'N) it is very close to this average, i.e. c.35‰, (Pickard & Emery, 1990; confirmed by personal field observations, 1992, 1994).

Salinity tolerance limits

From these data, it would seem that all three true mangrove species found in Belize will grow in soil and water containing levels of salt similar to that found in seawater. As we move inland to areas more irregularly flushed by the tides, due to greater evaporation and evapotranspiration the salt concentrations may increase. Where this occurs, fewer species are able to thrive. The lowest upper salt limit is for red mangroves, which seems to be around 60‰ (Teas, 1979), white mangroves seem to tolerate marginally higher levels, and black mangroves are the most salt tolerant, growing in areas with salinities up to 80-90‰, (Teas, 1979; Hong, 1992). Above about 100‰ no mangroves species seem able to survive and such areas are likely to be vegetated only by saline marsh species.

No quantitative data relating to salt tolerance limits could be found for buttonwood, the mangrove associate, but a passing reference is made in Tomlinson (1986, p232). He notes that it is "tolerant of high salinities and rather dry soils". Given that it can be found as a "back-mangrove" species, in comparatively well-drained areas, it is expected that it will have a salinity tolerance closest to that of the white mangrove, which occupies the most similar habitats.

Data detailing the lower salinity limit are sparse, and if mangroves are truly facultative halophytes, then in common with all other angiosperms, their lower salinity "limit" is in physiographic terms 0‰. However, it is likely that the effective lower limit is far higher than this, with mangroves being outcompeted ecologically at low salinities (except in relict inland sites or under other such "abnormal" conditions). Yet the key factor(s) that determine the dominant plant species in any particular area may well be not salinity but other associated soil conditions such as the degree and frequency of flooding. The diluting action of precipitation and freshwater run-off are also important in determining the salinity at any particular point.

Effects of clearance upon salinity levels and implications for the future

Clearance of mangrove in Belize should cause an initial rise in salinity values, which will later peak then gradually decline. The argument for this sequence of events is that initially, the removal of the forest canopy (and the flood reduction/prevention measures outlined earlier), should result in the exposure of the sediment surface to the sun, and thus increase the evaporation rate at a time when the loss of the vegetation has severely reduced the transpiration rate. This will lead to salts crystallising out, and thus a rise in surface soil salinity. However, removing the forest cover also increases the amount of precipitation reaching ground level. Without transpiration, net water movement in the soils should be downwards, (particularly if the soils are artificially drained) resulting in the leaching of salts, so decreasing surface soil salinity. The exact salinity level reached at any given site will therefore depend upon the balance achieved between evaporation, precipitation, drainage and further salt inputs (from the air, sea-spray or following a flood).

Salinity will also be altered by any modification to the terrestrial drainage pattern. If the area behind the mangrove is built upon, the runoff and throughflow patterns will be altered. If the water is routed via a network of canals, rather than remaining as overland or throughflow across the mangrove, then this possible source of further salt dilution will be lost, increasing the salinity of the cleared area.

It is unlikely that simple forest clearance without drainage in these areas would result in the creation of soil salinities so high that they proved toxic to any of the local mangrove species (>60‰) as long as the inland freshwater runoff is not impeded. Rather, it is more likely that clearance may result in a long term drop in mean salinity (fluctuations will still occur on both a diurnal and seasonal timescale). This resulting decrease in salinity may result in salt concentrations low enough to allow competition from other (i.e. non-mangrove) plants, *if* the local water levels remain low during the wet season.

Clay content and salinity tolerance

A simple statistical analysis was carried out upon mangrove sediment data from a range of locations spanning the coast of Belize (drawn from the 1991 fieldwork, published in Furley *et al.*, 1993). This aimed to consider McMillan's (1975a) controversial hypothesis that clay content affects mangroves tolerance to salinity levels (introduced in Section 4.2.2). Mean clay figures at sites occupied by mangrove vegetation were found to be in the range 4.5% - 23.7%. Interpreting these figures (shown in Figure 4.2) is problematic: their uneven distribution along the coast means that the x-axis values are really not evenly spaced, as displayed. Furthermore, site specific details such as the geological and geomorphic setting of an individual transect (whether it was an estuary, lagoon, etc.) may be as significant in determining the sediment fraction accumulating there as latitude. Given these limitations, a tentative interpretation reveals a confused picture in the north, but an increasing proportion of clay in near surface samples as one moves progressively south. Such a pattern is consistent with a move from coarser limestone derived material in the north, to finer fluvial quartz based sediments (from the Maya Mountains) in the south.[7] Combining sample data from the sites nearest Belize City gave a mean clay value of 8.1% ± 6.1%[8]. Albeit unlikely, if very high salinities were to be experienced in this area, according to McMillan's theory, this clay content would allow the plants to survive, though showing signs of damage.

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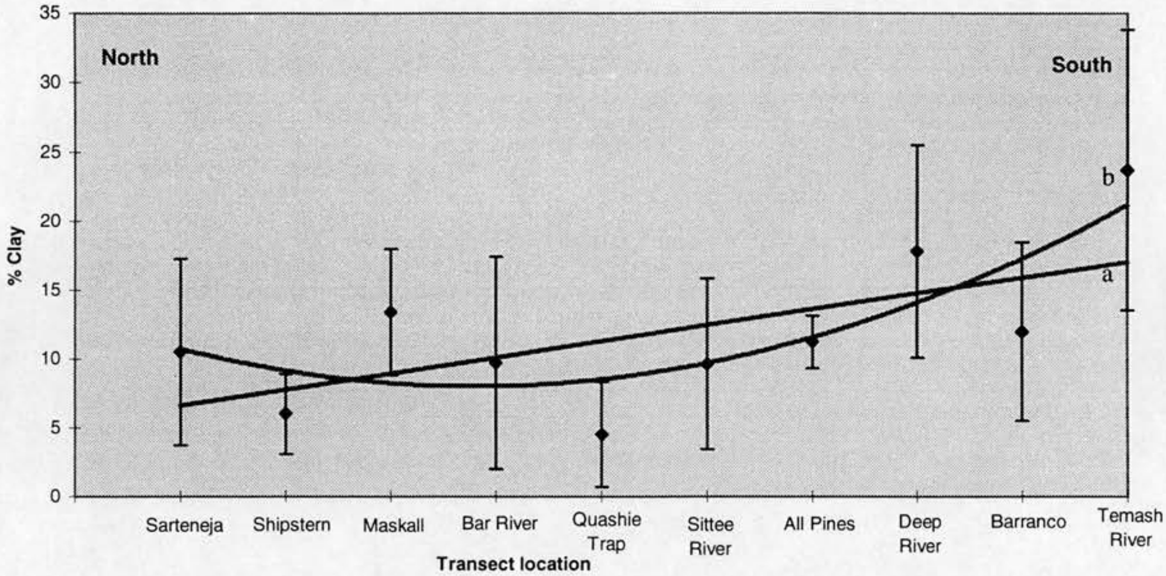
[7] This is rather a simplification of the pattern of coastal soils. It omits units identified by Wright *et al.* (1959) as *6a Siliceous lowland Pine Ridge* soils (no limestone, quartz accumulation occurring at the coast) just north of Belize City (also found at the All Pines Site in Figure 4.2) and *4d Toledo Coastal Strip* soils, a series of sandy- and loamy-clays outcropping south of Punta Gorda.

[8] This figure was obtained using data from mangrove covered sections of the three nearest transects: Maskall (sites 1-4), Quashie Trap Lagoon (sites 9-17) and Bar River (sites 11-20). This gives a total sample size of n = 36. The figure quoted is the mean ± one standard deviation, calculated using σ_{n-1} because of the small sample size. The previous figures were calculated in a similar way for the other transects.

Figure 4.2 Mean clay content of mangrove sediments along a north-south series of transects in Belize



Raw data for this graph and the transect locations are given in Furley et al. (1993). It should be noted that the transect locations are not evenly distributed along the coast of Belize. The point data are the calculated means, plotted bars show one standard deviation. A simple linear line (a) and a curve (b) have been fitted as crude trend indicators. These should be interpreted with care, given that the x-axis is not a numeric scale.

4.2.3 Insolation

Insolation, incoming solar radiation, is highly variable, depending upon factors such as cloud cover, sun angle, leaf angle, shading from other leaves and wind movement of branches. Variations in insolation will disrupt plant metabolic processes, effecting an increase or decrease. Sunlight also affects plant temperature and influences the development process, acting as a growth stimulus.

Low light levels

A lack of light leads to "starvation". Deprived of adequate solar energy, plants are forced to use other energy sources such as carbohydrates. Light levels within a mangrove forest below the canopy can be several orders of magnitude lower than direct sunlight (McKee, 1994b). To cope with this, mangroves have developed four *tolerance* strategies:

1. Increasing the leaf area to maximise a plant's ability to intercept incoming light.
2. Increasing the chlorophyll content of shaded leaves increases an individual leave's ability to absorb light.
3. Mangroves have developed specific arrangements of leaves on a stem to maximise light interception and minimise shading of each other. The mangrove species of Belize adopt varied leaf arrangements, which reflect their different habitat preferences and differences in leaf size. The smaller leaved *Avicennia* and *Laguncularia* branches contain oppositely paired (decussate) leaves. The larger bijugate *Rhizophora* leaves grow as pairs angled at less than 90° to each other. The back-mangrove associate *Conocarpus* has leaves which grow in a spiral (Tomlinson, 1986).

High light levels

Like other surfaces receiving incident light, leaves can reflect, absorb or transmit the insolation. Leaves' ability to reflect light varies according to its wavelength - plants are generally able to reflect 70% of infra-red radiation, 6-12% of the visible spectrum, but only 3% of ultraviolet light (McKee, 1994b). As well as the wavelength of the insolation, the degree of leaf damage is further dependent upon the leaf structure and orientation. Excess light results in three effects:

1. Photoinhibition - stimulated by the excess light, reactive molecules are formed within the leaves to destroy photosynthetic reaction centres.
2. Photodestruction of chlorophyll, preventing photosynthesis.
3. Inactivation of the nucleic acids and proteins.

Mangroves have developed four light *avoidance* strategies:

1. Increasing the leaves' reflective properties, through colouration, thickening and the development of a waxy coating to the cuticle and the growth of cuticle hairs.
2. Increasing the content of non-chlorophyll pigments in the leaves, to reduce the amount of light able to penetrate the leaf surface.
3. Heliotropism - re-orientating the leaves at such an angle as to minimise the amount of light falling on the leaf surface.
4. Synthesis of compounds within the leaf capable of absorbing UV radiation, such as the tannins found in *Rhizophora* leaves.

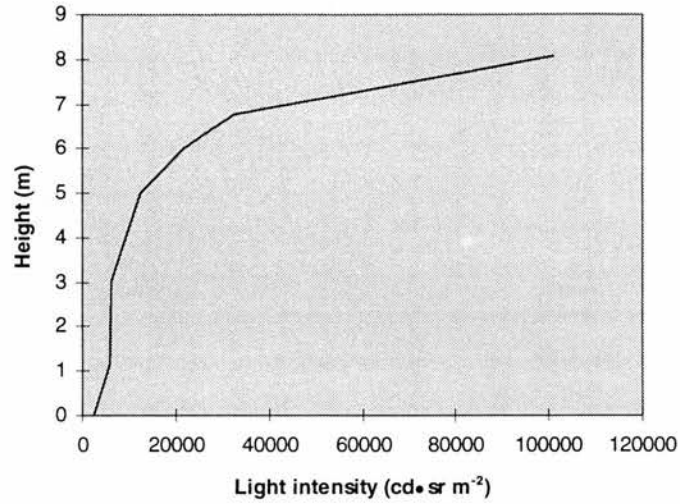
From McKee (1994b) and Pannier (1984a).

In order to cope with the differing light conditions found at the top of the canopy and below it, in common with many other plants, mangroves have developed a degree of leaf specialisation. In areas of high sunlight, mangroves have specially adapted *sun leaves* which dissipate excess energy through the chlorophyll (Björkman *et al.,* 1988). In darker areas with reduced stress levels, mangroves produce *shade leaves*. These are far more efficient photosynthesisers and their assimilation ability is less affected by high salinity levels than that of sun leaves. Thus mangroves found at field sites experiencing high salinity levels may show a predominance of shade leaves, regardless of the light levels experienced there.

Light level tolerance limits

There are no published tolerance limits for mangroves, probably because the limits of other associated stress factors (such as salinity considered above) are reached before those of light. However, a semi-quantified indication of the effects of different light levels upon mangroves follows. Clearance of areas of mangrove forest will have a significant effect upon the light levels. Removing the canopy will result in a far greater percentage of the insolation reaching previously shaded sections of the mangrove and the ground below, affecting the forest structure and biomass partitioning. The undisturbed forest conditions in Belize are likely to be similar to those found by Golley *et al.* (1962) shown in Figure 4.3.

Figure 4.3 Vertical distribution of light in a red mangrove forest



Adapted from Golley et al. (1962). These data were originally presented in foot candles, but were converted into candelas, the SI units. This measure is not widely accepted as being meaningful by all plant physiologists, as it is based on the sensitivity of the human eye (Salisbury & Ross , 1992). For conversion purposes, the full range of the x-axis as displayed is approximately 11,150 foot candles.

Working in an undisturbed red mangrove forest in Puerto Rico, they found that 95% of the available light had been intercepted only 4 m below the top of the canopy (which was about 8 m above the ground). 90% of the leaf biomass and the majority of leaf chlorophyll were in the light intense upper 4 m. This efficient light interception by the undisturbed canopy acts to suppress the development of an understorey in mangrove forests. Clearance may stimulate the development of non-mangrove ground-dwelling species, such as *Batis maritima*, a common coloniser of mangrove gap-sites. Three further effects upon the remaining mangroves are considered below: photosynthetic efficiency, species balance and seedling survivorship.

Photosynthetic efficiency

Clearance would result in much higher light intensities near the ground along cut edges exposed to the sun. This would mean existing shade leaves on the plants would suddenly be exposed to sun leaf conditions, resulting in potential leaf tissue damage and so plant stress. With such a damage-induced reduction in the total photosynthetic output, individual mangroves on these edges will be less able to compete with other plants, which in turn may be stimulated by the increased ground surface light levels. Because shade leaves are more tolerant of high salinity levels than sun leaves, then the mangroves' photosynthetic efficiency would be further impaired if clearance results in increased salinity levels. If such stresses continue over time, then the structure of the new edge must alter. This may be because of plant death if the mangroves fail to adapt, by replacement with more sun-tolerant terrestrial species, or the development of mangroves with a higher proportion of sun leaves at low levels in these conditions of increased insolation.

Species balance

The timing of the clearance may be important in determining the plant species attempting to colonise this new site. The types of seeds and propagules present at these sites will be crucial, determining whether they are ready to exploit this opportunity offered by higher ground insolation levels. There is a marked seasonal pattern of clearance in Belize, with the vast majority of clearance occurring in the dry season (approximately January to May). The significance of the timing of seed dispersal varies with species, because of differences in the propagule residence time. The time of clearance is not really significant in the case of *Rhizophora*, where seedlings have been found to have residence times of up to a year (Rabinowitz, 1978c; Ellison & Farnsworth, 1993). However, seedlings of *Avicennia* and *Laguncularia* have not been found to survive more than six months after dispersal. Ellison & Farnsworth (1993) give the time of this dispersal as between November and December, but *Avicennia* seed dispersion was observed personally in the field at a mainland site in August 1992. If this was just a freak occurrence and the dates given by Ellison & Farnsworth are correct, then clearance occurring at either end of the dry season is likely to favour regrowth by *Rhizophora* seedlings. Clearance at other times will result in competition at these sites from all three Belizean true mangroves. The time of clearance can thus affect the future species balance of a mangrove area because of differences in the seedlings' tolerance to light.

Seedling survivorship

Ellison & Farnsworth (1993), working at a site on the shore of Placentia Lagoon in Belize, have shown that seedling survivorship after 1 year was higher in disturbed plots where the canopy had been removed (90% of seedlings survived) than in areas where the canopy was still intact (78%). Seedlings in these sites exposed to higher levels of insolation had significantly more leaves, had a greater total biomass and increased in height at twice the rate of those under the canopy. Seedlings may have been better able to tolerate the harsh light and temperature regime of these areas than mature plants, because their lesser height makes them closer to the moderating effect of the standing water. A previous study (Farnsworth & Ellison, 1991) has shown that plants in the exposed sites are also subjected to a lesser degree of herbivory than those under the canopy. Therefore clearance, through its effect upon seedling survivorship, is likely to encourage the growth of young mangroves along these exposed edges at the expense of older trees, altering the age structure of the forest stand.

However, it should be noted, that the opportunities for regrowth at these exposed sites offered by changes in the light regime may be severely curtailed by further activities associated with development. Construction of roads and dwellings, covering the soil surface with clay fill and periodic re-burning of the cleared area will all reduce the chance of seedling establishment.

4.2.4 Temperature

A plant's temperature fluctuates with that of the ambient environment. Accordingly, plants have developed a certain degree of tolerance to temperature-induced stress. Mangroves are sensitive to extremes of both high and low temperatures. Indeed, the avoidance of freezing conditions is considered to be a major factor in limiting the latitudinal distribution of mangroves (Chapman, 1975). Blasco (1984) posits air temperature as the basic climatic factor governing the geographical distribution of mangrove species. The two temperature extremes offer differing problems to the plants, requiring different coping strategies.

High temperatures

These may cause plant damage by imposing limits upon key physiological processes, through membrane damage or enzyme denaturation. Death of parts, or even the entire plant is possible, eliminating it from a particular ecological niche, or reducing its competitive vigour. Three signs of high temperature injury are:

1. Chlorotic mottling of leaves and fruit (propagules).
2. The development of necrotic lesions, especially on stems and the seedling hypocotyl.
3. Eventual death of the plant.

After McKee (1994b), Pannier (1984a) and Ball *et al.* (1988).

Mangroves show up to six high temperature *avoidance* strategies:

1. Heliotropism - leaves are orientated to minimise insolation interception. Andrews *et al.* (1984) showed this to be a highly efficient strategy - the decrease in photosynthetic assimilation due to lower light levels arising from a steep leaf angle is less than the decrease due to the stresses imposed by higher leaf temperatures on shallow angle leaves. Ball *et al.* (1988) have found leaves angled as steeply as 75° to the sun in the most exposed sites (similar to those seen earlier in
2. Figure 4.1).
3. High leaf reflectance properties to deflect incident radiation, avoiding a rise in temperature.
4. A reduction in leaf size. This enhances the leaves' boundary layer conductance, increasing its ability to conduct sensible and latent heat, allowing it to maintain a temperature closer to that of the ambient air.
5. An alternative strategy for leaf temperature change avoidance is an increase in succulence. Although increasing the leaf volume at the expense of the boundary size, the higher water content gives the leaf a larger specific heat capacity. This dampens the leave's rate of temperature change, and is thought to reduce the time spent in unfavourable temperature ranges. It is more common in

species with a low salinity tolerance, which cannot afford the carbon assimilation loss associated with a reduction in leaf size.

6. Dissipation of heat through transpiration and evaporative cooling.
7. The adoption of cool habitats: mangroves are found growing in water and their thick canopy provides considerable shade for leaves below. The presence of water acts as a thermal buffer, dampening fluctuations in soil and so root temperatures.

After McKee (1994b), Pannier (1984a) and Ball *et al.* (1988).

They have also developed two *tolerance* strategies:

1. Mangroves have developed specialised proteins and synthesis mechanisms. Strategies include creating heat-stable proteins, able to tolerate the high leaf temperatures, using a rapid synthetic process to replace heat-denatured proteins, and the synthesis of substances which protect proteins from damage.
2. The development of carbohydrate reserves to support thermally induced increases in the respiration rate.

From McKee (1994b) and Pannier (1984a).

Upper temperature limits

The temperature at which such damage begins is in the range of 40°C to 55°C (McKee, 1994b; Odum *et al.*, 1982). Tissue sensitivity to thermal damage is dependent on its stage of growth, young actively growing tissue (e.g. seedlings, flowers, leaf tips) is far more susceptible than mature tissue (e.g. bark). McMillan (1971) found that very young black mangrove seedlings along the coast of Texas were killed at temperatures of only 39°C to 40°C, whilst established seedlings and trees there remained undamaged. Andrews *et al.* (1984) found that stomatal conductance was inversely related to leaf temperature. They also found that net photosynthetic assimilation was markedly influenced by leaf temperature, and the changes were of sufficient magnitude to imply that they were not just related to changes in stomatal conductance, rather the temperature was also affecting the metabolic process. Their results, using *Rhizophora apiculata* leaves in Australia and those of Ball *et al.* (1988), suggest that the optimal leaf temperature for assimilation is in the range 22°C to 30°C, and that above 37°C carboxylation is minimal.

Low temperature limits

Mangroves are tropical plants, Waisel (1972) has shown that they do not develop well in regions where the average annual temperature is below 19°C. They do not tolerate temperature fluctuations greater than 10°C, nor freezing conditions for even short periods. Saenger *et al.* (1977) have shown that mangroves do not grow in areas where the average temperature of the coldest month is 16°C or lower. Boaden & Seed (1985) give an even more restricted optimal range - average temperatures rarely falling below 20°C and seasonal fluctuations less than 5°C. They highlight the fact that such tolerances vary with species, but claim that even the hardiest mangroves cannot survive air temperatures below -4°C. Avicenniaceae are the most cold tolerant of all mangroves (West, 1977) and Odum *et al.* (1982) report a semi-permanent shrub form of *Avicennia germinans* that exists on the northern coast of the Gulf of Mexico, growing back from the roots after annual frost damage.

McMillan (1975b) studied the chilling tolerance of *Avicennia germinans* and *Laguncularia racemosa* along the Gulf of Mexico and Caribbean coasts. He found that *Laguncularia* throughout this latitudinal range had no chilling tolerance, but that poleward populations of *Avicennia* had developed some chilling tolerance, able to withstand temperatures as low as 2°C to 4°C for short periods. Individual *Avicennia* plants transplanted from more equatorial locations (in this case the Caribbean) lacked this tolerance. Using laboratory experiments, he was able to demonstrate that this poleward chilling tolerance was not related to the plant's response to preceding local photoperiod or temperature conditions, and concluded that chilling tolerance was an inherited property.

Lugo and Zucca (1977) found that in response to low temperatures, mangroves decrease their structural complexity. In cold conditions, mangroves showed a decrease in tree height, leaf area index[9] and leaf size, with a corresponding increase in tree density. Furthermore, they concluded that additional environmental stress factors such as increased salinity further reduced mangroves chilling tolerance.

Cold ocean currents may also have an inhibiting effect upon mangrove growth. Moguedet (1980) suggests that the poor development of West African mangroves around the Kouilou estuary in the Congo is due to the effect of the nearby cold Benguela current.

Effects of clearance upon temperature levels and implications for the future

The cold temperature effects discussed above are unlikely to be found at the fieldsites considered in this work. Given Belize's tropical location (15°N - 19°N) and mean monthly minimum temperatures in the range of 16°C to 18°C in winter and 24°C to 25°C in summer (Hartshorn *et al.,* 1984), freezing events are highly improbable. The lowest recorded temperature for the Belize City area is 8°C (Walker, 1973). Although under the correct meteorological conditions temperatures can be depressed well below these averages - known locally as "northers" (Hartshorn *et al.,* 1984) or "nortes"[10] - the drop in temperature is still insufficient to cause freezing conditions. None of the climatic effects of forest clearance are thought likely to alter this situation and so low temperature effects will not be considered further.

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[9] The ratio of the total surface area of a plant's leaves to the ground area available to the plant. This measure is used when considering cultivation density and plant productivity in the context of plant size.

[10] Arctic air masses forming during the northern winter pushing cold, wet, north-easterly air masses much further south

In contrast, leaf surface and soil temperatures at the exposed edge and in cleared areas of mangrove should increase, because of the removal of the canopy. The effects of this are likely to be similar to those in the discussion of insolation, above.

4.3 Other limits to growth

Whilst the four factors listed above are the most obvious and easily quantifiable stress factors facing mangroves, there are other processes which can also affect mangrove development: tidal action, sedimentation, precipitation, aridity and wind. These stem from two main factors, firstly mangroves' littoral location, exposing them to the action of waves and sediment bearing currents; and secondly the local climatic components. These environmental factors are therefore considered below, together with chemical factors: soil pH, redox potential and nutrient levels. The possibility of pH imposing stress upon mangroves is not generally considered in reviews of mangrove stress, but its inclusion here stems from the implications of two recently published papers suggesting that pH may strongly influence mangrove zonation in both Thailand and Japan.

4.3.1 Tidal action

Although as McKee (1994a, p3) notes that whereas "Tidal influence is... ...not a requirement" and therefore, strictly there are no tidal limits to either mangroves' distribution or tolerance, it does play "an important indirect role" in the mangrove ecosystem. Tidal inundation maintains salinity, reducing the competition from other plants. Carrying saltwater upstream against the flow of the river, tidal flow extends the area inhabited by mangroves around estuaries. Tidal action also helps in the dispersion of mangrove propagules. Thus, the absence of such tidal activity will serve to inhibit mangrove growth.

More directly, an absence of tidal action prevents the daily transport of sediments, nutrients and clean, oxygenated water into the mangrove and the export of particulate organic matter and reduced compounds, particularly sulphides, (McKee, 1994a). Irregular tidal inundation can result in the development of hypersaline conditions (as outlined earlier, in Section 4.2.2).

Areas of high wave energy inhibit the development of mangroves - strong waves impede the establishment of propagules, prevent the accumulation of fine, nutrient rich sediments and serve to expose the shallow roots of existing trees.

Effects of clearance upon the tidal regime and implications for the future

Tidal action is important in determining the nature of mangrove ecosystems in Belize. Although there is a relatively low tidal range, around 30cm (Kjerfve *et al.*, 1982) Belize is subject to frequent storms and irregular hurricane impacts. The most important factor pertaining to the impact of clearance is its effect upon tidal penetration - whether it is increased due to the removal of vegetation cover from land near the coast, or reduced by engineering measures. Three effects are considered below: propagule sorting, the accumulation of reduced compounds and changes in sediment characteristics.

1. Tidal action together with the new morphology of the cleared site may be important in determining which plant species try to recolonise it. Rabinowitz (1978a, b, c) has shown that there is an element of tidal sorting of mangrove propagules. The longer *Rhizophora* propagules tend to become stranded at the shore or in deep water, whilst the smaller *Avicennia* and *Laguncularia* seedlings are carried inland, to be deposited above the mean water mark. Preventing tidal penetration is therefore likely to inhibit regrowth of *Avicennia* and *Laguncularia* species, and limit *Rhizophora* regrowth to the coastal edge, if external sources of seeds are required.
2. A reduction in the tidal flushing of a site following clearance will cause the accumulation of reduced soil compounds as long as the site remains flooded, or the water table remains close to the surface. These may become present in sufficiently high levels to pose a toxicity threat to plants growing there. Of the possible recolonising plants, mangroves, with their morphological adaptations detailed above (such as root oxygen translocation), are the most suited to tolerate such conditions.
3. In the long term, the nature of the sediments may change following clearance. If tidal inundation increases, there will be a net export of particulate matter, exposed by the removal of the binding vegetation. This is likely to have a detrimental effect upon local water clarity and the health of neighbouring reef and sea-grass beds. If saltwater incursion is prevented, the resulting loss of this marine input of material means that terrestrial sediment sources will predominate in the cleared region. Thus in general, sediments will become enriched in quartz sands and show lower levels of carbonate based materials. Such variations will be site-specific, dependent upon factors such as the distance to the nearest river or canal, the surrounding hydrology, the geology of the water catchment area.

4.3.2 Sedimentation

The relationship between mangroves and sediment supply is complex. Mangroves rely on sediment input as a source of mineral nutrients, to replace those lost in the export of mangrove-detritus. In a study combining field measurements and computer modelling of upland runoff, Lugo *et al.* (1976) showed that over a timescale of tens of years, reductions in the upland runoff and mineral burden resulted in related reductions in mangrove productivity. Conversely, too rapid an accumulation of sediment, whether from terrestrial or marine sources, inhibits mangrove growth. Odum & Johannes (1975) report that exposed regions of the aerial root system are vulnerable to clogging by fine suspended materials, preventing oxygen intake. Similarly, deposition of sediment upon the surface of mangrove soil can prevent the exchange of gases and mineral nutrients (Lugo & Snedaker, 1974). Rapid accumulation of sediments (for example after a hurricane, or following the disturbance of the natural coastal geomorphic processes by dredging, mangrove clearance or harbour construction) can lead to mangrove mortality. There are two causes of this: smothering of pneumatophores, leading to direct tree death, and secondly changes in the assemblages of species in the mangrove muds (Lugo & Snedaker, 1974). Mangroves growing on actively accreting shores, typical of much of Belize, experience a gradual change in the sediment fauna. Rapid disturbance to this slow process may result in the death of the community, leaving it open to colonisation by "outside" species (Lugo & Snedaker, 1974).

Effects of clearance upon sedimentation processes and implications for the future

As detailed above in the discussion of tidal action, clearance of areas of mangrove may affect the sedimentation processes occurring there, particularly the particle size and source of deposited material. Burning of the timber after clearance would result in a single large input of carbon-rich material, which could affect local surface fertility conditions if this material can be retained *in situ.*

4.3.3 Precipitation and aridity

In humid climatic areas, the intense precipitation acts to leach the soils continuously and dilute the salinity levels (Blasco, 1984). However in inland sites, where rainfall is both far less frequent and less intense, evaporation may lead to the development of highly saline conditions. In a study in Gujarat, a highly arid part of India, Blasco found such acute hypersaline conditions in areas only inundated twice a year (during the equinoctial tides), that no vegetation grew. Local precipitation rates can thus affect the ability of mangroves to survive in an area, through their effect upon salinity levels.

Effects of clearance upon precipitation and aridity and implications for the future

Clearance of small areas of mangrove are unlikely to alter the local precipitation patterns in Belize, thus having no noticeable impact on precipitation and aridity effects.

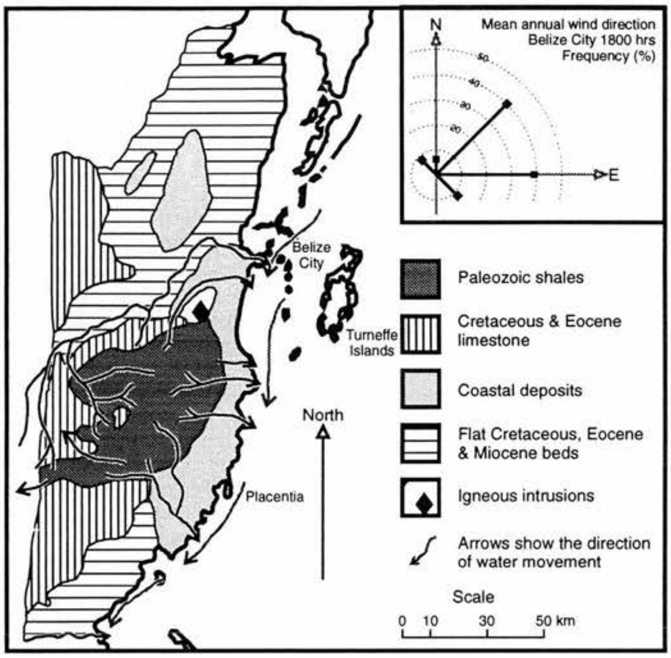
4.3.4 Wind

Blasco (1984) cites three effects of wind upon mangroves: alterations to coastal morphology by the deposition of wind transported sand; aligning coastal features and currents; the risk of hurricane and cyclone damage. These are discussed below:

1. Winds carrying sand affect the local coastal morphology and so affect the development of local mangroves. If the deposition rates are great enough to allow sediment build up, mangroves may become progressively buried, as is occurring along the south west coast of Madagascar (Blasco, 1984). Such sand-bearing winds however, are not common across Belize.
2. The prevailing wind direction exerts considerable control over the local coastal geomorphology, such as aligning longshore currents and transporting sand, clay and silt short distances. Figure 4.4 shows the present pattern of coastal sediment transport. The shape of many features along the coast, such as the Placentia peninsula, are indicative of the current depositional regime - southward moving ocean currents combining with winds blowing predominantly from the east and north-east to transport the marine and fluvial sediments south.

3. Eastern shores of tropical landmasses are exposed to the risk of hurricane and tropical cyclone damage.

Figure 4.4 Influences of wind directions and currents upon Belize's coastal geomorphology



Source: Map adapted from Wright et al. (1959). Wind data taken from Walker (1973).

Reports of hurricane damage to mangroves are common - an account of hurricane damage in the West Indies is given by Borgesen (1909), Davis (1940) records hurricane destruction of Florida mangroves. Chapman (1944) attributes relict patches of dead mangrove in Jamaica to hurricane damage. Blasco (1975) has looked at cyclonic activity in the Bay of Bengal. Both Stoddart (1963) and Vermeer (1963) have looked at the impact of Hurricane Hattie on Belize, with particular reference to its effect upon the mangrove covered cayes (offshore coral islands). After the recent devastation of mangrove regions by Hurricane Andrew in Florida, it is anticipated that more publications will be forthcoming.

Such accounts generally place hurricane impact upon the mangrove into one of three classes: *minor* (defoliation of some of the mangrove); *severe* (destruction of parts of the mangrove ecosystem); *destructive* (resulting in the death of almost all the mangroves). As well as the effects of the high winds, mangrove death can result from the accompanying flooding. Venkatesan (1966) notes that the *tsunami* accompanying the November 1952 cyclone in Cauvery, south India, resulted in the suffocation of large areas of *Avicennia* because the forest was submerged for a fortnight to depths of up to 2 m.

However, as Blasco (1984) points out, many of these reports are highly descriptive, merely listing the area and extent of damage. An exception is the analytical approach adopted by Jiménez & Lugo

(1985). They observe that mangroves have many natural ecological adaptations to mass mortality events such as a hurricane. The strategies of abundant production of seedlings, quick rearrangements of forest zonation and the rapid rate of tree growth and succession allow mangroves to recover quickly, as can be seen in revegetated areas in Belize which lie along the track of hurricanes, such as the Turneffe Islands.

Effects of clearance upon wind speeds and implications for the future

Removal of the vegetation cover is likely to increase the rate of erosive activity, and the potential impact of destructive forces such as hurricanes. Without the protective buffer of fringing mangrove, wave energy reaching the shore will remain undiminished. Clearance carried out without proper regard for the function of mangrove in preventing coastal erosion may result in the future loss of coastal lands.

4.3.5 Soil pH

Soil pH has often been considered a factor in controlling the distribution of many terrestrial plant species, for example leguminous plants are known to favour neutral soils, while pine trees prefer acidic soils. However, considerations of mangrove zonation and distribution has generally ignored pH in favour of salinity when explaining these patterns (it is absent from papers such as McKee, 1994b; Odum *et al.,* 1982; Lugo & Snedaker, 1974). Two recent studies of basin mangrove forest (*sensu.* Lugo & Snedaker, 1974) by Wakushima *et al.* (1994a, 1994b) have questioned this assumed dominance of salinity over pH. If their results and interpretation are correct, then mangroves show a species-specific pH tolerance, implying that pH can be considered as a stress factor for mangroves.

They found significant correlations between mangrove species and a range of soil properties, including salinity and pH. A selection from their results is summarised in Table 4.1 below.

Table 4.1 Soil pH and salinity of four mangrove species in Thailand (1988-89)

	Rhizophora apiculata	*Rhizophora mucronata*	*Avicennia alba*	*Lumnitzera racemosa*
	n = 166	n = 105	n = 73	n = 72
Salinity (‰)				
Dry Season 1	23.3 ± 1.1	30.2 ± 0.9	31.8 ± 1.5	21.7 ± 1.7
Dry Season 2	30.5 ± 0.8	30.5 ± 0.9	35.2 ± 0.9	28.0 ± 1.3
Wet Season 1	14.4 ± 1.1	22.8 ± 0.7	24.4 ± 2.3	21.7 ± 4.2
Wet Season 2	14.3 ± 0.7	22.3 ± 0.7	23.0 ± 2.4	21.7 ± 4.1
Mean	29.0 ± 0.7	25.8 ± 0.6	27.8 ± 1.2	23.2 ± 1.1

continued overleaf

	Rhizophora apiculata	*Rhizophora mucronata*	*Avicennia alba*	*Lumnitzera racemosa*
	n=166	n=105	n=73	n=72
Soil pH				
Dry Season 1	6.33 ± 0.07	7.20 ± 0.07	6.80 ± 0.18	5.43 ± 0.17
Dry Season 2	6.27 ± 0.07	6.97 ± 0.06	6.73 ± 0.14	5.47 ± 0.19
Wet Season 1	6.31 ± 0.06	6.99 ± 0.06	6.92 ± 0.10	5.35 ± 0.28
Wet Season 2	6.34 ± 0.08	7.08 ± 0.17	6.91 ± 0.09	5.42 ± 0.23
Mean	6.31 ± 0.04	7.00 ± 0.03	6.85 ± 0.06	5.41 ± 0.08

Modified from Table 2, Wakushima et al. 1994b. Values are the mean ± the standard error, taken at depths >20 cm. This table contains only data gathered in Thailand. Earlier data from Japan is not included, because Japan lacks a seasonal climate. However the Japanese results are very similar to the dry season values obtained in Thailand for mangrove species found in both countries. Surface (<20 cm) soil samples were omitted from the analysis. Previous work (Wakushima et al. 1994a) had shown that surface soil properties varied markedly from subsoil measurements.

In the accompanying discussion, they point out that there are many other factors which may influence the distribution (inundation period, sediment composition, elevation, etc.). Yet it can be seen from the data that whilst there is considerable seasonal variation in salinity levels, the pH values have only a very narrow range. From this they suggest that each mangrove species has its own preferential pH range, and spatial variations in soil pH contribute strongly to the observed distribution patterns. Whilst the data patterns look seductive, such an inferential approach fails to identify a mechanism for the pH imposed stress.

The availability of soluble cations, and the number and species of soil micro-organisms are known to vary with pH (e.g. Brady, 1984; Salisbury & Ross, 1992). Metals which precipitate as hydroxides under alkaline conditions (such as iron, copper and manganese), show a relatively simple relationship, with their availability to plants decreasing as the pH rises. Other metals such as phosphorus may show a peaked distribution, with the maximum availability occurring over a narrow pH range (pH 5.5 - 6.5 in the case of phosphorus). Equally, under certain pH conditions, the amount of a substance available to plants may be so great as to reach toxic levels. Aluminium toxicity can be a problem in some soils with a pH below c.4.7 (Salisbury & Ross, 1992).

Thus the differences in the observed pH zonation of the mangroves may relate to each species' nutrient requirements, notably their ability to fix phosphorus and nitrogen at varying pH levels and their tolerance of extreme metal concentrations. An examination of pH-induced mangrove stress should therefore seek to establish these requirements and the effects of pH upon them for each mangrove species. As yet such work remains to be completed. In the case of the five mangrove species found in the neotropics, they await even an equivalent descriptive piece detailing the relevant pH range of each tree species.

Effects of clearance upon pH and implications for the future

Mangrove clearance could affect pH in three ways:

1. It could decrease litter input. The removal of the forest cover will result in an accompanying decrease in the litter input (although this may still be quite high in areas close to the forest edge). The loss of this organic input would serve to increase soil pH, by limiting the formation of organic acids.
2. It could create a short term carbon peak. Conversely, decomposition of the large input of organic material, resulting from the felling and possible burning of the mangrove, may result in a short term spike in soil acidity, due to the formation of organic acids. The size of any such peak will be related to the rate of decomposition. This in turn will be influenced by soil temperature, pH and redox conditions as well as the presence or absence of soil macro-fauna such as grapsid crabs, preying upon such material. From personal observation, the numbers of such crabs appears far higher in recently cleared areas than in abutting regions of remaining forest, which may be indicative of a greater short-term availability of food in cleared areas.
3. The pH of the groundwater will be dependent upon the substances dissolved within it. The balance between soil nitrification and denitrification may be significant here. Denitrification results in the release of ammonia, which is highly soluble and if not taken up by plants could act to increase the pH of mangrove waters.

4.3.6 Nutrient levels

There is a distinct lack of published data detailing mangroves' nutrient requirements. However, many writers have expressed the view that (undisturbed) mangrove systems are already limited by the availability of nitrogen and phosphorus (Hicks & Burns, 1975; Lugo *et al.*, 1976; Naidoo, 1987). While Clough *et al.* (1983) have found typical levels of these two nutrients in mangrove soils to be fairly high - around 200-1500 μg total P g^{-1} oven dry weight (of which 75-85% is expected to be in the form of organic phosphorus[11]) and c.600-2000 μg total N g^{-1} oven dry weight - their experiments involving the addition of nitrogen and phosphorus show increased mangrove growth rates.

Naidoo (1987) notes the apparent contradiction implicit in these figures, particularly the nitrogen limit to plant growth which seems strange in soils which are typically anaerobic and thus have high levels of nitrogen present as ammonium, a form available to plants. One possible reason for this can be taken from the work of Helal *et al.* (1975), who found that the uptake of ammonium by barley roots is hindered by competition from sodium ions; these are present in very large numbers in saline mangrove soils. Another possible explanation is offered by Morris (1980). In studies of the mangrove component *Spartina alterniflora*, he speculates that poor oxygen diffusion into the rhizosphere together with the presence of metabolic poisons such as hydrogen sulphide may act to inhibit plant uptake of

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[11] From the work of Hesse (1962, 1963).

ammonium. Whilst saline, reducing conditions are indeed present in mangrove soils, it seems likely that the real limit to plant growth in mangrove soils is the form of mineral nitrogen. Boto *et al.* (1985) suggest that the true limit to plant growth in mangroves is not ammonium-N deficiency, but a lack of nitrate-N, which is quickly reduced to nitrogen and nitrous oxide gas in the anaerobic soil conditions.

High levels of sodium ions also present problems for mangroves in their attempt to utilise other macronutrients, notably potassium, and the divalent magnesium and calcium, important in plant metabolic functions. Joshi & Misha (1970) measured the ion concentration gradient that mangroves have to overcome in potassium uptake. Plants have an internal sodium to potassium ratio of approximately 1:1, yet this is achieved by selective potassium uptake from seawater and mangrove soil water, which have a sodium to potassium ratio of c.38:1 and 9:1 respectively. Furthermore, they infer that mangrove soils must show limited magnesium availability. They found that mangroves withdrew magnesium from ageing leaves before senescence even though excess levels of this ion in plant tissue can inhibit photosynthesis and chlorophyll synthesis. Joshi *et al.* (1974) report similar withdrawals of phosphorus and potassium from older leaves, suggesting levels of these nutrients are also limited. Thus, even in undisturbed mangrove forests, it would seem that the availability of nutrients is insufficient for maximum plant growth rates to be achieved.

Effects of clearance upon soil nutrient levels and implications for the future

Forest clearance acts to release nutrients stored in the standing timber of the mangrove forest. Since leaves are lost through the act of felling trees rather than senescence, they have higher nutrient levels. The practice of leaving the felled timber to dry out *in situ* before removal, mechanically compacting them into the soil or eventually burning the wood, aids the movement of these stored nutrients into the mangrove soil and water. Thus, immediately after clearance, nutrient levels near the cleared area are expected to show an increase, particularly those rapidly released such as potassium, calcium and magnesium. Levels of nutrients released more slowly through mineralisation, such as phosphorus, carbon, nitrogen and sulphur, will also show an increase, but over a longer time period.

However, these nutrient gains cannot be sustained, as there is no further nutrient input (e.g. from litter) because of the tree loss. If mangroves are not able to recolonise the cleared area quickly (as they do naturally in areas affected by lightning strikes) then soil conditions are expected to become increasingly unfavourable for their re-establishment.

4.3.7 Redox potential

Redox potential is essentially a measure of electron activity. The redox potential affects the mobility (and thus availability to plants) of elements in solution, and whether they are likely to be oxidised or reduced. Hesse (1971) has shown that the oxidising or reducing state of a soil is most significant in wet or waterlogged soils, whose chemical properties are largely determined by the availability or absence of oxygen. Thus, the state of the redox potential is a significant factor in mangrove soils. It is an important factor to measure because many reduced forms of soil compounds e.g. sulphides and ferrous iron, common in anaerobic mangrove soils with very low redox values are toxic to terrestrial plants.

Clough *et al.* (1983) claim that the redox potential of mangrove soils is rarely greater than +100 mV and is usually much lower. However, such figures are probably site averages, masking a greater range of values. McKee (1993) has shown an association between the distribution of mangrove species and spatial variation in soil redox potentials. Mixed forest areas and those dominated by *Rhizophora mangle* were found to have moderately reducing soils (Eh 100-300 mV), those dominated by *Avicennia germinans* had strongly reducing soils (Eh $\leq$ -100 mV). Furthermore, she has demonstrated marked spatial variations in soil redox potential, dependant upon the distribution pattern of mangrove roots which have been found to oxygenate regions of the rhizosphere.

Low redox potential values common in mangrove soils act to limit which plants can grow there. Very few terrestrial plants can tolerate the extreme reducing conditions found in some mangrove soils. Whilst the claims of Odum *et al.* (1982, p2) seem overly optimistic:

> "Anaerobic sediments pose no problems for mangroves"

they do seem able to tolerate very reducing conditions, because of their ability to export oxygen through their roots, creating localised areas suitable for bacterial activity. Therefore, it is thought that the real limit to mangroves posed by soil redox potential conditions, is not by low, but high values, i.e. a high concentration of oxidised species in the soil. The limit to their distribution is not physiological, rather the loss of their competitive advantage at high redox values, where terrestrial plants are able to exploit the aerobic soil conditions more efficiently.

Effects of clearance upon soil redox potential and implications for the future

Draining the mangrove will have an immediate and highly significant effect upon soil redox potential values. Spaces in the soil, previously waterlogged, will become filled with air. This change to aerobic soil conditions will result in a high (positive) redox potential and the oxidation of previously reduced (potentially toxic) soil compounds, providing favourable soil conditions for terrestrial plants to exploit.

4.4 Conceptualising the environmental change arising from clearance

Figure 3.6 the abstract nutrient flow diagram developed in chapter three, provides an overview of nutrient movements and storage within the mangrove. In order to reveal how the effects of clearance and drainage may alter this, attention must now be focused upon the effects of clearance and drainage upon the key variables involved, drawing upon the mangrove tolerance limits discussed above.

Overleaf, the identified inter-relationships between the effects of forest clearance and drainage upon a range of key variables and indicators of change - pH, water depth, redox potential, leaf temperature, forest biomass partitioning and salinity - are summarised using a series of flow charts (Figure 4.5 to Figure 4.8). In these diagrams, the causes of change are displayed at the top, and the resulting processes of change follow below. The ensuing changes in the variable considered (e.g. water depth) are represented using a cartographic "spring-balance" analogy: processes are displayed as arrows, attempting to deflect the balance's needle either up or down. Note however, that to maintain clarity no indication of the temporal scale(s) over which these processes act, or the relative magnitudes of the induced changes are given in these diagrams. Because of their summary nature they are necessarily simplified, and it is acknowledged that they are not exhaustive - there may be other processes resulting in mangrove change which have not been included here.

4.4.1 Effects of mangrove forest clearance and drainage upon pH

The five factors arranged along the top of Figure 4.5 have been identified as capable of affecting soil pH. The figure at the bottom right shows how differences in pH can affect mangroves, through its effect upon nutrient availability and the level of soil micro-organisms. The figure shows how different aspects of clearance and drainage may serve to either raise or lower soil pH.

Soil acidity may increase, resulting in a lower soil pH through several factors. If tidal inundation of the site is reduced, this will be accompanied by a decrease in marine sediment deposition. Given the close proximity of the barrier reef, much of this sedimentary material will be carbonate based and so alkaline, which would have previously acted to buffer soil acidity.

Preventing the tidal movement of water across the site will also significantly reduce flushing of the area, serving to maintain reducing soil conditions. This will favour bacterial activity associated with denitrification, resulting in the conversion of mineral-nitrogen to ammonium. Forest clearance reduces the plant cover and thus the volume of ammonium uptake by the vegetation. This resulting excess of ammonium dissolves readily in water, acting to raise soil pH.

When the site is cleared and possibly burnt, a large carbon store is released. This large input of organic material may result in a gradual increase in the level of soil organic acids, lowering the pH.

Drainage of the site may well be the most significant influence upon soil pH. In other mangrove areas of the world, site polderisation during conversion of mangrove areas into paddies for rice growing has often been accompanied by soil acidification (e.g. Hesse, 1961a; Bloomfield & Coulter, 1973). This is because the drop in the water table creates oxidising soil conditions, converting soil sulphides and pyrite to sulphate compounds, which dissolve to form dilute sulphuric acid.

4.4.2 Effects of mangrove forest clearance and drainage upon water depth and redox potential

Figure 4.6 shows how water depth at the field site and the associated redox potential of soil and water, depend critically upon the effectiveness of drainage and sea-exclusion activities undertaken at the site. Both these factors have "either/or" effects, indicated diagramatically by the purple coloured decision gates. These activities affect mangroves in two ways: the bottom left of the diagram shows how water levels influence soil redox potential, which determines the form (whether toxic or available for plant uptake) of nutrients; the bottom right shows how the physical depth of water at the site acts to constrain the species able to grow there.

A well executed drainage plan should result in a lowering of the water table at the site, the diversion of inland water sources (such as the network of canals draining Faber's Lagoon near the three field sites) and facilitate evaporation of water from the soil surface. Combined with a continuous sea wall preventing further marine incursion, the water table at the site should drop significantly and oxidising conditions develop in the upper layers of the soil.

However, drainage of coastal areas around Belize City are hampered by their low elevation. Poorly implemented channels designed to drain the site to the sea may actually result in increased landward penetration of the site by seawater, particularly during storms. In such a case, sea walls will act to impede the waters from receding, maintaining flooded soil conditions.

4.4.3 Effects of mangrove forest clearance and drainage upon leaf temperature and forest biomass partitioning

Figure 4.7 shows how two factors - forest canopy removal and the construction of drainage channels - affect leaf temperature (shown at the bottom right hand side of the diagram) and forest biomass partitioning (the bottom left of the diagram) at the site.

Removal of the forest canopy results in immediate increases in insolation levels, both at ground level in the newly cleared area, and in sub-canopy locations along the cut edge. This results in higher leaf temperatures in these areas, possibly decreasing photosynthetic efficiency and in extreme cases resulting in tissue damage. Increases in temperature will be amplified by site drainage as this removes the buffering action of standing water.

Increases in insolation will gradually alter the balance of sun and shade leaves on mature plants and stimulate the growth of unshaded seedlings. Both these activities will favour the movement of nutrients to leaf growth activities, at the expense of root development, which may leave the plants less well adapted to future changes, e.g. storm impact, increases in salinity or reduced nutrient availability.

4.4.4 Effects of mangrove forest clearance and drainage upon salinity

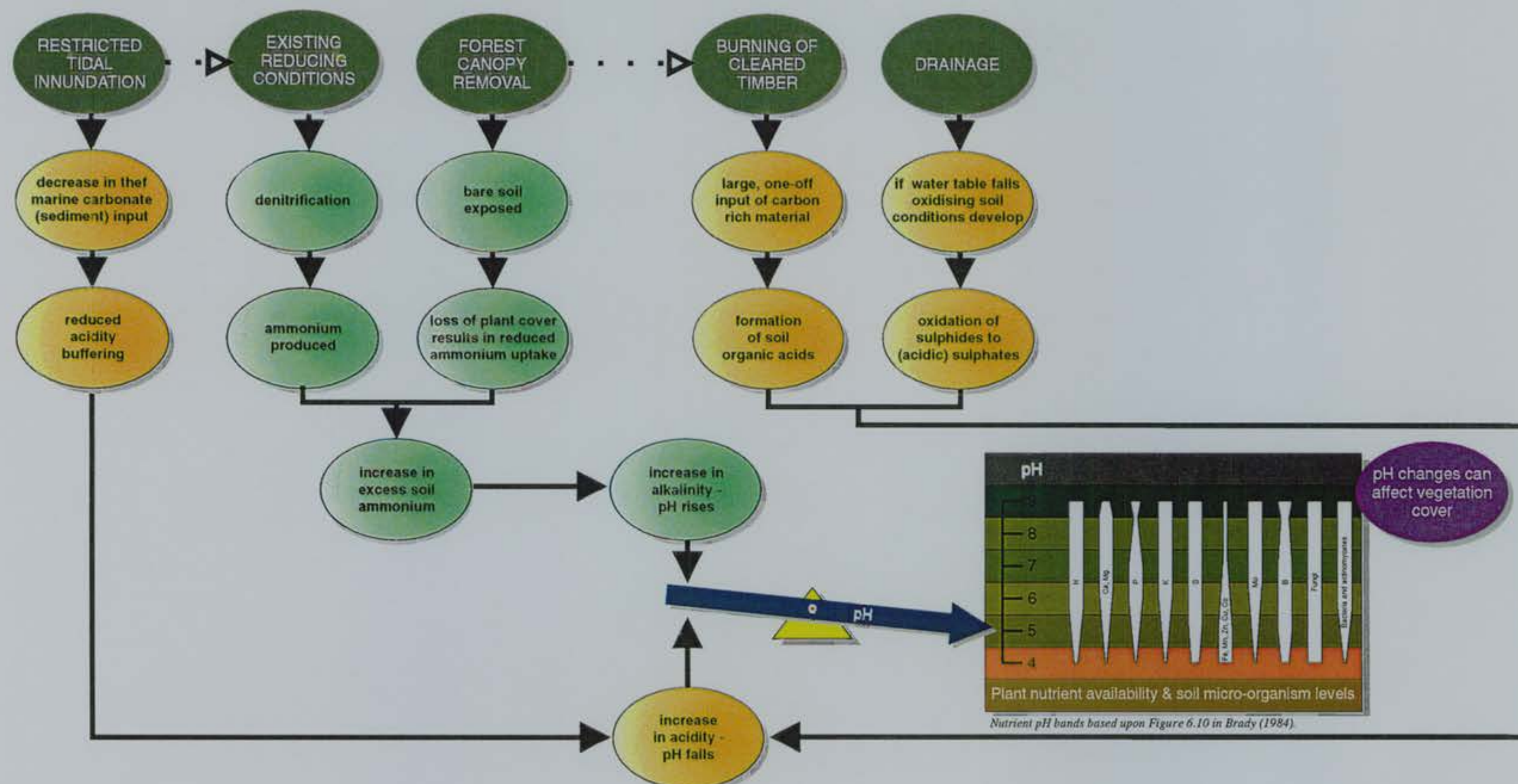
Expected changes in water salinity resulting from forest clearance and drainage are shown in Figure 4.8. Essentially, this figure draws attention to the sensitivity of mangrove water salinity levels to the balance achieved between water inputs and evaporation rates.

Salinity levels may be expected to increase if the hinterland drainage of the site is modified, routing freshwater away from the mangrove. Removal of the forest canopy will act to compound this concentration of salts in the water, by increasing evaporative loss. Poorly conceived drainage and sea wall schemes, (as detailed in Section 4.4.2) may act to increase salinity by introducing and then retaining further salts in the system. Conversely, other clearance effects will act to reduce the salinity of water in the soil. Removing the vegetation will eliminate transpiration losses and prevent interception of precipitation by plants in the cleared area. Draining the site will result in the dominant direction of water movement in the soil becoming "downwards". Wet season precipitation will thus leach soluble salts from the soil, resulting in a lower salinity level of interstitial water, and also floodwater, should the water table rise again.

4.5 Summary

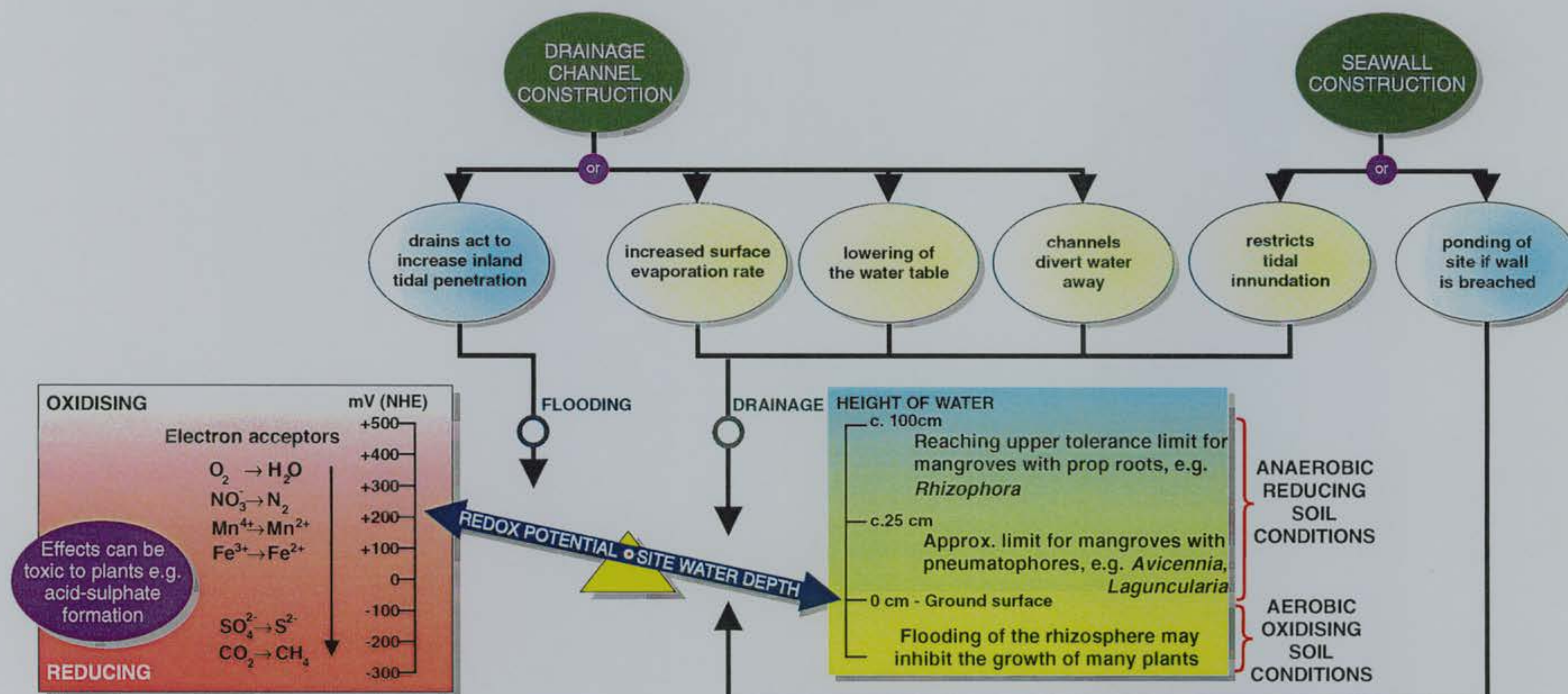
This chapter began by considering the stresses imposed on mangroves by the immediate environment. It continued by examining how two key causes of potential change - mangrove forest clearance and site drainage may affect the physical, chemical and environmental properties of mangrove areas. Forest clearance can be seen to affect the import and export of nutrients into the system (drawing on the work of chapter two) and the local micro-climate of the site; drainage modifies the salinity and redox potential of the site, resulting in changes in the soil pH and the ionic state of compounds present in the soil.

Figure 4.5 The effects of mangrove forest clearance and drainage upon pH



The five processes expected to influence pH are shown above, in dark green: restricting the frequency of tidal innundation (flushing); which may alter the existing reducing soil conditions; removal of the forest canopy; the possible burning of the fallen material; and draining the site. In the second line, the effects of these processes are shown, coloured according to the resulting change in soil and water pH. Effects which will increase the pH (increase alkalinity) are shaded in pale green.Those which will result in a decrease in pH (increase acidity) are shown in yellow. This figure shows how the final pH level is determined by the balance between inputs from the decay of organic material and the drainage conditions (and thus redox potential) of the soil. At the bottom right hand corner of the diagram, the striped box shows how different pH values affect the level of micro-organisms and available nutrients in the soil.

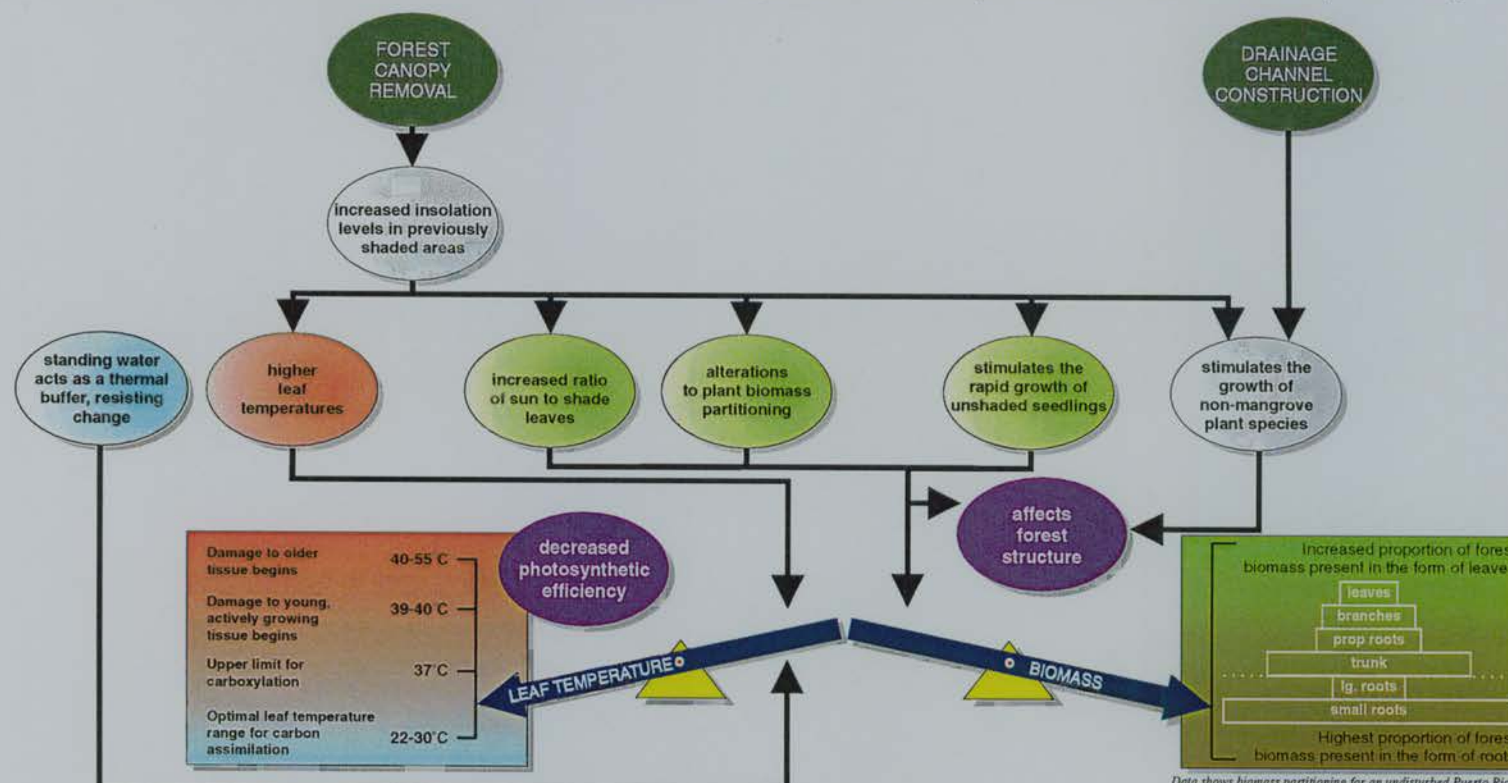
Figure 4.6 The effects of mangrove forest clearance and drainage upon water depth and redox potential



Oxidation-reduction data from Figure 7.1 in Boto (1984)

The two processes expected to influence water depth and thus soil redox potential are shown above, in dark green: the construction of drainage channels at the site; and building seawalls. In the second line, the effects of these processes are shown, coloured according to the resulting change in the water level. Effects which will increase the water level are shaded in blue. Those which will result in lowering are shown in pale yellow. This figure shows how the final water level results in changes in the soil redox potential. At the bottom left hand corner of the diagram, the shaded box shows how soil redox potential affects the cation species present in the soil. At the right, the shaded box shows the known water level tolerance limits for the mangrove species found in Belize.

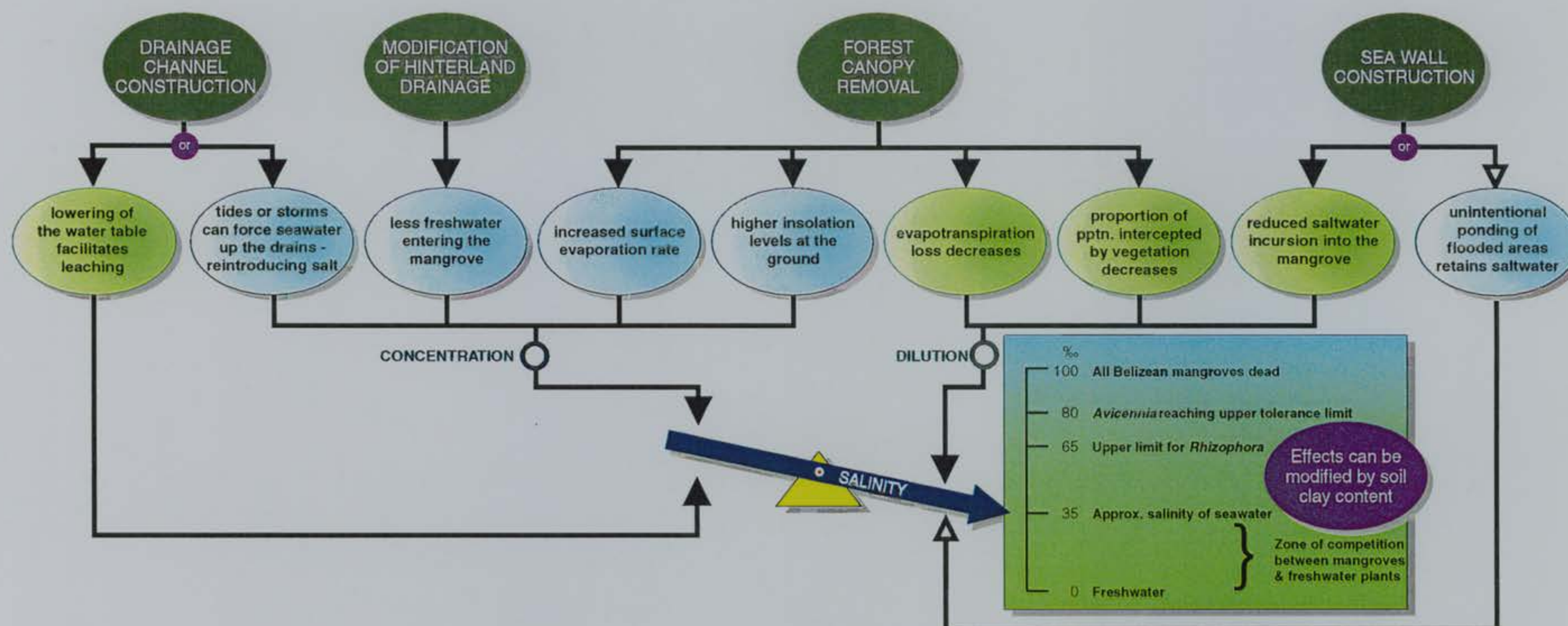
Figure 4.7 The effects of mangrove forest clearance and drainage upon leaf temperature & forest biomass partitioning



Data shows biomass partitioning for an undisturbed Puerto Rican red mangrove forest. Adapted from Golley et al. (1962)

The two processes which will influence leaf temperature and forest biomass partitioning are shown above, in dark green: removal of the forest canopy; and drainage channel construction. In the third line, the effects of these processes are shown, coloured according to the resulting change in biomass partitioning and leaf temperature. Factors acting to increase the proportion of biomass in the form of leaves are shaded in green, those acting to increase leaf temperature are shown in red. Two other effects are shown shaded in grey - this indicates their multiple cause and effect nature. The left hand shaded box at the base of the figure shows how increases in temperature act to retard leaf reaction rates and may damage or even kill tissue. At the bottom right hand corner of the diagram, the shaded box shows the typical biomass partitioning for undisturbed red mangrove as found in Belize.

Figure 4.8 The effects of mangrove forest clearance and drainage upon salinity



The four processes expected to influence salinity are shown above, in dark green: the construction of drainage channels at the site; modifications to the hinterland drainage; removal of the forest canopy; and building seawalls. In the second line, the effects of these processes are shown, coloured according to the resulting change in the level of salt in the remaining soil and water. Effects which will increase the concentration of salt are shaded in blue. Those which will result in a dilution in salt levels are shown in pale green. This figure shows how the final salinity level is determined by the balance between increased evaporation from the cleared surface and a lower transpiration loss, because of the removal of the trees. Artificial drainage can act to push this balance in either direction, depending on the design of the scheme. At the bottom right hand corner of the diagram, the shaded box shows the known salinity tolerance limits for the mangrove species found in Belize.

Whilst work reviewed in this chapter has shown mangroves possess considerable tolerance to variations in site environmental variables, nevertheless upper and lower limits to this tolerance do exist. Where the precise limits and the effects of crossing such thresholds have been quantified, they have been detailed in the text above. Table 4.2 summarises the findings of this chapter and the series of diagrams above (Figure 4.5 to Figure 4.8) highlight the relationships between these variables, elucidating the processes of change.

Table 4.2 Summary of mangroves' environmental tolerances

	Rhizophora mangle		*Avicennia germinans*		*Laguncularia racemosa*			
	Upper limit	Lower limit	Upper limit	Lower limit	Upper limit	Lower limit	Effect of Clearance	Effect of Drainage
Flooding	>100cm	none	20-30cm	none	20-30cm	none	variable	decrease
Salinity	60‰	none	80-90‰	none	60-80‰	none	variable	decrease
Insolation	?	?	?	?	?	?	increase	none
Temperature	40-55°C	15-20°C	40-55°C	4°C *	40-55°C	15-20°C	increase	increase
Tidal regime	high	none	mod-low	none	mod-low	none	Increase?	decrease?
Wind speed	moderate	none	low	none	low	none	increase	none
pH	**	**	**	**	**	**	variable	decrease
Sedimentation	high-mod	none	mod.	none	mod.	none	variable	decrease

** Avicennia trees have been known to survive in areas which occasionally experience a short frost, but 4°C is the lower minimum temperature limit commonly quoted. The other figures in this row are average annual temperatures.*
*** Precise upper and lower pH limits have not been determined for each mangrove species, but the work of Wakushima et al. (1994b) suggests that mangroves show a preference for certain pH ranges.*

The table contains both the first four long-recognised stress factors considered in Section 4.2 (which have the potential to be precisely quantified) and the other influential variables from Section 4.3 (some of which are more commonly expressed in semi-quantitative terms, e.g. a *moderate* sedimentation rate). To the right hand side, two further columns have been added, which show the expected changes in the value of these properties following mangrove clearance and drainage. From this table, earlier nutrient budget modelling and a consideration of published work, suitable soil, water and other environmental variables have been selected for measurement in the field. These variables are listed in chapter five.

This chapter has defined the processes of change involved in mangrove clearance and drainage, and identified a suite of variables expected to show the predicted changes. Now, more detailed consideration must be given to the arena in which these processes are examined - the field site, and the sampling methods employed to measure and determine their effect. These factors are discussed in the next chapter.

5

Sampling concepts, strategy & statistics

The choice of field site

This chapter aims to assess three sets of problems relating to the field areas: field site selection, sampling issues and conceptual issues relating to processes of change through space and time.

Field site selection highlights issues of representativeness, on both a local and national scale (Section 5.1), problematic because of the dynamic and varied nature of mangrove forests. The site-selection process involves the resolution of both conceptual and pragmatic issues. Sites should reflect the different stages of clearance (defined in Section 5.3.2), and allow the comparison and possible combination of data from different sites (Section 5.4). The sites should also provide suitable access and the methods employed allow time for the fieldwork to be completed. The sampling strategy adopted and the associated statistical analysis (discussed in Sections 5.4.1, 5.4.2 and 5.4.3), have been designed to critically test the research hypotheses. Several different research approaches are needed to satisfy the various methodological issues highlighted above, when testing the main research hypothesis, restated below:

> *Mangrove forest clearance (and drainage) result in sufficient physical and chemical changes in the soil, water and surrounding environment, that such altered areas differ significantly from those where the forest cover remains.*

The methodological issues to be addressed in research design can be divided into two: initial definitional *conceptual issues* and the more pragmatic points relating to *sampling design*. They are considered at length later on, but a brief summary follows:

Sampling design issues

- This chapter looks at possible spatial sampling strategies which might be employed in the comparative study and the question of whether large areal plots or linear transects are more suited to highlight differences between forest and cleared areas.

- Suitable statistical tests need to be selected to answer the question of whether there are changes in individual soil and water properties in these areas (that will result in statistically significant differences between sites in the forest and cleared areas). This is essentially a reductionist approach.
- To complement this, a more holistic statistical approach - ordination is explored which combines the variables together to show whether (and how) the forest and cleared areas differ as a whole.
- Spatial autocorrelation has traditionally been seen as an obstacle to parametric statistical testing. Increasingly though, it is being re-interpreted as the underlying cause of spatial patterns and so it needs to be quantified. The chapter considers how semivariogram analysis can identify the scale over which it operates, and so ensure that the sampling interval used during fieldwork is adequate to pick up the spatial pattern.

Conceptual issues

- The study requires resolution of apparently unambiguous definitions such as what constitutes "forest", defining the process of "clearance", and how to delimit "boundaries".
- Temporal aspects of the study provide a further layer of complication. Sites may vary in age, as well as in spatial location. This necessitates the consideration of two questions: which methods are suitable for the comparison of sites of different ages and whether mangrove soil and water property datasets from different years can be amalgamated. This requires a working conceptualisation of the way processes operate through time: whether they must be thought of as truly continuous, or only causing significant change between discrete stages. The conceptualisation considered uses five stages: pre-clearance → immediate post-clearance → long-term post-clearance → immediate post-drainage → long-term post-drainage.
- Spatial aspects of the study need careful further consideration too. This chapter discusses whether the field sites can be thought of as separate systems, with such different geology, hydrology, vegetation, soil, that they cannot be properly combined or compared. Or whether alternatively, they are sub-samples of a larger single target population. It is also useful to know whether the changes due to forest clearance and drainage occur across space in a shallow surface layer, or whether the values also change with depth.

To answer these questions a range of relevant representational and statistical methods are considered.

5.1 Sampling design issues relating to field site selection

5.1.1 Fieldwork aims

The field surveys need to answer two questions:

To show whether mangrove forest clearance (and drainage) results in sufficient physical and chemical changes in the soil, water and surrounding environment, that such altered areas differ significantly from those where the forest cover remains.

To reveal how such a process of change is manifested on the ground, allowing the quantification of any gradient of change running into the forest, indicating how far such changes penetrate and thus affect the remaining forest.

The "classical" method for studying the effects of forest clearance involves the long term monitoring of large plots of land, which are partially cleared during the study period. This method has been widely used in ecological research, e.g. Jordan (1987), Sizer (1991), and by workers in the *Minimum Critical Size of Ecosystems Project* in Amazonia, such as Lovejoy & Oren (1981), Lovejoy *et al.*, (1983, 1984) and Zimmerman & Bierregaard (1986). In a study interested in quantifying edge effects[1] and/or the minimum sustainable width of a forest buffer, the forest would be selectively cleared to leave strips of forest of various widths, which would then be monitored for signs of change. Such an approach was not considered suitable for this study, for two reasons:

1. It is highly destructive, requiring the felling of large experimental areas of forest. The clearing of these areas would be expensive and the loss of these areas of mangrove could have a serious ecological effect upon the surrounding area. As such, this approach was felt to be incompatible with the conservational aims of this work and generally requires a large team of researchers.
2. It would require a long period of continuous observation. This was not to prove possible for two reasons. Firstly, the imposed overall time limit placed upon the research was felt to be insufficient to adequately capture the full process of change. Secondly, fieldwork was confined to several relatively short repeat visits, preventing continuous monitoring.

Instead, it was decided to focus upon locally cleared areas of mangrove forest, avoiding the need to further deplete the mangrove cover. This would allow the simultaneous measurement of soil, water and other environmental properties in both the cleared and remaining mangrove forest areas, with the remaining forest areas acting as a statistical control. The temporal restrictions could be overcome by employing a *spatio-temporal* substitution - rather than monitoring single areas continuously over time, research could be carried out at sites in similar locations, each at a different stage in the clearance process. Amalgamating the data from each site would allow the construction of a time series.

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[1] Defined in chapter one.

The problem of estimating the size of a minimum sustainable[2] width of forest buffer (identified in Section 3.9) can be addressed by concentrating on quantifying forest edge effects. By assuming that significant changes in the environmental conditions (notably water depth and salinity) result in the mangroves being out-competed by other plant species, measurements of the penetration of change into the forest will allow estimations to be made of a minimum sustainable mangrove buffer unit.

5.1.2 Field site choice

Fieldwork carried out in 1991 (in conjunction with the Departmental Expedition to Belize) has shown that mangrove forests vary along the coast of Belize, according to the underlying substrate and the nature and volume of sediment inputs, (Furley & Minty, 1992; Furley *et al.*, 1993). This national scale variation means that comparisons of several partially cleared sites spread along the coast of Belize would be difficult, differences due to their location may make combining the data unwise, and mask any similarities in their response to change. Instead, it was decided to concentrate fieldwork in a particular area, allowing the research to focus on localised changes caused by clearance and drainage. Several sites currently undergoing mangrove clearance were considered - Belize City, Placentia, Punta Gorda and Sarteneja, which can be located on Figure 1.1. Table 5.1 below describes each potential field site:

Table 5.1 Potential field sites in Belize, 1992 field survey

	Inputs	Mangroves	Clearance	Accessibility
Sarteneja 18° 23' N 88° 10' W	Carbonate dominated inputs, lagoonal deposition.	Dwarf *Rhizophora* common, behind a narrow coastal and lagoonal fringe, nutrient supply is limited, and high salinity values occur in the dry season.	Small scale clearance.	Scattered areas of clearance, poor road network, making a boat essential for access.
Belize City 17° 30' N 88° 12' W	Organic and carbonate inputs - lies near the organic/carbonate deposition boundary.	Mixed coastal fringe, with large area of basin mangrove behind, rapidly decreasing in height.	Greatest area of large scale clearance nationally, fuelled by demands for housing & commerce.	Cleared areas concentrated around roads, allowing easy access.
Placentia 16° 32' N 88° 20' W	Some organic and large carbonate inputs.	Peninsula covered with mixed dwarf and medium height fringing mangroves.	Locally significant small areas of clearance, fuelled by tourism.	Clearance concentrated, but in some areas access is easier by boat.
Punta Gorda 16° 08' N 88° 47' W	Organic dominated inputs.	Some of the tallest, most luxuriant mangrove in Belize, coastal and riverine fringing mangrove, nutrient rich sites.	Clearance low, but concentrated along the coast, leading to erosion problems.	Clearance immediately around Punta Gorda accessible on foot, other areas require a boat for access.

[2] Assuming a definition of forest buffer "sustainability" as the ability of an area to continually reproduce itself even in the face of competition from other plant species, such that over time the thickness of the mangrove buffer is maintained.

Sarteneja was rejected because it was thought to be atypical - the mangroves in this area are relatively nutrient-poor, and as has been noted in chapter two, are noticeably dwarfed in comparison with other parts of Belize. Clearance around Punta Gorda has been far more limited than in many other parts of Belize. This probably relates to its relatively remote location with respect to the large population centres in Belize, and the availability of many other potential development sites inland. The limited clearance activity there was thought to restrict the choice of available field sites. Many possible areas may lie some distance upstream, making regular access difficult. For these reasons, Punta Gorda was rejected as a potential field area. Clearance around Placentia has accelerated (Brately, *et al.*, 1993). However, because of its peninsular nature and extremely localised population pressures, questions were raised about its representativeness. The emergence of a strong case for Belize City resulted in the eventual rejection of Placentia, despite its potential.

Belize City was selected for four reasons:

1. It is the area undergoing the most rapid clearance in Belize and so should show the most acute signs of stress.
2. Because of its central position along the coast, the field site will show aspects common to both organic and carbonate dominated depositional environments.
3. The well developed road network, which has facilitated much of the clearance activity will also allow easy access to potential field sites.
4. It is an area which has already received attention from local conservation organisations (such as *Belize Audobon Society, Belize Center for Environmental Studies*) and visiting researchers (e.g. McShane, 1991) providing sources of historical material.

Two periods of fieldwork were planned - a detailed analysis of a single partially cleared site in 1992 and follow-up work in 1994, looking at several other sites, to build upon the earlier work and examine the process of clearance at a range of scales.

5.1.3 1992 Fieldwork rationale

The 1992 work was designed to allow the development and testing of sampling techniques whilst investigating the scale and nature of change. The large number of current clearance schemes around Belize City meant that there were many potential field sites to choose from. Discussions with Simon Zisman, (*ODA/TFMP Mangrove Specialist*) and Lou Nicolait, (*Director, Belize Center for Environmental Studies*), reduced this number. Many potential sites were eliminated because of plans for imminent construction or covering with clay-rich fill. Others were the subject of contention, either due to problems relating to clearance permit application, or disputed ownership. Owners of such sites were thought unlikely to grant permission for the field work for the full three month period, due to its perceived connection with the Forest Department of Belize. Three suitable sites remained and are listed in Table 5.2 below:

Table 5.2 Potential field sites around Belize City, 1992 field survey

	Mangrove	Site History	Current Activity	Water Depth
Northern Highway "North End Estates"	Tall and medium mixed mangrove, dissected by the road - field site lies on the inland side.	Field site was being cleared from the road to c.50m inland. No drainage activity.	Clearance underway.	Water table at the surface.
Western Highway "Burnt" site	Tall and medium fringe and basin mangrove, dissected by the road - field site on the coastal side.	Field site had been manually cleared around February 1991 and cleared area burnt.	Drainage planned for August 1992.	Site submerged to a depth of c.10 cm.
Western Highway Haulover Bridge site	Tall and medium fringe mangrove forest, tall mangrove next to Haulover Creek.	Area had been partially cleared in 1991 and clay fill dumped to allow vehicle access.	Small marina development, work halted pending a Forest Dept. inquiry - no clearance permit.	Undulating topography, water depths vary from below soil surface to c.25 cm.

All three sites (shown in Figure 5.1) share a mangrove cover of mixed red and black mangrove, common to much of the Belize City area. The Haulover Bridge site has the tallest mangrove, probably due to localised high nutrient input from the adjacent Haulover Creek. This, it was felt, makes it atypical of the area as a whole and so it was rejected. All three sites have been recently cleared by hand, although clearance work was still being carried out at the Northern Highway site in 1992. It was thought that such clearance may interfere with the fieldwork activity, so this site was also rejected. The Western Highway "burnt" site was selected for detailed examination, considered particularly suitable because of the possibility of imminent drainage[3], allowing measurements before during and after drainage of the site. The landowner kindly consented to the fieldwork proposals. The exact location of the "burnt" site can also be seen in a later illustration of all the fieldsites, Figure 5.9.

5.1.4 1992 Fieldwork (Burnt field site) techniques

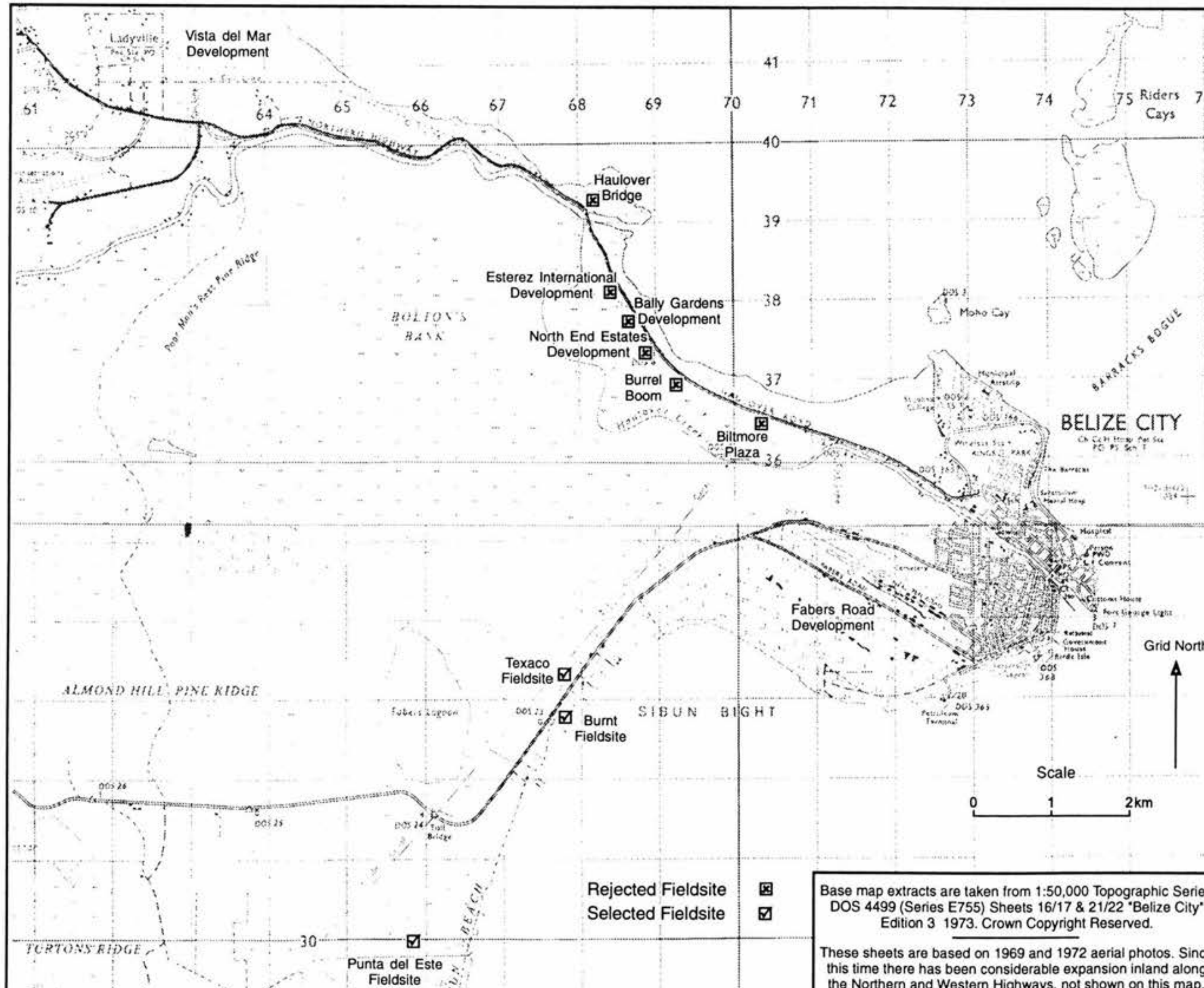
A range of environmental variables were selected to allow the testing of the research hypotheses. Soil samples were taken using a soil corer, water samples from dipwells. These two devices were specially constructed for the fieldwork and are described below:

Soil corer

Soil samples were taken using a cylindrical mangrove soil corer, which is modified from a design given in Boto (1984). It is constructed from stainless steel for both strength and to minimise sample contamination because of this metal's resistance to corrosion. The corer is shown diagramatically in appendix two. It has a circular cutting head with coarse teeth for cutting through mangrove roots. If necessary, it can be hammered into the ground, by fitting the driving cap to the top of the tube. When inserted into the ground, a cylinder of soil is forced into the main body of the corer, a "core catcher" acts to prevent it slipping out when the corer is removed.

[3] Regrettably, this never happened.

Figure 5.1 Location of potential field sites around Belize City



Many properties such as soil redox potential, change rapidly upon exposure to the air. Therefore, a series of holes has been drilled along the corer's length, allowing *in situ* electrode insertion. A plastic sleeve fits around the corer, covering the holes during the coring process, but which can be rotated to allow access to the holes, one pair at a time, once it has been removed from the soil. After electrode measurements, the core is expelled from the corer using a plunger, allowing full description and sampling to be carried out.

Water sampling from dipwells

After taking a soil core, a c.75cm length of plastic pipe, with holes drilled along its length, was placed in the hole, which promptly filled with water. This creates a dipwell, allowing water samples to be taken, after letting the sediments disturbed during the coring process settle out. Water samples were collected from the dipwells, using a sample bottle fitted to the end of a sampling tube (shown in the appendix two).

Variables measured

The variables which the predictions of chapter three suggest will highlight change are listed in Table 5.3 together with the measurement scale employed, using the relevant statistical measurement terms, e.g. interval or ratio. The measurements in this table have been divided into two groups according to their representation of depth (the significance of this is discussed more fully in Section 5.3.3). In general, measurements taken in the soil were repeated at different, identifiable depths. Measurements taken in water were taken only once for each location (not including repeat samples for replication) and are considered as representative for the whole depth profile. This single sampling value is because the water column could not be satisfactorily split into discrete units which could be sampled repeatedly without disturbing the others.

Table 5.3 Properties measured in the 1992 fieldwork

Samples at many depths	Measurement scale	Samples at many depths	Measurement scale
Layer thickness	ratio	Root abundancy	ordinal
Soil texture	ordinal	Mean layer depth	ratio
Soil colour	pseudo-interval	Field soil pH	interval
% Weight loss on ignition	ratio	Field soil redox	ratio
% Organic carbon	ratio	Field soil nitrate-N	ordinal*
Exchangeable magnesium	ratio	Soil extract nitrate-N	ratio
Exchangeable calcium	ratio	Soil extract ammonium-N	ratio
Exchangeable sodium	ratio	% Moisture loss	ratio
Exchangeable potassium	ratio	% Dry matter	ratio
Exchangeable manganese	ratio	% > 2mm	ratio
Extractable phosphorus	ratio	% < 2mm	ratio
Sulphate-S	ratio		
Total iron	ratio		

Single depth samples	Measurement scale	Single depth samples	Measurement scale
Field water pH	interval	Surface insolation level	interval
Field water conductivity	ratio	Water depth	ratio
Litter thickness	ratio	Sampling site surface elevation	ratio
Layer 1 bulk density	ratio	Field drainage	ordinal

** Field soil nitrate-N measurements were made using semi-quantitative test strips. All measurements are made using soil samples unless stated otherwise.*

Two surface spatial sampling strategies were employed at the Burnt Site in 1992 (shown in Figure 5.2), each addressing a different research question. An areal plot was established, centred on the forest edge. Samples from cleared and forest areas could then be compared, allowing the testing of the first research hypothesis: that there is a significant difference between cleared and forest soil, water and environmental properties. Near this areal plot, a series of three shorter linear transects were marked out, to address the second research question: quantifying the degree of penetration of changes into the forest. The rationale behind these two strategies is discussed below.

5.1.5 Areal plot rationale

A rectangular areal plot was marked out at the field site, centred on the cut forest edge. A 10 x 10m rectangular grid was superimposed upon this area, and it was divided into three sampling units (as defined in Section 5.3.1) as shown in Table 5.4 below:

Table 5.4 1992 Areal sampling site statistics

	Size (*x, y*)	Area		Number of sample points	
Forest	40m x 40m	1600m²	(44½ %)	35	(45 %)
Transition Zone	40m x 10m	400m²	(11 %)	8	(10 %)
Cleared	40m x 40m	1600m²	(44½ %)	35	(45 %)

The grid was used as a reference for locating individual sampling points in the field. These sample points were distributed using a stratified random sampling design.

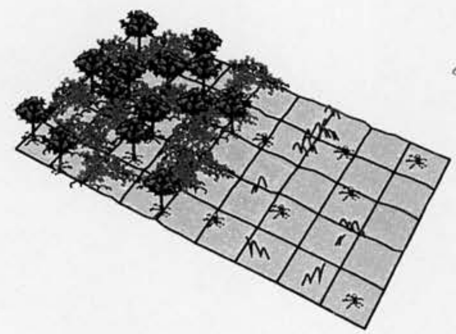
Choice of areal sampling strategy

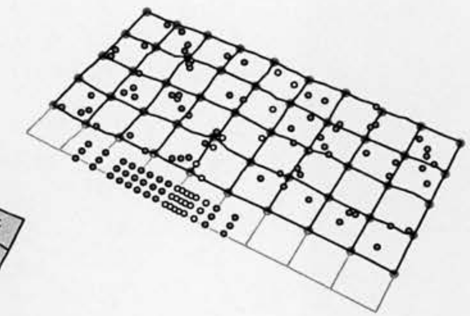
Three possible sampling designs were considered: a systematic design, a completely random design and a stratified random design - where points are randomly located within user-defined areas, (the stratification). These three sampling designs are illustrated below in Figure 5.3, for a nominal 21 sampling point strategy, in an area later split into three zones (1,2 and 3) in a manner similar to the cleared, transition zone and forest division of the 1992 field site. In this example, the values of a property measured at each of the sample locations in zones 1 and 3 are to be compared statistically, to highlight any significant differences. The smaller zone 2 is not used in the statistical comparison, but it acts as a buffer zone, occupying the area where points are likely to be most similar - the boundary between the two other zones - thus maximising the chance of measuring a difference between zones 1 and 3. The sample point co-ordinates were created by random number generation where appropriate.

Figure 5.2 1992 Burnt field site sampling strategy

These diagrams offer a stylised view of the field site - a partially cleared area of mixed basin mangrove forest. The squares represent the soil surface, for diagrammatic purposes it has been rotated by an angle of 60° azimuth and elevated by 40° to give a pseuedo 3D effect. The black squares are 10m across. To emphasize changes in the micro-relief, a vertical exaggeration of x7 has been used.

The vegetation symbols, whilst drawn approximately to scale are at a much reduced density. The presence of a given tree on this diagram is not intended to imply the presence of that particular species, or even necessarily the presence of a tree at that exact location in the real field site.





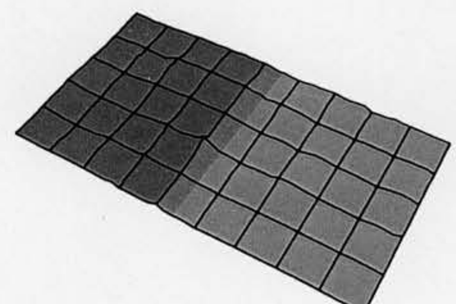
The "wire-frame" image to the left shows the location of the sampling sites, on the same projection as the other three field site diagrams. Below this figure the same point data is shown in plan view.

The sampling sites are shown as solid circles, their colouring reflects the vegetation zone in which they occur. In addition, 50 field site marker poles (of known elevation) are also shown in these two figures, drawn as open red circles.

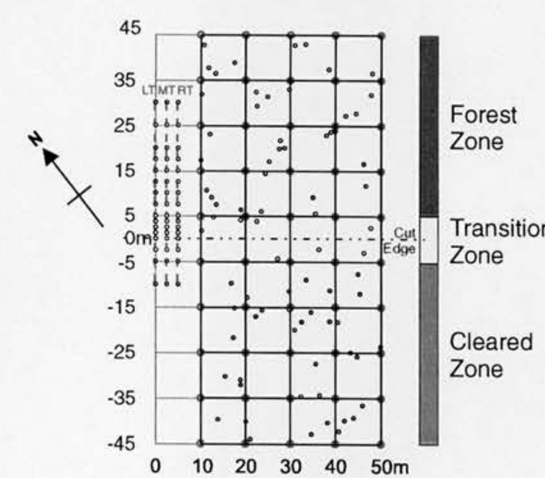
These two diagrams also show the two sampling patterns employed. The major portion shows a series of thirty six 10x10 m squares, which have been used to establish co-ordinates for a series of random points. The sampling was stratified to assist comparison - thirty five points were chosen from each of the cleared and forest zones, and eight from the transition.

To the northwest of these are three parallel linear transects (LT, MT and RT) each with sixteen sample points. They have a varying sampling interval, with a sampling bias favouring points in the forest. These transects were designed to quantify the magnitude of any changes in the forest, stemming from the neighbouring clearance.

This figure shows the simplest way to classify the field site into vegetation classes. This is to use two units - a forest zone (shown in green) and a cleared zone (in brown). The size, shape and most significantly the position of the mutual boundary between these two units, is dependent upon the defined forest edge.



As discussed in the text, delimiting this edge is problematic and may vary according to the application. The edge could be drawn along a line by the most exposed tree trunks, around the furthest protruding roots, or even the edge of the ground overshadowed by the forest canopy. Further definitional problems arise in deciding when trees on the edge cease being part of the forest, becoming outliers instead.



One possible solution is to see the edge not as a linear (planar) feature but rather as a zone. This figure shows a third vegetation unit added in grey - the transition zone. It is 10 m wide, centred approximately on the cut line. A distance of 5 m from the cut edge was selected as it was the furthest observed limit of root growth and overshadowing of soil in the cleared zone.

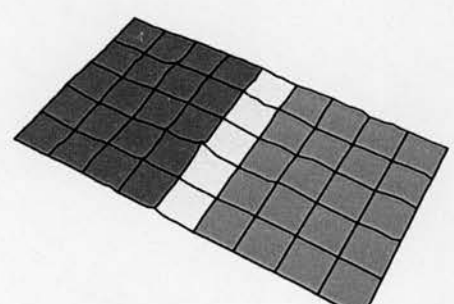
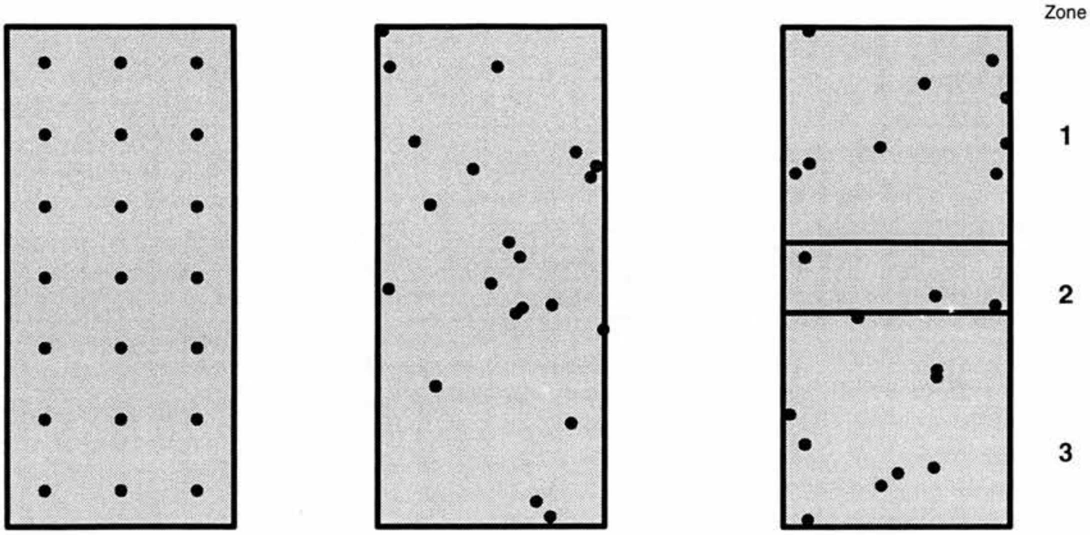


Figure 5.3 Three possible areal sampling strategies



	SYSTEMATIC	RANDOM	STRATIFIED RANDOM
Number of points			
Zone 1	9 points	10 points	9 points
Zone 2	3 points	5 points	3 points
Zone 3	9 points	6 points	9 points
Distribution of points	even	random	random

This diagram highlights the differences between these different approaches. The figures represent the distribution of points in each of the three zones, whose boundaries are shown in the stratified example.

The **systematic approach** gives an even coverage of points (a desirable feature for later interpolation procedures), distributed across the three zones in proportion to the area each one occupies. The even distribution of points (in the key zones 1 and 3) allows the use of comparative statistics which require an equal number of points in each zone. The systematic sampling grid creates a constant (non-random) sampling interval, thus preventing the use of tests assuming a random distribution. The sampling interval is a function of the area of the site and the number of sample points, both of which are determined subjectively by the user. This spacing is critical as it determines the minimum spatial scale over which relationships can be detected. Its regular form also affects the patterns displayed - it may give greater emphasis to linear patterns whose direction of trend coincide with one of the axes or those whose period is a multiple or factor of the sampling interval. Similarly, it may act to suppress trends which do not coincide with the grid, or are acting at a scale finer than the grid[4]. Because of a lack of previous information regarding the scale of spatial variation, it was felt that there was inadequate data to inform the choice of a suitable sampling interval. As the systematic sampling strategy also places severe restrictions upon the available statistical tests (failing the requirement for an assumed random distribution), these were felt to be adequate criteria for its rejection.

The (simple) **random approach** allows the greatest statistical utility, as many parametric tests assume a random distribution of sample points (ignoring the issue of spatial autocorrelation for the moment). However, as can be seen from Figure 5.3 it is likely to result in an uneven spatial coverage. With a relatively small number of sample points, there may be large areas of the site where few point data are available. Statistical comparison may be made difficult as there will probably also be a different number of points in each zone. Comparative tests of data from zones 1 and 3, both of the same area, often assume an equal number of points. This is not the case in the randomly sampled example above: 10 points lie in zone 1, but only 6 in zone 3. The likely resultant uneven coverage and zonal distribution of points was felt to be sufficient reasons for this approach not to be adopted.

The **stratified random approach** is an attempt to combine the above methods in a way which retains their advantages. The user subdivides the field area into relevant zones before comparison, and specifies the total number of points to be selected in each zone. This allows the use of comparative statistical tests which assume that zones of equal area also contain an equal number of points. Within each zone, the points are randomly distributed, thus avoiding the problems associated with the fixed sampling interval used in systematic sampling. For these reasons, this strategy was adopted in the 1992 areal sampling scheme, noting that the success of such a sampling technique is dependent upon the validity of the field site subdivision, which is a subjective process.

Stratified random sampling creates a series of points with a wide range of lags (the distance between two sample points) which can be used to calculate semivariograms (see Section 5.4.3). This allows the quantification of spatial autocorrelation for each measured property. If semivariograms for this site had been calculated from previous work, then the choice of sampling strategy used might have been different. A stratified sampling technique (possibly using the modified "unaligned sampling" method outlined in Webster & Oliver, 1990) would be more efficient, yet retain the possibility of certain statistical comparisons. Therefore such a technique is suggested for future areal comparative work in this area.

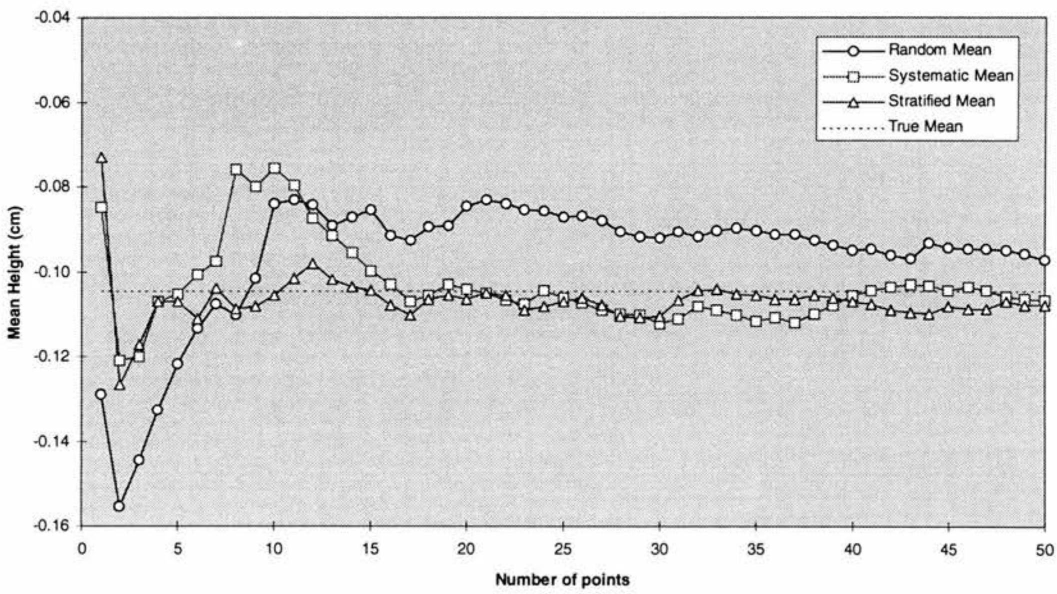
[4] A simple example of this last point is a study recording topographic measurements in a ploughed field. If the sampling positions all fall on the top of ridges, the interpolated topography would show a flat plain with minimal topographic variation, rather than showing the regular ridge and furrow pattern actually there as a result of the ploughing.

Number of sampling points

The number of sampling points is essentially a compromise between areal representation and sampling efficiency. Many parametric statistical tests require a minimum of 30 values (Ebdon, 1985) suggesting a minimum of 30 points in each of the two key zones in the comparison - the forest and the cleared areas. A figure of 35 points in each of these zones was selected to amply satisfy the statistical requirements, whilst restricting the required number of samples to a manageable level. The distribution of sampling points between the three zones (35 in the cleared, 8 in the transition zone and 35 in the forest) reflects the proportional area occupied by each of these zones.

To test whether the number of sampling points selected was sufficient to adequately represent the variation over the field site, mean field site surface elevation (height) was plotted against a range of sample sizes. This is shown in Figure 5.4. Field site height was chosen for this test for two reasons - it is simple to gather height data, and because it is a property which can be seen with the naked eye (unlike pH for example) any errors such as particularly high or low points are easy to re-check in the field. Secondly, because surface elevation was also measured at the 50 poles which were used for locational purposes during sampling, the dataset is large - the complete dataset comprises 176 points.

Figure 5.4 Variations in mean height according to sample size



This figure shows the mean height along the x-axis as calculated from the number of sample points specified on the y-axis. For example at 5 along the y-axis, the mean height for any given sampling approach is calculated from the first 5 height datapoints. At point 20 along the y-axis, the mean height is calculated from the first 20 datapoints, etc. The lists of datapoints for each sampling strategy have been randomly ordered to prevent samples from similar sites being added in turn to those selected. Three sampling strategies are shown, the random, stratified random and systematic strategies, as discussed above. For comparative purposes the "true" mean height, calculated from 176 points scattered across the field site is given. Heights are measured relative to the observed lagoon level.

The graph shows the changes in mean height occurring with an increase in the sample size for the three sampling strategies discussed above. Each dataset comprises 50 points. The points used for the systematically sampled data are the 50 poles which mark the intersections of a 10 m grid across the field site. For the truly random sampled data, 50 points were selected at random from a 78 point dataset combing the areal sampling points (35 in the cleared zone, 8 in the transition zone and 35 in the forest). For the stratified randomly sampled data, 50 points were also chosen from this 78 point dataset, with the proviso that the balance between the sample points in each zone reflects the area each zone occupies over the field site.

The graph shows that after a period of fluctuation, the value of the mean begins to stabilise as the number of sample points increases. For both the stratified and the systematic-random sampling strategies, this occurs around 20-25 samples. As expected, the true random sampling strategy takes longer to settle down. With reference to the selected sampling approach, the systematic-random sampling technique, this means that samples of 35 points in each of the two main sampling zones are easily sufficient to approximate the true mean value. Although the number of points in the transition zone is less, they do represent a lesser area, and thus this is not felt to seriously compromise the validity of the sample sizes used in the fieldwork to represent the true value of zonal means.

Implementational issues

Points to be sampled were located to the nearest centimetre in the field using randomly generated x and y co-ordinates, relative to the 10 m grid. The selected location was used as the centrepoint for soil coring and the insertion of dipwells in the resulting hole, allows water sampling. Strictly, this method produces only a semi-random distribution of points, it deviates from a true random distribution in two ways: it employs sampling without replacement and a slight anti-edge bias in the selection process. The implications of these two points are discussed below.

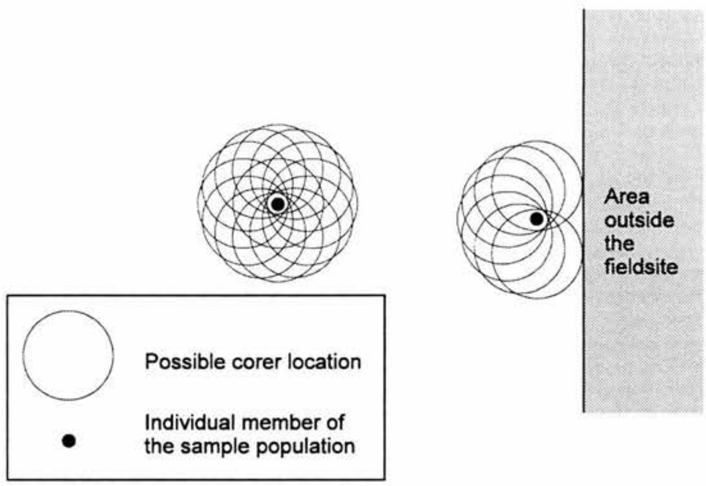
Sampling without replacement

Environmental measurements are often destructive, requiring the removal of material from the site for later analysis in the laboratory. Thus a given member of the sample population (such as a sample of water or soil) can only be taken once - sampling without replacement. Theoretically, if two sampling locations were selected where the centrepoints for coring and dipwell location were so close together that the columns of sampling material overlapped, then a problem would result. Either a new second sampling point would have to be selected, or the analysis results corrected in an attempt to reflect the influence of the overlapping soil or water in both samples. If such a situation had arisen in the field, then a new randomly generated point would have been sampled. This decision was made for practical reasons: coring a site which has already been partially cored is difficult and likely to result in considerable physical disturbance to the sample. A similar resampling strategy was devised in case the selected points proved impossible to sample - for example lying underneath a living tree trunk. Sampling such a site would have required the removal of the tree, something that was not considered practical or desirable. Thus for environmental reasons this second compromise to a truly random distribution was accepted, although in practice the situation never arose, probably because the lack of understory in the mangrove means that only a very small proportion of the soil surface is obscured. Both these compromises are not thought to affect the random nature of the sample points significantly.

A slight anti-edge bias

A further source of sampling bias is introduced because the method of sample site location (to the nearest centimetre) is at a finer resolution than the actual sample support - the diameter of the corer and dipwell (56 mm). This difference in size and thus between the total and target sampling populations becomes significant only at the edge of the site, shown below in Figure 5.5.

Figure 5.5 Variations in the likelihood of selection near the field site perimeter



In central areas of the field site, shown in the left hand side example, any given point has an equal chance of being sampled, it lies within the same number of possible coring circles (only a few of which are shown for illustrative purposes). In this region, the sampling requirements for a random distribution are satisfied, every member of the population has an equal chance of being selected.

The right hand side of the diagram shows the situation at locations within one coring diameter (56mm) of the edge of the field site. The number of possible coring circles in which a point lies decreases as we approach the edge. Points cannot be included in potential corer locations whose centre-point lies outwith the field area. In the most extreme case, a point lying right on the perimeter of the field site, will only be included in one possible corer location. Thus the probability of any given point being chosen decreases towards the very edge of the site.

This area of error is very small: a 56 mm zone in an area 40,000 mm (40 m) wide and 90,000 mm long. As such it is not thought to be significant - in most visual representations of the site, an area this small will not be discernible. For completeness though, such an error could be effectively eliminated in the final representation of the data by reducing the area mapped by 56mm in all directions, creating a zone of equal probability.

The area of soil sampled by the corer (or equally the area of water enclosed by the dipwell) cannot be used as an alternative unit with which to divide the field site up in a random manner. This is for two reasons:

1. The sampled area is not a simple divisor of the field site area. This would mean that if the site was divided up from left to right in units equal to the diameter of the corer, at the extreme right hand end, the final portion would be of a size less than a whole corer diameter. Thus sampling at this location would be either of a smaller area (volume), or include material from outwith the field site.
2. Secondly and more significantly, both sampling devices have a circular cross-section. This means that these units do not tile (tessellate). Therefore in creating a grid using circular elements we would be faced with two options - producing a sampling grid where the circles overlap, resulting in the problems of over-representation and sampling without replacement outlined above, or producing a grid where the circles are packed as tightly as possible, but where gaps remain. This would mean that certain sections of soil and water would have a zero probability of being sampled, those lying outwith a circle.

Summary

The areal sampling of the field site was carried out in a rectangular area 40 m wide and 90m long, the 90m axis being centred upon the forest cut line, giving two areas of 40 by 45 m, one cleared, one still covered in mangrove forest. The rectangular site was then subdivided into 3 units (for reasons discussed in Section 5.3.1), a 40 by 40 m forest unit, an equal-sized 40 by 40 m cleared unit separated by a 40 m wide by 10 m long buffer strip - the transition zone. These three units were used for stratified random sampling, where 35 points were chosen in each of the forest and cleared zones and 8 in the transition zone, their numbers reflecting the proportional area of each zone. This sampling technique was selected for two reasons:

1. It allows the use of comparative statistics with two requirements - randomly distributed sampling locations and also equal number of points in the two zones being compared.
2. It does not suffer from problems related to using a fixed sampling interval.

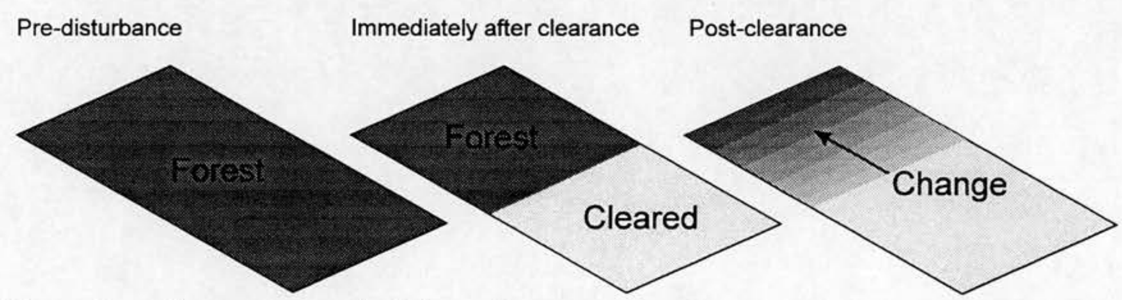
This compromise between random positioning and zoning of the points in space also allow a limited degree of semivariogram analysis, although a more regular point interval (such as intervals all multiples of a "unit lag") would have been more suitable for this method.

Implementation of this strategy revealed two sources of minor bias - sampling without replacement and a tendency for a slight anti-edge bias. Neither of these are considered serious enough to invalidate the assumption of randomly distributed points. This sampling strategy has been devised to allow the comparison of measurements in sites from the forest with those from cleared areas, to see if there is a significant difference in their values. As such it tests the first research hypothesis. The third unit, the transition zone, has been added to avoid problems with classifying points near the cut edge.

Theoretical patterns of change

Figure 5.6 below shows theoretical changes in the areal pattern of a spatially distributed variable following clearance. The left hand image shows the rectangular field site before disturbance, when it retained a uniform cover of mangrove. The central rectangle shows the site immediately after partial clearance, where the mangrove cover has been removed from the lower half. The right hand rectangle shows the same area some time after clearance, with no further reduction in the mangrove forest cover. The rectangles are coloured according to the value of some soil, water or environmental property. Before clearance such a variable should show low variation across the site, as displayed in the left hand image. The centre rectangle shows the same variable mapped immediately after clearance. It is expected that the clearance process will result in a change in the value of the measured variable in areas where the forest has been removed. Thus the rectangle shows a marked division, with values of the measured property forming two discrete areas, separated by the cut forest edge. The right hand image is produced after measuring the value of the variable again, some time after clearance. During this time following clearance it is expected that diffusion processes will serve to lessen the gradient between the two values, and so the boundary between the two units is far more poorly defined in this final mapping than in the central one. The figure maps a variable whose value declines in forest sites after clearance. Not all variables will respond this way, and it could equally have been drawn showing the change affecting values in the cleared zone. Litter levels, for example, will gradually increase in the cleared zone after clearance, and so in this case the direction of change is reversed.

Figure 5.6 The theoretical pattern of change following clearance

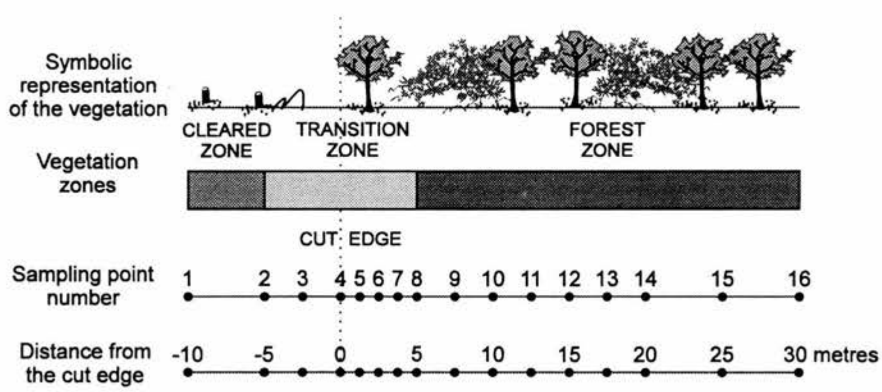


The areal sampling strategy outlined above aims to compare the values of such a variable, to see if there is a significant difference in values in the cleared and forest areas. By sampling areas at different stages in the clearance process, it is hoped that a picture of the temporal nature of such a change can be produced.

5.1.6 Linear transect rationale

Linear transects were established running perpendicular to the cut forest edge, to address the second research question, quantifying the degree of change within the forest. The illustrations at the right hand side of Figure 5.2 shows the three linear transects lying in an undisturbed area to the north west of the areal sampling grid. The transect lines each pass through the three sampling units: sampling points are located in the forest, cleared areas and in the transition zone. Unlike the areal sampling scheme which was designed to facilitate a comparison of the forest and cleared areas, the transects do *not* evenly span the cut. Sampling points are biased towards a forest location, as this is the area of interest. Along each line, sampling points are located at variable intervals, with the greatest concentration of points around the cut edge, and sample point density decreasing in both directions away from the cut. Again this reflects the aim of this strategy: to highlight changes near the forest edge. Figure 5.7 below shows the distribution of sample points along a transect line, and its relationship to the sampling units.

Figure 5.7 Linear transect rationale, 1992



The transects were chosen to sample points at distances of up to 30 m into the forest. This distance was chosen for two reasons. First of all, it exceeds the width of the legally required 66' (20.1 m) forest buffer zone required by the *1936 66' Reserve Act* (discussed in Section 3.9) and so the results of the transect work will allow statements regarding long term change and the stability of these features to be inferred. Secondly, 30 m was considered a suitable distance to detect edge effects. Although there is a lack of published work concerning quantification of edge effects in mangrove, considerable work has been carried out in other tropical and temperate forests. Williams-Linera (1990) working in Panama, found changes in forest properties up to 15-25 m into the forest in plots beside areas cleared for pasture. Ranney *et al.* (1981) in their review of edge effects in forests in Wisconsin, found changes in marginal areas 15-30 m from the forest edge.

Figure 5.8 Idealised variation along a transect

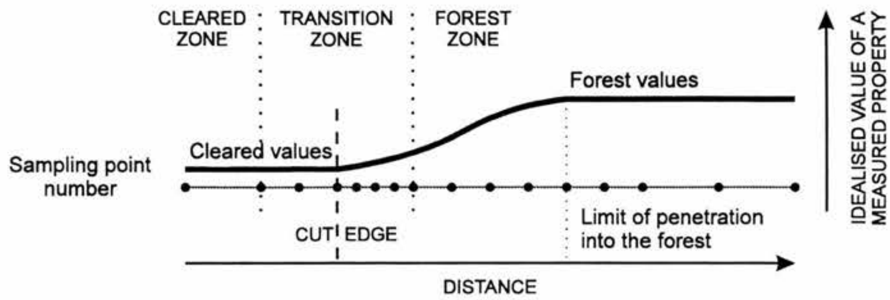


Figure 5.8 shows an idealised view of variation along the transect. It is effectively a line graph, with distance along the x axis as in Figure 5.7 above, and some measured soil or water property (for example pH, or organic carbon content) displayed up the y axis. In the case shown above, before clearance, assuming relative uniformity across the site, all sample points along the transect would have shown "high" values, similar to those shown in the extreme right hand side of the graph. Clearance has altered the value of this measured property, seen in the far lower y values shown for points early in the transect, on the left hand side of the graph. The difference between values of this measured property in cleared and forest sites results in a gradient across the boundary. The figure shows readjustment occurring in the remaining forested area, with forest values depressed near the cut edge. The distance at which forest values regain their sill level (become horizontal once more) can be used to quantify the degree of disturbance to the forest, the penetration of an edge effect.

Similar to the point raised in the discussion of Figure 5.6, this idealised graph is only one possible case, other variables may show high values in the cleared zone and lower in the forest (for example ground level insolation) resulting in an effective reversal of the curve shown above.

5.1.7 1994 Fieldwork rationale

Building upon the 1992 work, a very detailed examination of a single site, the 1994 fieldwork was devised to answer two further questions. By working at other locations around Belize City, the fieldwork would show whether the trends found in the 1992 data were restricted to that one site, or common to others. Secondly, returning to the 1992 site for resampling would allow an examination of the temporal aspects of change. To maximise the number of sites examined, it was decided to adopt a transect approach in each area.

5.1.8 1994 Field site selection

Potential field sites were selected using information gathered from local sources and personal observation. Initially a list of suggested sites was drawn up following conversations with Lou Nicolait and Frances Griffith, (*Belize Center for Environmental Studies*), Lydia Waight, (*Belize Audobon Society*), Earl Green, (*Chief Forest Officer*), and Richard Wilson, (*Programme for Belize*). Further sites were added through field reconnaissance with Peter Furley, concentrating on areas along the main arterial routes out of Belize City, viewing sites on foot, by vehicle and a short low level light aircraft flight. The locations of these potential field sites are shown in Figure 5.1. Table 5.5 below describes the potential field areas.

Table 5.5 Potential field sites around Belize City, 1994 field survey

	Mangrove	Site History	Current Activity	Water Depth
Northern Highway Site 1: "Esterez International"	Tall (10-15 m) mixed basin mangrove, dominated by black mangrove. Inland, separated from the coast by a road, coastal fringe completely cleared.	Site has been cleared in a series of pushes from the road. Hard core rubble forms a road running 75 m into the site. No drainage.	Little sign of any activity - mangrove separated from clearance by 40-50 m of dense rushes grasses - regrowth?	Site flooded, in some areas water over 40 cm deep .
Northern Highway Site 2: "Bally Gardens"	Mixed red and black mangrove (8-10 m high) with occasional buttonwood. Inland, location, coastal fringe on the other side of the road has been cleared and developed - housing estate.	Site has been cleared and timber removed. No attempt at drainage.	Three distinct vegetation zones, from the road - cleared area being recolonised by low grasses, regenerating mix of low mangrove (c.2 m) and shrubs, remaining mangrove (8-10 m high). Suggests no activity at present.	Site flooded to a depth of over 50 cm.
Northern Highway Site 3: "North End Estates"	Mixed red and black basin mangrove (8-10 m high). Inland site, separated from the sea by a road, no remaining coastal fringing mangrove on seaward side.	Site has been cleared a long way back from the road (c. 1 km). No drainage, but partial cover of clay-rich fill.	Cleared area has been partly covered in fill, in an attempt to raise the land above the water table. Grasses and rushes (1-2 m high) colonising this area, suggesting little current activity.	Water table lies above the soil surface in remaining areas of mangrove, but below added fill surface.
Northern Highway Site 4: "Burrel Boom"	Mixed basin mangrove, red (15-18 m tall) most common, also black & some buttonwood. Inland site, separated from the sea by the road. Coastal fringing mangrove removed to allow development.	Site has been cleared a long distance inland. Access to inland area provided by a fill track. Remainder of cleared area has a variable cover of fill - standing water visible in some areas.	Little colonisation of filled area, suggesting considerable thickness of deposited material. Narrow (10-15 m) zone of regeneration - red mangrove and buttonwood.	Water table obscured by fill. No signs of drainage.
Northern Highway Site 5: Behind the "Biltmore Plaza"	Tall (15-18 m) red mangrove, with extensive aerial root network (both drop and prop roots) growing along canal edge.	Site has been cleared and the soil surface scraped mechanically. A network of drainage channels was dug in Feb./March 1994.	Fill roads have been laid and plots marked out. Many of these are being built upon. Very disturbed.	Water table 1-2 m below soil surface.

continued overleaf

	Mangrove	Site History	Current Activity	Water Depth
Western Highway "Texaco" site	Tall and medium fringe and basin mangrove, rich in epiphytes, dissected by the road - field site on the inland side. Notable topographic rise to north.	A square plot has been cleared in Feb. 1994 for the construction of welder's premises. Timber left where it fell. Litter blown inland.	Fill has been dumped at roadside, landowner awaiting a bulldozer before spreading material. Signs that part of the forest may have been thinned for scaffolding poles.	Water table variable - hollows are flooded to a depth of 3-5 cm, but many areas of soil have dry, oxidised upper regions.
Western Highway "Burnt" (1992) site	Tall and medium fringe and basin mangrove, dissected by the road - field site on the coastal side.	Field site has been manually cleared around February 1991 and cleared area burnt. Regrowth in cleared area burnt again in 1994 dry season.	Drainage planned for August 1992 - never carried out.	Site submerged to a depth of c.10 cm during initial visit (3rd July) but water level dropped 10 days later, to c.5 cm below surface, exposing orange algal mat.
Western Highway "Punta del Este" site	Narrow coastal fringe of tall red & black mangrove, which continues along the canal. Majority of site covered in short (c.2 m) stressed red and black mangrove.	First wave of clearance in 1991. A second wave followed in 1994. Mechanical earthmovers brought in to dig deep drainage ditches and level soil surface.	Drains linked to canal by cutting through tall fringing mangrove. Manual clearing of mangrove observed in adjoining areas.	Water table close to the soil surface. Soil nearest the drains show signs of drying. Material dug out to form drains completely dry.
Western Highway Haulover Bridge site	Tall and medium fringe mangrove forest, tall mangrove next to Haulover Creek.	Area has been partially cleared in 1991 and clay fill dumped to allow vehicle access. Timber left where it fell, exposed trunks rotten.	Small marina development, no obvious work since 1992. Regeneration zone of black and red mangrove 20-150 m wide.	Undulating topography, water depths vary from below soil surface to c.25 cm.

Northern Highway sites

The first four sites along the Northern Highway were all found to be very similar. They were partially cleared areas of basin mangrove, with a water table above the soil surface, except where clay fill or rubble had been dumped. These sites have experienced only forest clearance and so could be placed in the passive post-clearance stage of change (defined below in Section 5.3.2). The absence of drainage means that soil conditions remain reducing and anaerobic in both cleared and forest areas. Thus analysis of such sites is not expected to produce results significantly different from the 1992 study, and so will not yield data suitable for constructing a time series. Combined with the considerable access problems, notably the long walk in through the flooded, thickly vegetated areas of regeneration, these sites were not considered suitable for further study.

In contrast to these still-flooded areas, the site behind the Biltmore Plaza has been severely drained, placing it in a later stage in the process of change. Exposed areas of oxidised soil beside the canal look promising sites for an examination of nitrous oxide emissions, but do not really merit detailed transect study. The soil in this area has been heavily disturbed: scraped flat and covered in clay fill which in places is over 50 cm deep. The only remaining mangrove is in a flooded area, separated from the site by a deep canal, requiring boat access.

Western Highway sites

The first site considered along the Western Highway, was the "Texaco" site (so-called because it lies opposite the Texaco Depot serving Belize City). Although there were no signs of drainage by the landowner, perhaps because of the local topographic rise to the north of the site, and the drainage ditches dug along the road, the soil surface at this site was noticeably drier than the areas visited so far. Disturbance of the remaining forest, especially areas near the road was initially concerning, but a detailed reconnaissance of the area showed that a transect line angled at approximately 45° to the cut edge would avoid the most disturbed areas. This site was therefore selected for further analysis.

The "Burnt" site, which had been the focus of the 1992 work, initially appeared unpromising for further work. The site was still covered by standing water, so little further change was expected. Although measurements taken at this site would allow temporal comparison of data, it was not felt to be the strongest candidate for further study. This decision was later reversed, when for reasons that cannot be satisfactorily explained, the water level at the site dropped, leaving the surface soil exposed. The cause of this drop in the water table remains unknown - there was no obvious change in the rainfall in this area, nor in the water level in other nearby sites. Discussions with George Hanson the Belizean Government Forest Department's Mangrove Manager led to the suggestion that it may have been due to variations in the level of water in the nearby canals and lagoons, which are expected to influence the surrounding hydrology. Whatever the reason for this change in water levels, it placed the site in a different position in the hypothesised process of change - a newly drained site. This made it a much stronger candidate for re-analysis, and it was therefore, resampled.

The site at the Punta del Este development, is covered in a different type of mangrove: much shorter, stressed near-dwarf red mangrove with frequent short black mangrove emergents. It has also been subjected to considerable anthropogenic drainage, but unlike the Biltmore Plaza site, large areas of felled timber remain. This minimal disturbance to the underlying soil combined with the obvious artificial drainage, made this a very suitable site for sampling.

The final provisional field site was the Haulover Bridge site, considered (and ultimately rejected) in 1992. The attraction of this site was the large area of mangrove regrowth in the cleared area immediately adjacent to the remaining forest, which had been spotted from the air. Arriving at the site on foot, the reasons for this rapid regrowth were clear - the site remained flooded to a considerable depth. This meant that the site was likely to be similar to those rejected along the Northern Highway -

soil and water very similar in both the cleared and forest areas, so it was rejected as a suitable site for work attempting to highlight differences.

Selected sites

Three sites were therefore selected for examination in 1994: Punta del Este, Texaco and the "Burnt" Western Highway field site. Their locations are shown in Figure 5.9, overlain on a 1988 c.1:42,000 aerial photograph of the area, showing the extent of mangrove forest cover before these sites were cleared. Individual annotated aerial views of the field sites are shown in Figure 5.10, Figure 5.11 and Figure 5.12.

Permission from the landowners to carry out the fieldwork and information about their clearance history was obtained with help from the Forest Department's Mangrove Manager. Information regarding their hydrology (given below) was obtained through site visits and aerial survey.

5.1.9 Fieldsite hydrology

The fieldsites all have a broadly similar hydrology: water movement across the sites is severely impaired. This is a combination of two factors, the low elevation of the fieldsites and the high clay content of the underlying soils. The sites are gently undulating coastal plains, with very little differences in elevation (the Burnt site is the flattest, with a measured maximum difference in elevation of only 17 cm). The Punta del Este site shows a similar absence of slope, with only the Texaco site showing a discernable trend, a slight downwards slope towards the road. The soils at the three fieldsites are predominantly clay, which impedes both horizontal and vertical sub-soil water movement due to the lack of connected pore-space.

Drainage at the Burnt Site is further impeded by the construction of two small embankments, effectively ponding the site. The inland terrestrial drainage pattern (shoreward) does not continue across the fieldsite because it is constrained by a pair of ditches and embankments which lie either side of the Western Highway (shown in Figure 5.10). This means that water from inland areas is generally routed to flow around, rather than across, the fieldsite, although there is a small, sporadic flow towards the coast from overflow pipes which run from the ditches through the embankment into the fieldsite.

At the coast, a sandy ridge, possibly of storm origin has been locally raised, in an attempt to prevent tidal innundation of the site. This ridge (over 50 cm above the high tide mark), is sufficiently high to prevent waves from lapping across the site during normal wind conditions, although it is likely to be topped during storms. Furthermore, given its porous, sandy nature, water may percolate through this barrier, resulting in a small, tidal fluctuation in the water level behind this ridge. However, if this occurs, then the amplitude must be either very small, or the effect limited to the immediate vicinity of the shore, because regular monitoring of the lagoon levels near the road in 1992 showed no significant fluctuation in the lagoon levels during the field period. Surface water movement across this site is therefore controlled largely by the prevailing wind direction. Sub-soil drainage is very poor, with no directional component acrooss the fieldsite, except perhaps in the immediate vicinity of the shore.

The Punta del Este site lies further from the coast, with the area sampled several hundred metres from the shore, so no significant tidal "surging" of the groundwater is expected. The low elevation of the inland area and the presence of Jones' Lagoon means that there is very little surface runoff which reaches the fieldsite. The major controls upon its hydrology are artificial: the network of canals to the West and immediate South of the site, and secondly the series of large drainage ditches dug by the contractors to the East of the field area. These have acted to enhance vertical water movements, locally lowering the water table, but horizontal movement of water across the site remains minimal.

The Texaco site differs from the other two slightly, in that there is a perceptible slope across the fieldsite, with maximum elevations inland and the lowest ground nearest the coast. The hydrological effect of this slope is less than might be anticipated. This is because of two factors: the presence of a second-low lying area further inland of the fieldsite and effective drainage near the road which acts to conduct water away from the fieldsite. The Northern edge of the fieldsite lies at the foot of a narrow ridge (approximately 20-50 m in width), which runs parallel to the shore. This is possibly a fossil storm ridge or shoreline feature. Whilst resulting in a localised movement of surface water across the fieldsite towards the shore, this same ridge acts as a barrier to water movement from areas further inland. Despite this surface water flow from the higher, forested areas, the water table at the low-lying (partly cleared) area next to the road still lies below the surface. This is interpreted as being the result of two factors, increased evaporation loss from the exposed soil in the cleared areas and efficient surface drainage because of the nearby drainage channel running alongside the Western Highway. The fact that the water table also remains below the surface in areas of forest abutting the cleared area, suggests that the land drain has the greater effect upon the local hydrology. Later examination of the soils (this study) reveals the presence of mottles (see for example, Figure 9.3), indicating a history of fluctuating soil-water conditions. Thus this site shows the most variable hydrology, with the soil undergoing periods of waterlogged and then relatively drained conditions, depending upon the balance between inputs from precipitation and local surface runoff, and water export via the drains which run along the road.

5.1.10 1994 Fieldwork techniques

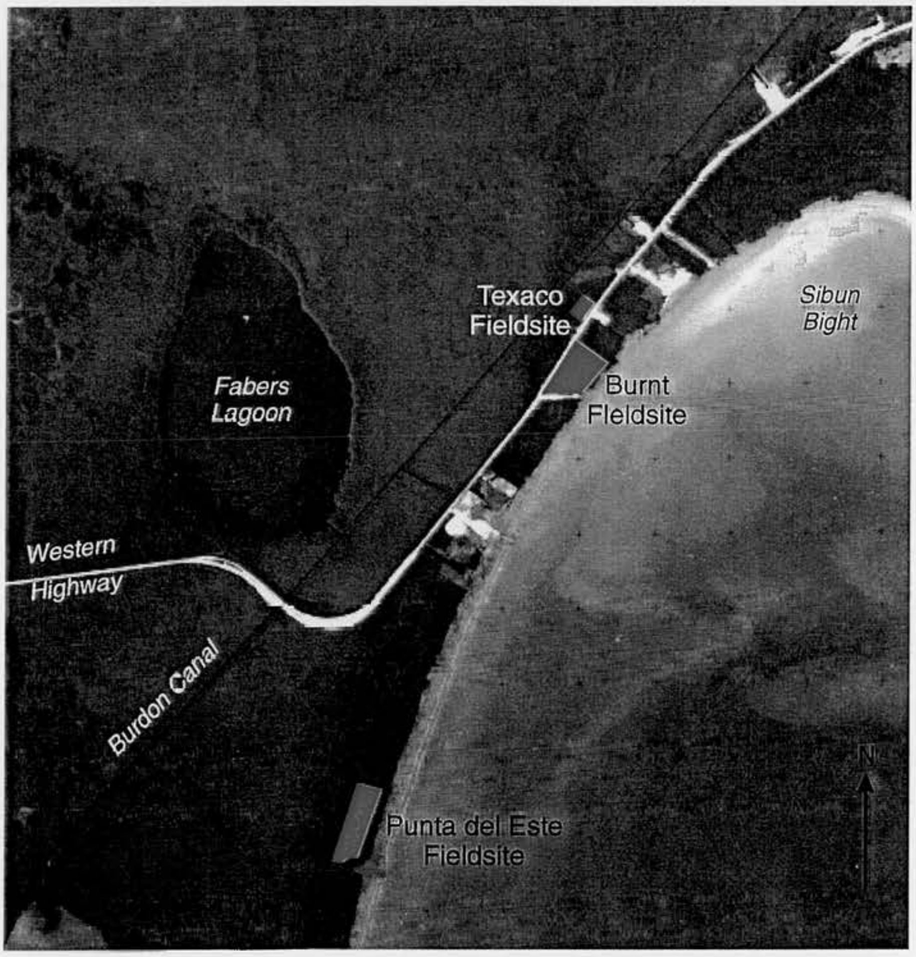
To maximise the number of sites visited, it was decided to confine the 1994 sampling to a linear transect technique. The approach is conceptually very similar to that in 1992, with some implementational differences discussed below.

Modifications to the transect intervals

The transect interval used along each line has been made constant, so that when transect data are combined, the maximum number of lags[5] can be generated. At both the "Burnt" and Punta del Este site, the sampling interval is 5 m, with 13 points on each line, resulting in a 60 m transect, centred on the cut line. The portion of these transect lines lying in the forest zone (30 m) is comparable to that in the 1992 transects, but unlike the 1992 work, the length of transect line in the cleared zone matches that in the forest, i.e. is also 30 m long. A different (10 m) sampling interval was used between the 13 points of the Texaco transect, this was chosen for two reasons. The Texaco transect line, unlike the other sites, does not lie perpendicular to the forest edge. To avoid areas of disturbance - thinned sections of forest and rusting machinery in the cleared area - the transect line lies at an angle of approximately 45° to the cut edge, as shown in Figure 5.11. The angling of the transect line means that were the sampling interval the same as that used in the perpendicular transects, it would not be able to detect changes as far into the forest as the others. Secondly, increasing the sampling interval allows the generation of more long-distance lags, providing increased confidence in the higher values of the derived semivariograms.

[5] Lags are used for producing the semivariograms, allowing quantification of spatial autocorrelation. A lag, is measured as the distance between two points in space. Regularly spaced sampling intervals produce very large numbers of lags, for distances which are exact multiples of the sample interval. (See chapter eight for a fuller discussion of this).

Figure 5.9 Locations of the 1994 fieldsites

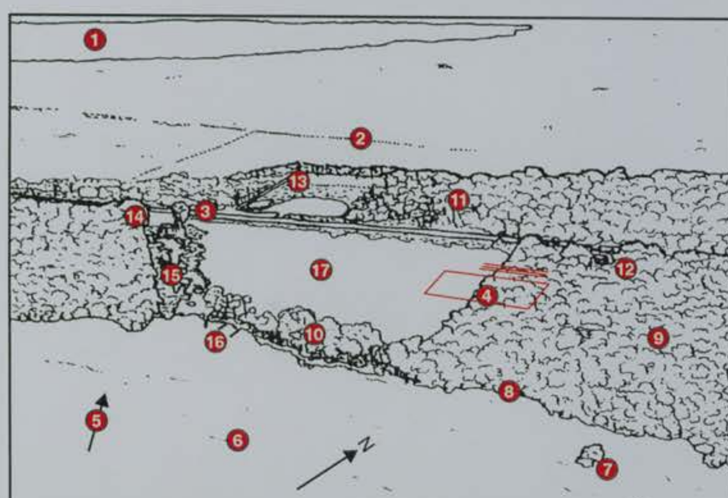


This figure is based on an extract from aerial photograph 0454 V1 1PRU A RAF 0530 032100ZMAR88 taken at 21000 feet in March 1988. The scale is approximately 1:42,000. (Crown Copyright Reserved).

Figure 5.10 Annotated view of the Burnt fieldsite

SCALE VARIES ACROSS THE PHOTOGRAPH (Taken in August 1992 by Simon Zisman)

SCALE VARIES ACROSS THE PHOTOGRAPH (Taken 1st July 1994)

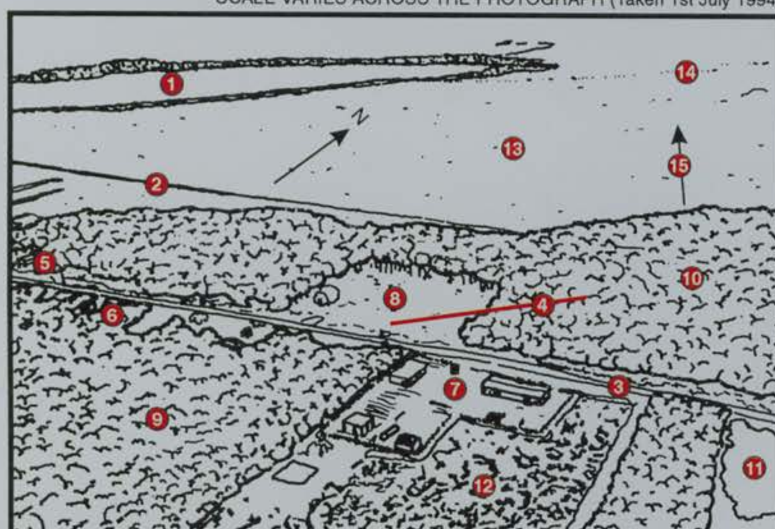


ANNOTATED AERIAL VIEW OF THE BURNT FIELDSITE (1992)

1. Fabers Lagoon, fringed by medium height mangrove
2. Burdon Canal
3. Western Highway (flanked by drains on both sides)
4. Study area and 1992 transect lines: LT, MT and RT. 1994 transect (BC) was very near RT
5. Observed prevailing wind direction (arrowhead indicates direction of movement not source)
6. Waves breaking parallel to the shore
7. Red mangroves growing in shallow water offshore
8. Fringing red mangrove
9. Tall mixed red, black and occasional white mangrove
10. "22 yard" buffer of black mangrove
11. Traditional wooden house built on stilts
12. New concrete, single-storey house
13. Clay infilling of cleared site
14. Abandoned dwelling (unfinished)
15. Grasses recolonising a cleared and filled area
16. Exposed coast eroded by storm and wave action
17. Flooded clearing

Figure 5.11 Annotated view of the Texaco fieldsite

SCALE VARIES ACROSS THE PHOTOGRAPH (Taken 1st July 1994)



ANNOTATED AERIAL VIEW OF THE TEXACO FIELDSITE (1994)

Photograph taken August 1994.

This photograph shows mangrove vegetation typical of the Texaco fieldsite.

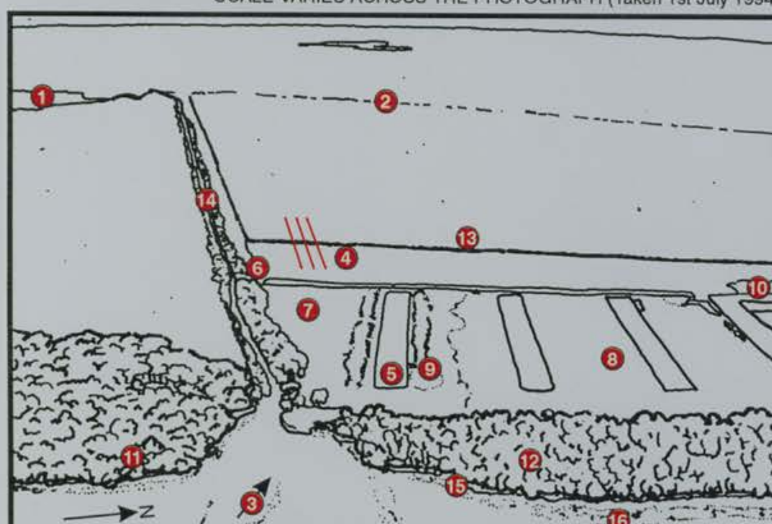
The prop roots of the large red mangrove in the foreground of this picture join the main trunk at a height of c.1m above the ground.

The trees are tall, widely spaced and many are covered in epiphytic plants such as the large cacti seen here. This suggests that the stemflow may be rich in nutrients at this site.

1. Fabers Lagoon, fringed by medium height mangrove
2. Burdon Canal
3. Western Highway (flanked by drains on both sides)
4. Transect line (angled to avoid disturbed area near the road)
5. Traditional wooden house also seen in the aerial view of the Burnt Field Site
6. New concrete single storey houses
7. Texaco fuel depot, built upon raised area of clay fill
8. Recently cleared area (brash covered)
9. Tall mixed red and black mangrove
10. More tall mixed red and black mangrove, growing on a slight ridge, parallel to the road
11. Area covered in iron-rich clay fill, ready for construction
12. Cleared area, flooded above soil surface, being recolonised by dwarf mangrove
13. Dwarf mangrove
14. Inland boundary between the dwarf mangrove and savanna
15. Observed prevailing wind direction

Figure 5.12 Annotated view of the Punta del Este fieldsite

SCALE VARIES ACROSS THE PHOTOGRAPH (Taken 1st July 1994)



ANNOTATED AERIAL VIEW OF THE PUNTA DEL ESTE FIELDSITE (1994)

The photograph to the right was taken at the edge of the cut line at the Punta del Este fieldsite. The transect line PRT was later set to run just to the left of the tall mangrove in the foreground.

The mangroves are far smaller and more densely packed at this site compared with the other two. Most of the trees seen in this picture are red mangroves, although a few spindly black mangroves can be seen on the horizon, emerging from the canopy.

The large volume of litter and brash in the foreground of the picture testifies to the recent clearance of this site.

Photograph taken July 1994.

1. Jones Lagoon
2. Burdon Canal
3. Observed prevailing wind direction
4. Transect lines (from left to right, PLT, PMT & PRT)
5. Land drains
6. Area where land drains were to join into canal system (not breached at the time of the photograph)
7. Recently cleared area (brash covered)
8. Cleared and mechanically smoothed area (no timber on the surface)
9. Mechanised clearance in progress
10. Areas covered in iron-rich clay fill, ready for construction
11. Fringing red mangrove
12. Black mangrove buffer (red removed)
13. Stressed, short (2-3m) mixed red and black mangrove forest
14. Taller forest along the canal (greater nutrient input and/or greater freshwater flushing)
15. Exposed coastal sediments
16. Seawater loaded with sediment

The number of transect lines

For reasons of sampling efficiency, at two of the sites: Texaco and the "burnt" site, the number of transect lines was decreased from three (as in 1992) to one. Instead, repeat sampling of the water properties were made on different days. The vegetation at the Texaco site is broadly similar to that found at the "burnt" site, allowing the extrapolation of trends found from the 1992 areal work to this area. The mangroves found at the Punta del Este site are much shorter, however, showing many of the signs of vegetative stress discussed in chapter four - leaves angled to minimise insolation, a dwarf form, few leaves and branches. Thus, far less confidence could be placed in the untested extrapolation of the 1992 trends to this area. For this reason, it was decided not to reduce the number of transect lines at this site, and three 60 m transect lines were marked out, each 2.5 m apart. This it was hoped, would allow a more representative picture of the spatial variation present in this area, to determine whether this site is really significantly different from the others.

Figure 5.13 overleaf, summarises graphically the different sampling intervals used at the various sites in this study.

The measurements carried out in 1994 were selected to be broadly comparable with those taken in 1992. However, the decision was made to bias the sampling towards water rather than soil properties - as these could be rapidly analysed in Belize. Table 5.6 below lists the measurements carried out at each site:

Table 5.6 Properties measured in the 1994 fieldwork

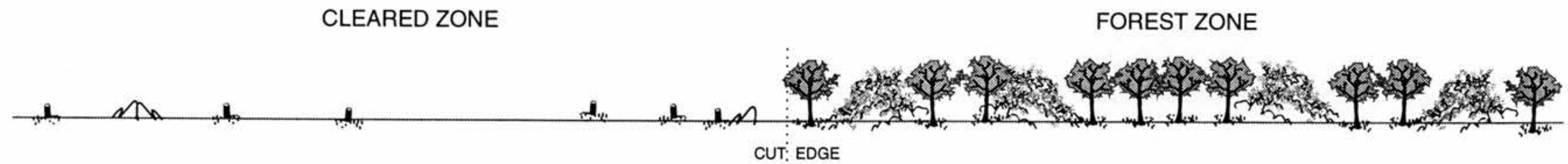
Samples at many depths	Measurement scale	Samples at many depths	Measurement scale
Layer thickness	ratio	Root abundancy	ordinal
Soil texture	ordinal	Field soil pH	interval
Soil colour	pseudo-interval	Field soil redox	ratio
Mean layer depth	ratio		

Single depth samples	Measurement scale	Single depth samples	Measurement scale
Field water pH	interval	Water chloride	ratio
Field water redox potential	ratio	Water sulphate	ratio
Field water conductivity	ratio	Water turbidity	ratio
% Leaf litter cover	ratio	Water suspended solids	ratio
Water depth	ratio	Water dissolved oxygen	ratio
Water nitrate-N	ratio	Water total dissolved solids**	ratio
Crude root biomass*	ratio	Field drainage	ordinal
Water reactive phosphorus	ratio	Water depth	ratio
Soil nitrous oxide flux	ratio		

* "Burnt" site only

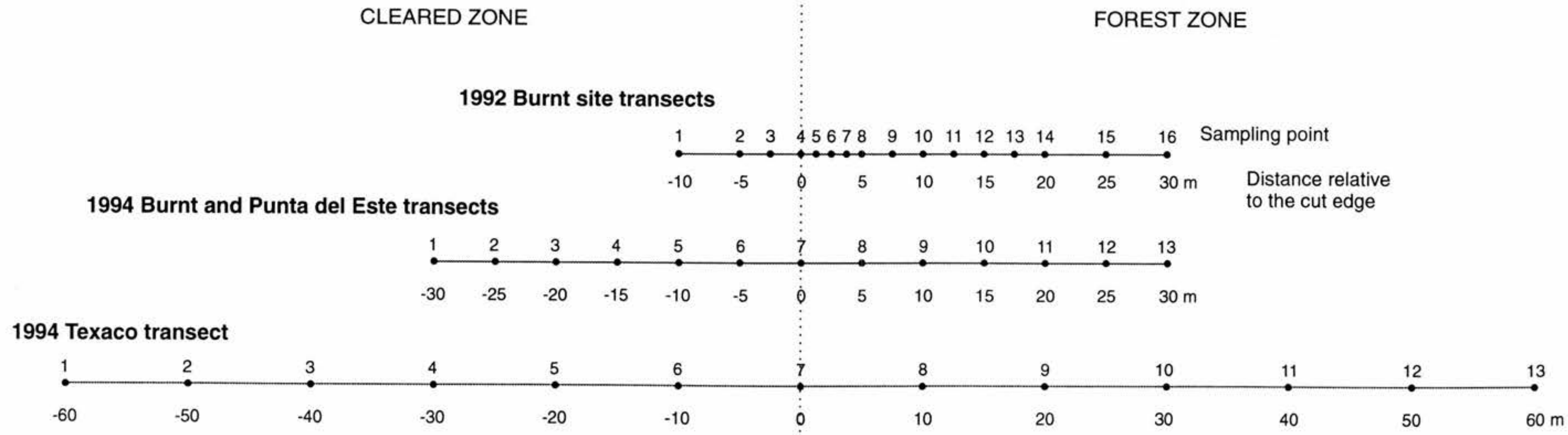
** TDS was found to be a multiple of conductivity, therefore not analysed further.

Figure 5.13 A comparison of the different transects used in the fieldwork



The vegetation cover at the fieldsites is shown schematically above. To the left are the cut prop roots and tree stumps of the cleared zone, to the right, the dense tree cover seen in the undisturbed forest.

Below, the transect lines are shown drawn to a common scale, centred along the cut line which marks the edge of the forest.



N.B. Unlike the others, the Texaco transect is angled at 45° rather than being perpendicular to the forest edge, so the sampling interval is not strictly comparable.

5.2 Laboratory and fieldwork measurement techniques

A wide range of potential field and laboratory analytical techniques exist. Boto (1984) and Pannier (1984b) provide a comprehensive review of techniques suitable for research in areas of mangrove forest. The methods selected in this analysis met three criteria:

1. A preference towards field rather than laboratory measures, to provide rapid analyses, and results known to reflect the conditions at the time of measurement.
2. Where possible the method selected was widely recognised, to facilitate comparison with other work. Particular emphasis was given to techniques which had proven effective in the harsh mangrove environment
3. Where further choice existed, the method which minimised the use of hazardous and/or toxic chemical reagents was selected, to reduce the risk to both the analyst and the environmental impact of the research.

Full details of the analytical techniques and instruments used are given in appendix two, but a brief outline of the methods is given below.

Soil pH and redox were measured directly using an electrode inserted into the soil column, immediately after coring, through access holes in the side of the specially designed corer (modified from designs published in Boto, 1984). This minimised the exposure of the sample to the air, preventing significant modification of soil properties through oxidation. The decision to measure soil pH in the field, rather than using a standard air dried soil-deionised water suspension technique in the laboratory, was made as this was felt to more accurately represent the actual conditions in the mangrove at the time of measurement (Pannier, 1984b). Whilst laboratory techniques are more easily replicated and many studies report soil pH as values obtained from this laboratory method (e.g. Ukpong & Areola, 1995; Furley & Minty 1992) this value is likely to differ significantly from those obtained in the field. Air-drying of the samples will alter the metal species present in the soil, favouring oxidised forms, which tend to lower soil pH.

Water pH, conductivity, dissolved oxygen, total dissolved solids and redox were measured using direct reading electrodes. In some cases the samples had to be diluted with de-ionised water to provide readings within instrument range. Water samples were taken from dipwells using a collection device illustrated in appendix two.

Soil colour was estimated in the field using a Munsell® chart in direct overhead sunlight. Ground level insolation was measured using a hand-held light meter. Root abundance soil texture and field drainage were estimated by eye using the classes published by the Soil Survey of England and Wales (1976). Percentage litter cover was also determined by eye.

Soil moisture loss and percent dry matter were estimated by weighing samples in the field and again after drying in the laboratory at 40° and 105°C. The percent of soil greater and less than 2 mm was ascertained by dry-sieving the samples using a 2 mm stainless steel sieve after grinding the soil in a pestle and mortar. Bulk density was measured using a stainless steel cylinder of known volume, inserted into the soil. Crude root biomass was estimated from the weight of roots washed out of a 10 cm long cored cylinder of soil.

Soil nitrate-N and soil ammonium-N were determined in 1992 from potassium chloride extracts taken immediately after fieldwork, stabilised and then analysed by flow injection upon return to the UK. Field measurements of soil nitrate-N taken in 1992 using semi-quantitative tests strips returned only zero values.

Two measures of organic content were taken - the rather crude weight loss on ignition (using a furnace temperature of 550°C) and organic carbon content, using the Walkley-Black method, modified for colorimetric analysis, (Black *et al.*, 1965). This second wet oxidation method provides a more reliable measure of soil organic matter content than the loss on ignition technique for samples with a variable carbonate content. The furnace regime of 2 hours at 550°C used in loss on ignition analysis is that recommended by Allen (1989). Some workers e.g. Ball (1964) have advocated lower temperatures, to prevent the loss of volatile minerals, but this is only achieved at the risk of incomplete combustion. Given the high anticipated organic carbon content of surface soil samples collected in the mangrove, the higher temperature regime was thought more suitable. This temperature regime is also that advocated by Boto (1984) for use with mangrove soils.

The levels of soil exchangeable cations was determined using a 1M ammonium acetate extract, buffered to pH 7. Ammonium acetate extract has been used by other workers for mangrove soils, e.g. Tam *et al.* (1995). Buffering this solution to pH 7 rather than pH 4 was felt to most closely represented the pH conditions of the field site. Exchangeable calcium, magnesium and manganese were then determined by atomic absorption spectrophotometry, exchangeable potassium and sodium by flame photometry.

The other water properties were all determined using a direct reading spectrophotometer. Available phosphorus was measured using a modification of Olsen's sodium bicarbonate method, (Olsen *et al.* 1954) designed for use with the spectrophotometer. This test has been widely used in mangrove soils (e.g. Tam *et al.,* 1995; Wong *et al.*, 1995) and is one of three standard methods for analysis of phosphorus, (Allen, 1989). The other two are known as Troug's method and Bray and Kuntz' method.

Troug's method (Troug, 1930) uses a sulphuric acid extract, it was not selected because its performance is not reliable in soils containing carbonates. Bray & Kuntz (1945) use an ammonium fluoride and hydrochloric acid extraction technique. The results are very sensitive to the reaction time, rendering it unsuitable for bulk analyses. Water reactive phosphorus (orthophosphate) was determined using an acid extract for use with the molybdovanate method; soil sulphate-S was determined by the calcium phosphate method; total iron by the phenanthroline method; water chloride by the mercuric thiocyanate method; and water sulphate levels by the barium chloride method. Turbidity was determined absorptometrically, using the spectrophotometer and the amount of suspended solids (non-filterable residue) was measured photometrically on this instrument.

Nitrous oxide gas flux was measured from samples collected in evacuated vials from soil cover tins placed in the mangrove, following the technique suggested by Hutchinson & Mosier (1981). The amount of nitrous oxide was determined by gas chromatography upon return to the UK.

An analysis of the vegetation growing in the forest area was carried out using the point centre quarter method (PCQM) of Cottam and Curtis (1956), using a modification designed to cope with the prop roots of *Rhizophora* employed by Ratter & Bridgewater (1992) in earlier mangrove survey work in Belize. Cintrón & Novelli (1984) recommend this method for use in studies of mangrove forest structure. Full results of this analysis are given in appendix one.

5.2.1 Soil units

In the discussion of results, the term "layer" is used when referring to units of soil extending over the field site. This deliberate avoidance of the term "horizon" reflects the fact that mangrove "soils" are really poorly consolidated sediments with weakly developed soil structure, They typically comprise of a layer of peat overlying of a series of marine clays[6]. The upper layer - "layer 1" referred to in the text is composed primarily of this organic material, "layer 2" is a sample from the upper part of the clay sequence. However the terms "A-horizon" and "B-horizon" were not felt to be appropriate because at some sites the distinction between the two units is far from clear. Two sources for this mixing can be identified:

1. For certain samples where there was only a very thin deposit of peat, bulking of sample material with that from greater depths was required to give a sufficiently large volume of material for laboratory analysis.
2. At some sites the soil appeared to be heavily disturbed (possibly by the burrowing actions of crabs, or human activity) resulting in a mixing of clay and organic material, making differentiation between the A and B units impossible.

[6] Chapter nine examines the distribution of the various soil units along the sampling transect lines. Figures 9.1, 9.2 and 9.3 show examples of typical soil profiles at the fieldsites.

Therefore, the concept of soil "layers" has been used to indicate differences occurring with depth. In 1994 some properties, such as soil pH and redox potential were also recorded at the soil surface, before coring. These samples are referred to throughout as "surface soil pH", "surface soil redox" to distinguish them from measurements made in soil layer 1 or 2.

Having selected the properties to measure, decided upon appropriate analytical methods, chosen suitable field sites and considered the applicable spatial sampling strategies, only a few conceptual sampling difficulties remained. These are discussed below.

5.3 Conceptual issues

Three conceptual difficulties were identified: how to define the sampling units, how to conceptualise process of change over time in a manner relevant to the sampling strategy, and whether it is possible to combine data from several field sites. These are considered in turn below.

5.3.1 Defining the sampling units

In the field, the sites can be readily divided into two: areas of relatively undisturbed mangrove - "forest" and those where the vegetation has been removed - "cleared" areas. "Undisturbed mangrove" is defined as that showing no signs of obvious human disturbance - no construction within the forest, significant tree-felling or thinning activity, or footpaths in the remaining forest. It is acknowledged however, that given the field sites close proximity to Belize City, and the present clearance activity occurring beside them, that the forest at all the sites is likely to have received occasional visits from local people, on hunting trips, for survey-pole extraction, etc. These forests will also have been subjected to "natural" disturbances, most notably hurricane impact. "Cleared" areas are defined as those where the original mangrove forest cover has been removed by either hand or mechanical means. This term therefore, applies to both sites where mangroves have been felled by hand, leaving severed trunks, prop roots and pneumatophores in the ground, and also to areas where the mangroves have been physically pushed over, resulting in a greater disturbance to the soil surface.

Identifying areas which have been subject to changes in the water level can be more difficult, requiring external information, or field indicators of past water levels. Most problematic is delimiting the edge of the forest: deciding where exactly the forest ends and the cleared area begins. Two difficulties can be identified, locating the cut line, and deciding what constitutes the forest edge.

Generally in Belize, because the land is usually subdivided into rectangular plots marked by survey lines, and the subsequent clearance of these sites tends to be total, the result is relatively straight cut-edges (clearly seen in aerial photographs) regardless of the clearance method employed. Thus locating the cut-line is not too difficult.

Defining the forest edge depends upon the purpose of the study - the location of the main tree trunks (which may be problematic with *Rhizophora* specimens), the furthest extension of surface or subsurface roots, or even the edge of the area overshadowed by the forest canopy, are all possible markers which at least theoretically, could be used to delimit the forest edge. Studies concerned with sub-surface processes may opt for a root-based definition, those more concerned with surface conditions, may use the shade limit.

In the present research, which looks at processes occurring both above and below ground, it was felt that there was insufficient background information to opt for one feature and so, for the purposes of areal comparison, a third sampling unit was defined - the "transition zone". This zone was located 5m either side of the cut line, a distance chosen because it encompasses the majority of surface root growth (identifying the "parentage" of every pneumatophore growing in a dense carpet can be a problem) and also includes the area continuously shaded from the sun at ground level. This results in three conceptual sampling units; such a representation for the 1992 "burnt" field site was shown in Figure 5.2.

5.3.2 Considering how "changes" act through time

Mangrove forests are extremely dynamic and in locations such as the edge of lagoons or coastal fringes, can change rapidly over time. As discussed above, an ideal study would follow areas of mangrove, from pre-clearance through partial deforestation and drainage, returning regularly to monitor changes. Given the imposed time limits, such a strategy is not possible and a spatio-temporal substitution is required. This means that rather than following the same sites as they change over time, the study will look at more sites in the same area, each at different stages in the clearance process (the stages are defined below). If the sites are carefully chosen to maximise their homogeneity then a time series can be created by amalgamating data from the different plots.

The "shape" of time in these processes needs careful consideration - the key question is whether it acts in a linear way. It is tempting to conceive of time in such a situation as an incremental, continuous linear process, with the forest slowly and steadily readjusting to changes imposed by the adjacent clearance. In this piece of research however, it is more convenient to view time as acting in discrete steps - a series of stages. A possible outline of these stages follows in Table 5.7. It highlights the sequence of short dynamic periods of rapid change when many soil, water and other environmental properties may change, followed by longer more passive periods, where the system readjusts to the new conditions, but experiences no further significant inputs or losses.

Table 5.7 A theoretical temporal model of mangrove disturbance

Pre-clearance passive	A relatively inactive period, with nutrient movement confined to traditional nutrient cycling paths - litterfall, freshwater sediment input, marine imports and exports, precipitation, etc. Minimal human disturbance due to low traditional utilisation of mangroves and mangrove products in Belize. Soils are anaerobic, with reducing conditions predominating.
Clearance dynamic	A major disturbance - damage to and removal of woody material resulting in the release of stored materials. Burning of materials will result in a rapid short-lived flush of nutrients to surface areas. Soils in the cleared area are exposed to direct sunlight.
Post-clearance passive	Readjustment to the lack of forest cover. Continued ponding of the site will slow down decomposition processes. No new litter input, soil and groundwater nutrient levels will have therefore, declined. Soils are still dominated by anaerobic and reducing conditions.
Drainage dynamic	Lowering the water table starts the oxidation of surface materials and accelerated decomposition of exposed roots and woody material.
Post-drainage passive	Soils develop an upper, oxidised layer, may show increasing acidity and possibly high sulphate levels if soil conditions are appropriate.

Initially, the assumption that the value of measured mangrove soil and water variables are relatively *passive* in the pre-clearance stage may seem to contradict the earlier claim that mangroves are extremely *dynamic*. This reflects both the dual role of mangroves: as colonisers or a (near) climax vegetation and also the differing emphasis placed by different writers. Fringing areas of mangrove are indeed dynamic, both in terms of forest structure and species composition. Exposed to the effects of storms and the tides, the accumulation of sediments around their roots leads to a rise in the surface sediment height and the eventual replacement of the zone initially almost entirely composed of *Rhizophora mangle* with a new, elevated "basin" region of *Rhizophora mangle* and *Avicennia germinans*.

The basin mangrove found at the study areas is such a mixed area of red and black mangroves, with additional occasional specimens of the white mangrove, *Laguncularia racemosa.* In such locations, with a water table at or very close to the soil surface, undisturbed areas of mangroves face little competition from other plant species, which cannot tolerate the reducing, anaerobic conditions and high salinity. Soil and water conditions are far more constant than on the fringe - relatively removed from the influence of the tides. It is for this reason, and the tendency for mangroves to form even-aged stands noted by Jiménez & Lugo (1985), that it is felt that the initial pre-clearance stage can be considered as effectively passive.

If this conceptualisation of time as a series of stages is correct, then it has significant implications for site selection. Merely selecting a series of sites of increasing age after clearance may not be sufficient to highlight the changes, especially if the chosen sites all lie in the same stage. Ideally, site selection should be such that it ensures that sites are chosen from each stage of this suggested stratification, allowing the maximum possible development of temporal arguments.

Another important consideration in site selection is the cyclical nature of the climate of Belize. Figure 3.1 has shown it to have a marked seasonal pattern, with a dry season in the temperate northern hemisphere "winter", and a warmer wet season in the northern hemisphere "summer". As was shown, this will affect the rate of many processes operating in the mangrove. Field sampling strategies need, therefore, to ensure that it is possible to clearly identify the cause of any observed differences in soil, water and other environmental properties (whether in results from different sites, or from the same site resampled later in time). To examine the effects of long term change following forest clearance and drainage, sampling should therefore, act to maximise the effects of a long term process of change in these variables, and minimise seasonal differences. This can be most easily achieved by confining sampling to the same season each year. For logistical reasons, fieldwork in this study was carried out in the months of July, August and early September (the very end of the dry season and the beginning of the wet).

5.3.3 Spatial differences

By gathering data at each field site at different sample-point locations and at different depths, a picture of the spatial pattern of variation at each site can be produced. Working at several field sites, separated physically by distances of the order of hundreds of metres, it is tempting to consider each site as a distinct, isolated area. If this is the case, then data from these sites cannot be reliably aggregated, preventing the identification of larger, regional trends. However, such a separation is only justified if the areas are physically different, that is that they vary significantly in terms of hydrology, geology, geomorphic region, etc. and are thus truly different areas, rather than each site being merely a sub-sample from the same target population. To test this idea, locational data for the chosen field sites are summarised in Table 5.8.

When examined closely, these sites seem more similar than may have first been expected. The sites all lie near the coast, with a common underlying geology and soils from the same sub-suite. The mangrove cover is similar at the Burnt and Texaco sites, with the Texaco site appearing to be an older, taller version of the Burnt Site. The mangrove cover at Punta del Este differs only slightly in that it is generally shorter, lacks a significant white mangrove component and appears more stressed. Hydrologically, the sites are all fed from terrestrial water sources, with drainage heavily influenced by drainage ditches dug along the Western Highway. Thus, the data tend to corroborate the theory that they are in fact sub-samples from a single larger sample population (perhaps near-coast basin mangrove forest sites around Belize City) and so careful combination of data from several sites seems realistic.

Table 5.8 Comparing the field sites

Field site	Location	Mangrove	Geology	Soil	Hydrology
Burnt 1992	Lies on coastal plain, between the Western Highway and the coast.	Mixed, basin mangrove forest. 51% red (7 m) 46% black (8 m) 3% white (8 m).	Unconsolidated Quaternary sediments.	Tintal Ycacos sub-suite. Peaty swamp and muck soil. (Marine clay overlain by a shallow layer of peat).	Nearly ponded - road & drains restrict terrestrial runoff, beach ridge limits tidal inundation. Standing water.
Burnt 1994	As above.	As above.	As above.	As above.	Water level dropped to c.3 cm below surface.
Punta del Este 1994	Lies on the coastal plain, between the W. Highway and the coast, edged by a canal.	Mixed, short basin mangrove forest. Plants show signs of considerable stress. 51% red (3 m) 38% black (5 m) 10% white (5 m).	Unconsolidated Quaternary sediments.	Tintal Ycacos. Peaty swamp and muck soil. (Marine clay overlain by a shallow layer of peat).	Drained by canal and artificial channels. Water table c.3cm below surface.
Texaco 1994	Lies on the coastal plain, inland of the Western Highway.	Mixed basin mangrove forest, trunks covered in epiphytes. 38% red (11 m) 36% black (16 m) 26% white (15 m).	Unconsolidated Quaternary sediments.	Tintal Ycacos. Peaty swamp and muck soil. (Marine clay overlain by a shallow layer of peat).	Terrestrial drainage unimpeded, runoff to sea intercepted by road drain. Water table c. 3 cm below surface.

Mangrove percentage figures are relative frequency values, values in parentheses are mean tree height; Data from PCQM analysis given in appendix one. Mangrove form after Lugo & Snedaker (1974). Geology after Baldwin (1979), given in Hartshorn *et al.* (1984). Soil descriptions after King *et al.* (1992) with additional detail from Wright *et al.* (1959) modified to match the principal land units.

In order to display the spatial pattern of variation at the sites, several visualisation techniques can be employed. These two approaches are shown in Figure 5.14. Two aspects of change need to be considered, which require slightly different approaches - variations with distance (changes in x and y) and variations with depth (z). Relationships in the x and y directions can be shown by draping an interpolated surface of data (showing changes in the measured property occurring in both the x and y directions) over a representation of the field site surface. Variations with depth (z) can be shown in two ways - either as a series of stacked surfaces, showing depth variations across a series of discrete z intervals; or as a series of transect diagrams, to show continuously any variation in z, similar to the panel diagrams used in geology to display borehole data. Such spatial patterns then allow the visual identification of the underlying relationships.

Interpolated surfaces represent the variation as a continuous surface, yet in fact each surface is derived mathematically from a series of point data, which may be either randomly or regularly distributed. There are many algorithms available for interpolating these surfaces, such as fitting a bivariate function, changing the size of the sampling grid, minimising the curvature over the surface, or kriging (UNIRAS, 1990).

The method employed in this work bilinear interpolation. This is less robust than kriging techniques, but these were not used because they require the calculation of semivariograms (a measure of spatial autocorrelation). Experimental generation of semivariograms using data from the 1992 field site (the focus of chapter eight) suggests that they are not adequately robust for kriging purposes, because the uneven distribution of sampling points leads to highly variable semivariogram values for low lag distances. Experimenting with different interpolation techniques did not give rise to grossly different representations of the surface patterns, the only significant algorithm-dependent differences arose around areas with extreme values. Therefore, although the inability to use kriging routines is regrettable, particularly as it means that estimation of confidence in the resulting interpolations cannot be made, the bilinear interpolation method appears to be satisfactory for the purposes of this research.

Visualisation techniques, such as a mathematical-based interpolation, display how spatial processes manifest themselves over an area. These techniques complement the more numerically based statistical analyses detailed below, which tend to suppress the spatial aspect of the process under consideration.

5.4 Sampling design problems

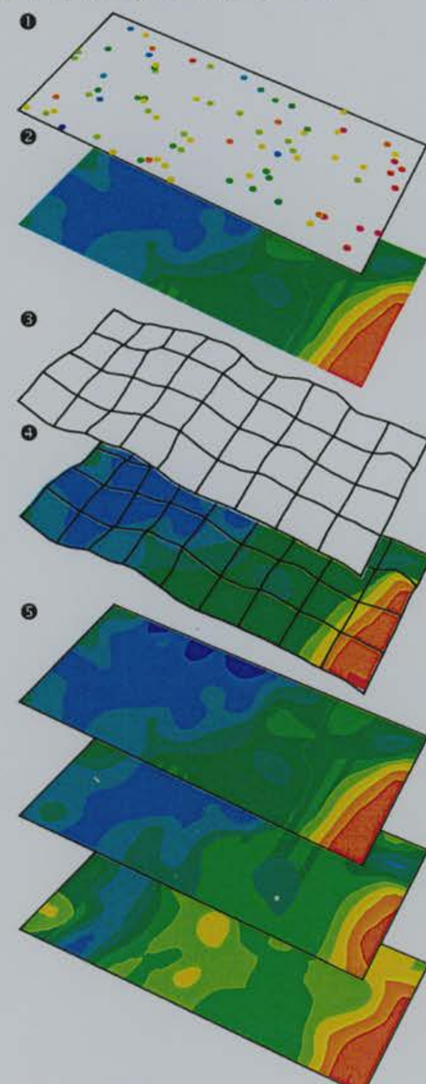
Designing a suitable statistical framework to highlight the differences between values in cleared and forest areas is dependent upon two features of the data: the units of measurement and the distribution of the values. These properties of the data constrain the choice of statistical tests. Two common comparative statistical tests are considered below in Section 5.4.1, the parametric *one way analysis of variance (ANOVA)* and the non-parametric *Mann-Whitney U test*.

Such a comparative approach treats each measured variable as separate. An alternative inferential aggregate method, *gradient analysis* (a mixture of ordination and regression techniques) allow the identification of changes (difference) in a suite containing many (or all) of the measured variables. This method can be used to see how variables act together to yield the observed difference between cleared and forest areas and is explored in Section 5.4.2.

The spatial patterns seen most clearly on the areal plots described in Section 5.3.3, are the result of a process known statistically as *spatial autocorrelation*. Section 5.4.3 describes a method for measuring this: the calculation of semivariograms. Figure 5.16 at the end of this chapter shows diagramatically how the various statistical techniques are used together to answer the questions posed by this piece of research.

Figure 5.14 Different methods of representing spatial variation

This figure shows two groups of visualisation techniques. Areal data can be represented by creating a continuous 3D data surface. Linear transect sampled data are better shown as 2D graphs.



Areal sampled data

❶ Areal sampling produces a set of point data at locations scattered across the field site surface. Depending on the property being measured, there may be one value for each point, e.g. the percentage of the ground surface covered by leaf litter, or a range of values at different depths, e.g soil pH. The diagram shows an overhead view of a set of (single depth) point data.

❷ These point data can be used to create a continuous two dimensional data "surface" showing how the measured property varies across the entire field area. This is achieved using an interpolation routine to provide data values for the missing points mathematically. There are many such routines, this diagram shows a surface created using a bilinear interpolator.

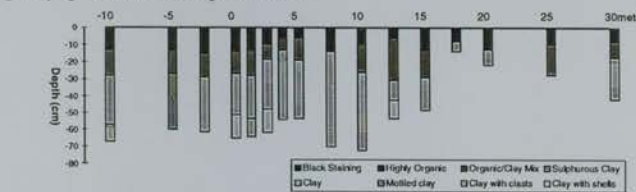
❸ Topographic measurements can be used to create a digital elevation model (DEM), a pseudo three dimensional representation of the field site surface, viewed from above.

❹ The interpolated surface which shows the spatial variation of our measured property can be "draped" over the DEM giving a similar pseudo "four" dimensional representation of the data. This can be useful for highlighting the influence of features such as topography and surface runoff. The draping process is akin to painting the surface of the field site different colours, each colour representing a range of values of the measured property.

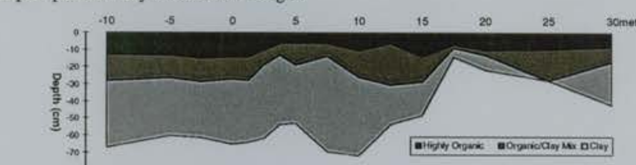
❺ The interpolation process can be repeated at each depth measured, to produce a stacked series of two dimensional surfaces, each layer showing variation at a given depth. This allows the continuous representation of changes in the measured property in x and y, plus changes over a discrete range of z values.

Transect data

Transects yield a series of data, which lie along a single straight line, marked out on the soil surface. The diagram below shows a series of soil cores taken along the LT transect at the "Burnt" Western Highway site in 1992. The transect line is shown running from left to right, with a rectangular pictorial representation of the soil units drawn for each of the sampling points, coloured according to the recorded soil type. The length of each soil column is proportional to the depth of the core, thus the transect provides a cross-section of the soil properties at a set of irregularly spaced discrete sample locations.

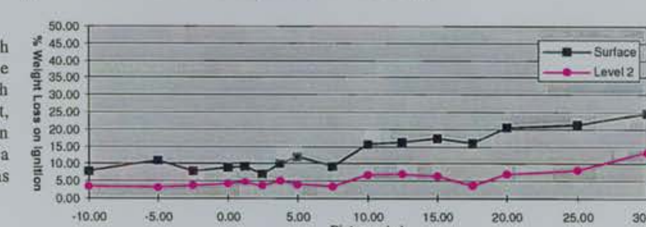


The soil columns shown above could be interpreted as providing a continuous range of values with depth. In fact the core data provides a single value averaged for each horizon, (or sub-sample in the case of exceptionally deep horizons), with each horizon abutting onto the next. In the case of the soil types, the maximum number of sampled points in any one column is eight.



Data from each cored column can be combined to show the variations with depth along the transect as a whole. The second diagram, similar to a "fence panel" used in geology, shows the simplest method of representing such data - drawing straight lines between the horizon boundaries at each known (cored) point. In this example, several mapped units have been combined (notably the five different types of clay shown in the figure above) to reduce the number of mapped classes, aiding interpretation. Equally, some layer boundaries have been assumed or inferred - these may arise from differences in the core descriptions (e.g. whether to record a section as a single organic-clay mix, or an organic layer with a clay layer below). Such decisions serve to highlight the subjective nature of these diagrams. It should also be noted that the position of the bottom of the lowest unit at each cored point is dictated by the core length there, and does not mark the lower limit of the soil. It is thought at all these sites that the clay unit continues further.

For data sets with values at only a single or a few depths at each sampling point, patterns in the data can be illustrated in a simple line graph, as shown.



5.4.1 Two dataset comparative statistics

Dividing the datasets into two according to their vegetative cover (such as field soil pH values into those from either forest or cleared locations) seems a simple method for investigating any differences in such a variable resulting from the process of forest clearance and drainage. Although finding a statistical difference is not sufficient ground to infer causality, it may be used as evidence to test a set of *a priori* hypotheses.

Grouping the data into two gives the crudest test, allowing the comparison of a representative measure of forest soil values against a similar measure of cleared soil values. Whilst this gives no real indication of the spatial pattern (the 3D distribution) or the scale and direction over which any processes act, as an indicator of difference, such testing can show whether further more complex transect and geostatistical analyses are warranted.

Two standard statistical tests suitable for comparing individual pairs of datasets are the Mann-Whitney U test and analysis of variance (ANOVA). The following discussion of their requirements draws from Ebdon (1985).

The Mann-Whitney U test

This is a non-parametric test, i.e. it does not assume randomly distributed, independent data. It uses ordinal (ranked) data. It carries out a test of the null hypothesis that the two samples are taken from a common population. If this is true, there should be no consistent difference between the two sets of values, and any observed differences will be within the range expected from chance in the sampling process. A full explanation of the statistical methods employed is given in appendix three.

Analysis of variance

This is a parametric test, assuming that the data sets are from normally distributed population(s). It considers the difference between two sample sets with data measured on the interval scale. It tests the null hypothesis that the two sets of data are random samples from a common, normally distributed population, or two identical, normally distributed populations, by comparing the value of the two sample variances. There are several variants of this test, the choice of which depends upon the expected relationships between the datasets. The form employed in these comparative tests is "one-way analysis of variance". This test yields the same result as another common statistical test: student's *t*-test.

Summary

The two tests are summarised in Table 5.9 below:

Table 5.9 Comparative statistical tests used in this research

	Type	Distribution	Measurements	1 or 2 tailed
Mann-Whitney U	non-parametric	no requirements	ordinal	both possible
One-way ANOVA	parametric	normality assumed	interval	both possible

Both tests are widely used in geographical research for comparative purposes. Whilst one-way analysis of variance test may seem more attractive, being able to use data on the interval scale of measurement, (that used in the majority of field and laboratory measurements: pH, ion concentrations, etc.) and thus is inclined to be a more powerful test, it is unlikely that the data will meet its stringent requirements for normality. (Normality can be tested for in a data set using tests which measures the goodness of fit between the test dataset and a specified theoretical distribution).

Environmental data are likely to fail a normality test for two reasons - skew and multimodality. Data are often positively skewed due to the presence of a few extremely high values, creating a long trailing tail in a frequency histogram. They may not be unimodal - rather than being spread across the entire range with a single mode, data points could be concentrated around a few "preferred states" each creating a local modal value, e.g. redox values may be concentrated around a few values which indicate the dominant reducing ion source in this area. If sulphates are being reduced to sulphides the redox will be between -150 and -180 mV (NHE[7]); if ferric iron is reduced to ferrous iron, the redox will be between +100 and +150 mV (NHE), whilst if the dominant change is from manganic to manganous, the redox is likely to be around +220 to +270 mV (NHE). Thus a frequency histogram of redox data may show several modal values, each one centred around a critical level where one ion is reduced to another.

If the data are skewed, but unimodal, it is possible that transforming the data mathematically (e.g. $x \rightarrow x^2$, $x \rightarrow \sqrt{x}$, $x \rightarrow \log x$, etc.) may modify the distribution sufficiently that it meets the normality assumptions. The efficiency of such transformations is discussed in a following section. Whilst allowing the use of parametric tests, such a transformation may make interpreting these results and future analyses, e.g. three dimensional mapping or studies of co-variance, more difficult to interpret or validate using new (untransformed) data.

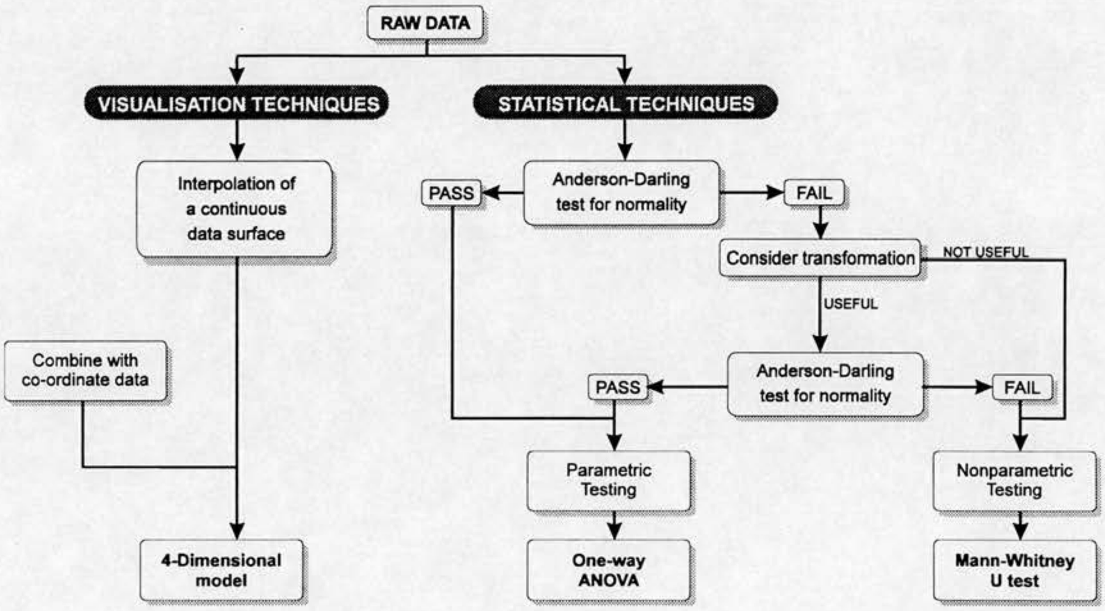
The non-parametric Mann-Whitney U test, which does not require normally distributed data, may prove more suitable. It has the added bonus that it maximises the number of datasets which can be used - ordinal measurements (e.g. root abundancy) plus all the interval data (which can be converted to rankings).

[7] Redox potential values are given in millivolts normal to the standard hydrogen electrode (NHE).

Both methods allow for either one or two-tailed testing. Two-tailed tests will reject the null hypothesis of no difference if the two datasets are significantly different, regardless of how the two datasets differ, effectively ignoring which dataset it is that has the greater variance or rank total. One-tailed tests are theoretically more rigorous, rejecting the null hypothesis only if two conditions are satisfied: the significant difference in the value of the variances or rank totals as before, plus a second test which predicts which dataset will yield the greater test statistic. Whilst initially more appealing, one-tailed tests suffer from the mathematical contradiction that rejection of the null hypothesis is actually easier (the value of their critical test statistic is always lower or equal to that for a similar two-tailed test). This has led to questioning of their validity, such as that voiced by Lieberman (1971) and so only two-tailed tests will be used in this analysis.

In summary, Figure 5.15 shows how comparative analysis of the datasets should proceed, (in an attempt to highlight differences between values measured in the cleared and forest areas), and how this statistical analysis compliments the earlier visualisation techniques.

Figure 5.15 Choice of comparative statistical tests



5.4.2 Aggregate comparative statistics

The comparative statistical approach discussed above, attempts to highlight differences in the soil and water properties between sites in cleared and forested areas by examining each measured property in turn (e.g. field soil pH) and testing to see whether there is a significant difference between values from the cleared area, when compared with those from the forest. This results in a series of individual refutations or corroborations of *a priori* theories concerning differences in the value of the selected variable in cleared and forest areas. To attempt to answer the wider question whether the forest and cleared areas differ significantly *overall*, rather than looking at the measured properties individually it may be illuminating to view them together. One method of doing this is to use a two-stage ordination analysis. Firstly, detrended correspondence analysis (DCA) techniques can be applied to the data. These try to separate the individual sampling locations, by generating a suitable suite of demarcation criteria using only the environmental measurements at the site. The results of such a classification can be compared with the vegetation zoning developed in the field. Secondly, a direct gradient method, canonical correspondence analysis (CCA) can be applied to both the vegetation and environmental data, in an attempt to identify environmental gradients which result in changes in the vegetation cover. The examination of the combinations, and contributions of the significant environmental properties from this analysis will allow key areas of difference to be inferred. The computer program CANOCO (ter Braak, 1987-92) will be used to carry out the ordination. These techniques are explained more fully in chapter seven and an explanation of the assumptions underlying these techniques can be found in appendix three.

If all the measured soil and water properties act independently of each other and are uncorrelated, then such an analysis should merely repeat the findings of the individual comparative tests carried out above. Such a situation however is unlikely, and an indication of the way in which the variables combine or counteract may be obtained through this second method, canonical correspondence analysis.

5.4.3 Measuring the spatial dependence

Spatial patterns in data imply that there is an underlying causal spatial process (such as point diffusion, or a distance-decay effect). Whether such a pattern is actually detected is dependent upon the sampling interval used. If the sampling interval is greater than the degree of spatial autocorrelation (which can be thought of as being akin to a point's "sphere of influence" then each measured data point is spatially independent from the others and thus no spatial pattern should result.

Spatial patterns reveal dependence, or spatial autocorrelation in the data - where a point's value is influenced by the values of points nearby. It is highly significant in studies of spatial processes. For different measured soil properties, both the nature of this relationship and the limits to the spatial range of the autocorrelation differ. Recent advances in geostatistical theory, (also known as regionalized variable theory) drawing largely from the work of Matheron (1965, 1969, 1971) and Krige (1966) allow the spatial autocorrelation to be measured using a device known as a semivariogram. The semivariogram displays the way the average semivariance between two sample points, changes with the sample spacing.

Advantages of semivariogram analysis

Calculation of semivariograms for each variable measured provides two benefits. It offers a precise method of interpolation of point data to be carried out (discussed in Section 5.3.3 above) and allows the validity of the sampling interval to be tested. The sill of the semivariogram reveals the maximum distance over which a variable exerts influence on the value of surrounding points. It follows that points which are further apart than this distance, with no intervening data points, are therefore unaffected by one another's values. Such points are said to be spatially independent. Sampling work is only useful if it measures spatially dependent variables, ones which can be used to produce an interpolated continuum of values. Thus we can use the semivariogram to check that the sampling interval for our given variable was suitably small (that is, the variable was measured at distances less than the semivariogram sill) and the resulting maps and interpolations are valid.

5.5 Conclusion

This chapter has explained the sampling strategies used in the research. Partially cleared mangrove sites were chosen as suitable locations for fieldwork, allowing the comparison of properties measured in cleared and remaining mangrove forest areas, without the need for new forest clearance. Sites have been selected which are at different stages in the clearance process, to allow the construction of a time-series of data.

Fieldwork programme

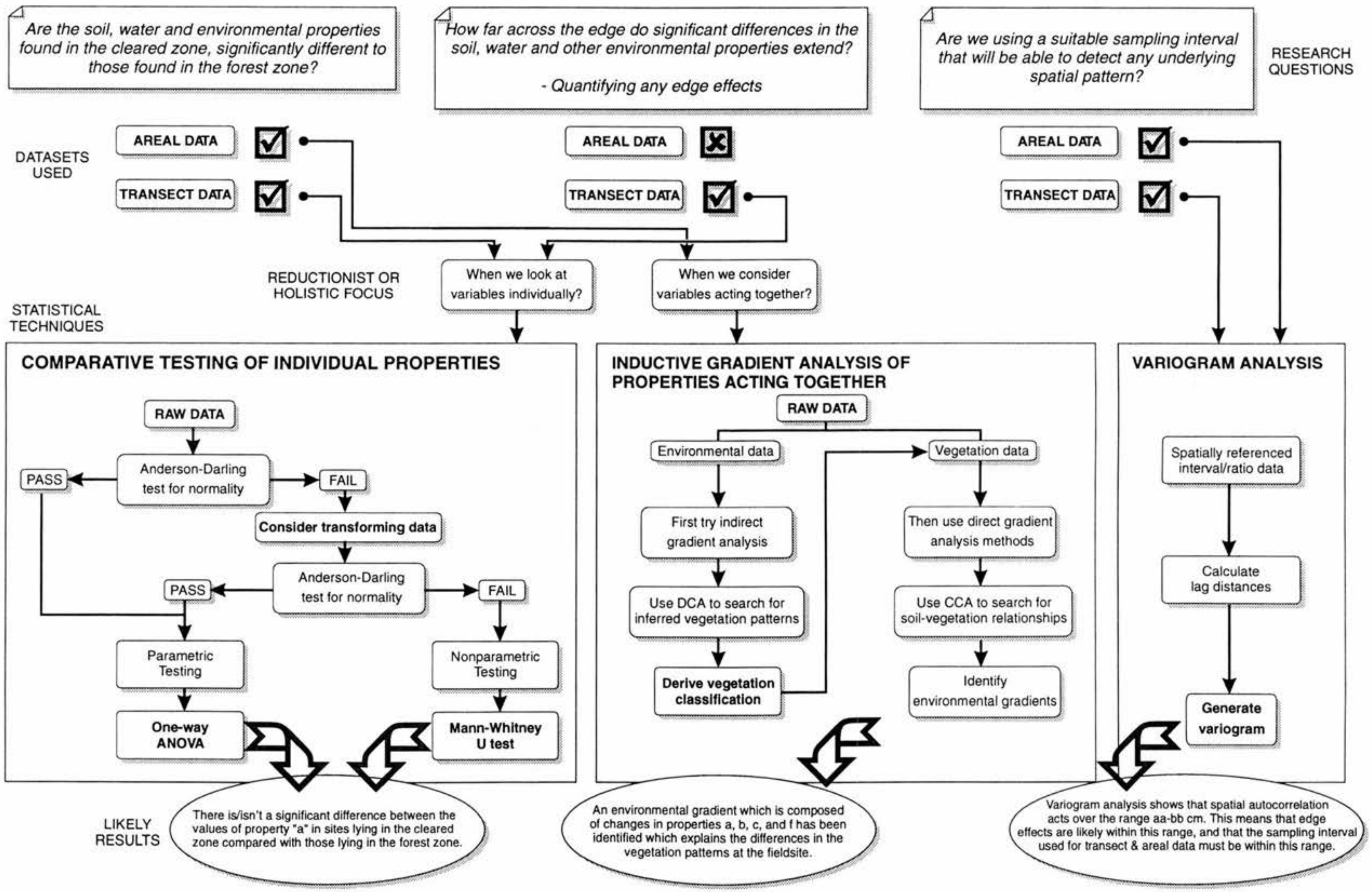
Fieldwork has been divided into two thrusts. The work in 1992 focuses on a single site - the "Burnt" site on the Western Highway, and concerns itself primarily with comparing the cleared and forested areas. Two sampling approaches are used, a large areal plot, to show spatial differences in three dimensions, and a series of three parallel linear transects (with a locational bias favouring points in the forest), designed to quantify the degree of penetration of change. For areal sampling, the site is divided into three zones: forest, cleared and a middle, transition zone. This overcomes problems in defining the forest edge. The 1994 fieldwork continues the transect approach, expanding the number of sites considered, to allow conclusions to be made about the representativeness of the findings of the earlier work.

Statistical testing

Many of the differences in the measured soil, water and environmental properties can be shown statistically. The Mann-Whitney U test and one-way analysis of variance have been selected as suitable tests for comparing the values of measured properties individually, in different areas. Gradient analysis techniques have been shown to be useful inferential tools to illuminate the processes responsible for differences between forest and cleared areas, showing graphically how the measured variables act together. Semivariogram analysis allows the measurement of spatial autocorrelation, providing an objective method for evaluating the sampling interval used. Figure 5.16 shows how these different statistical techniques are combined in this work.

The application of these techniques allows the testing of the research hypotheses. The testing of the datasets of mangrove soil, water and other environmental measurements, are now discussed in the remaining chapters.

Figure 5.16 Combining the statistical techniques



6

Searching for a difference

Changes resulting from clearance

Following clearance of mangrove forest, a pattern of changes in the values of certain soil, water and other environmental variables has been predicted from the discussion in chapters two and three. Some of these changes are immediately obvious, for example the increase in ground level insolation following the loss of forest cover and require little further corroboration. Others, such as changes in the concentration of nutrients dissolved in the groundwater are more subtle. The spatial pattern of change in such variables needs to be teased out through careful analysis. To test the predictions and quantify the direction and magnitude of such changes, a range of visualisation and statistical analysis techniques are employed to present the results.

In this chapter, the analysis focuses primarily on the first research hypothesis, individually comparing the values of a range of variables from forest and cleared sites, to highlight both similarities and differences. Having identified any such differences at a number of sites, the argument then considers the value of identifying a transition zone: the third unit used in descriptions of the field areas.

Both of these two reductionist research avenues seek to highlight which variables are changed (and in turn themselves change the environment) following forest clearance. The *combined* interactions of these variables are then considered in the ordination chapter which follows, and the question of whether such changes can be considered as an edge effect forms the focus for later discussion, using the transect data gathered in the field.

6.1 Visual comparisons of the results

A complete list of all the results from laboratory and field measurements is given in appendix four. One of the simplest methods of comparing the values of these measured properties to establish whether they differ between the forest and cleared zones, is to map the data creating a shaded contour map of the output (as detailed earlier in Figure 5.14). This allows a rapid visual assessment of the distribution of the measured property over space. Figure 6.1 shows the results of such 4-dimensional modelling of the data gathered in the 1992 fieldwork. The resulting patterns of the measured variables are discussed below.

6.1.1 Layer thickness

This is the thickness of the organic layer when measured as "layer 1" and a mixed organic and clay layer in "layer 2". Of these, the former is easier to define in the field, and thus relates more closely to a real, (uniform) phenomenon. Interpretation of the second layer data must, therefore, be made more cautiously. The visualisation given in Figure 6.1a shows a notable thickness in the organic horizon in samples found along the transition zone and also in some near the edge, within the forest. The shallowest layers are found in the cleared zone but overall, there is not a striking difference between values in the forest and cleared zones. This accords with the expected clearance process - manual felling should result in only minimal loss of topsoil. The increased thickness of soils around the cut edge may reflect the deposition of wind and water transported material, predominantly from the cleared zone. This material is deposited along the cut edge because of the velocity damping effect of the forest trees and the carpet of pneumatophores.

6.1.2 Mean layer depth

The mean depth values shown in Figure 6.1b are measured relative to the observed water level which remained constant throughout the 1992 field period. Values reflect a combination of two other properties: the elevation of the ground surface and half[1] the thickness of the layer. This accounts for the similarity between the thickness and the mean depth diagrams for the first layer. The second mean depth figure shows a far greater range than the layer two thickness diagram. This is because it has a greater potential for variation - this value is a combination of surface elevation, the total thickness of layer 1 plus half the thickness of layer 2. Together, the thickness and mean depth figures show that whilst the thickness of the lower layer (2) remains relatively uniform across the field site, the height at which this layer is found varies according to the local relief. This correspondence with the local topography suggests that either the soil horizon development is contemporary or the factors responsible for pedogenesis in this area have remained fairly constant over recent time.

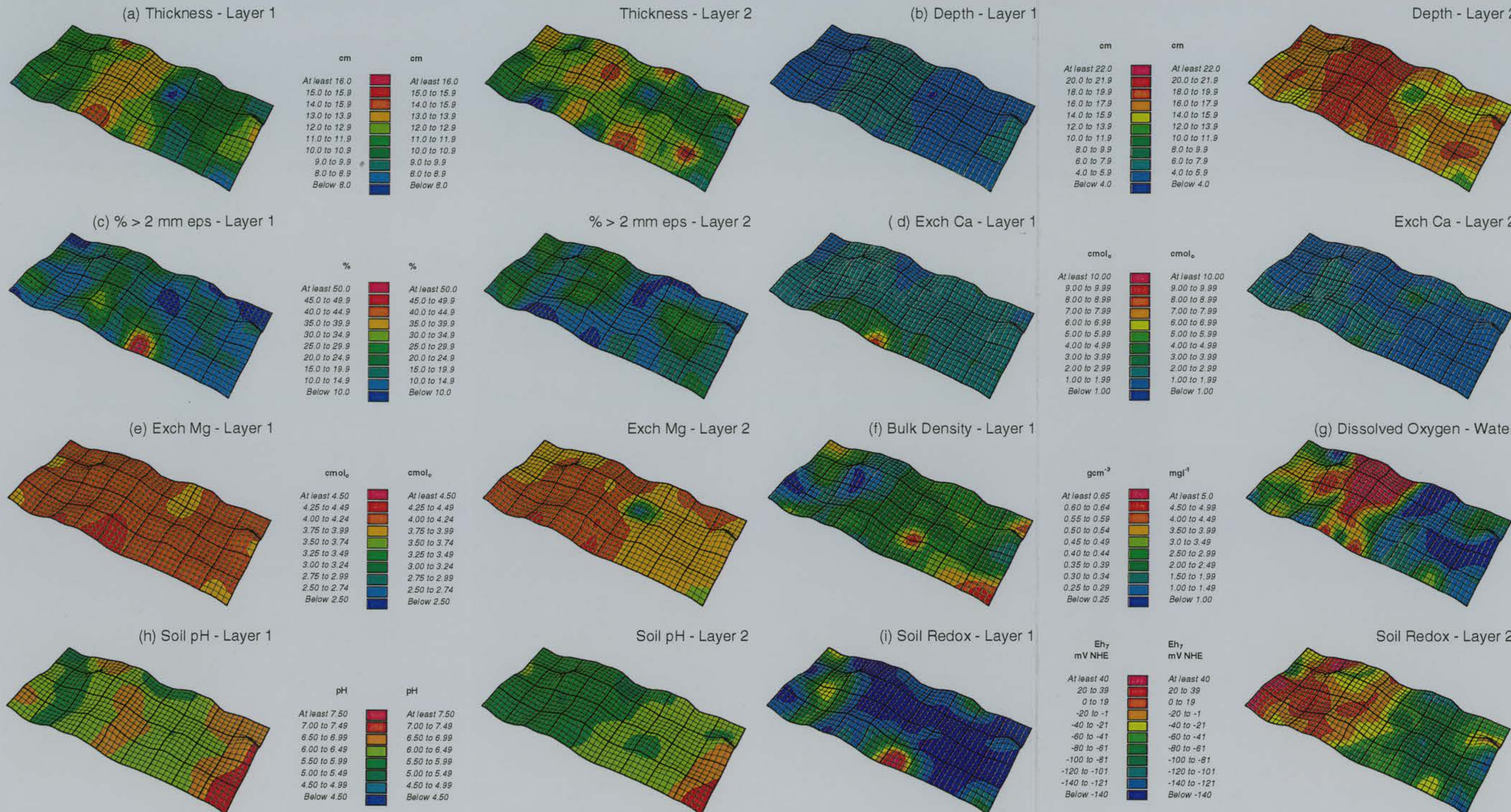
6.1.3 Soil particle size distribution: percent greater than 2 mm e.p.s.

The percentage of the soil found to be greater than 2 mm e.p.s. (sand) is shown in Figure 6.1c. The percentage of silt and clay is merely the complement of this and so is not shown. The sand fraction appears to be fairly evenly distributed across the field site, consistent with the view of minimal soil disturbance during clearance. There is one zone with high sand values, whose red colouring shows that in places the sand content is around 50%.

[1] "Half" because this provides a measure of the mean layer thickness, effectively the depth at which we find the centre of this layer.

Figure 6.1 - Burnt site 1992 4-Dimensional modelling: Soil and water variables draped over a 3-D representation of the field site topography

This series of diagrams shows views of the 1992 Burnt fieldsite, with a simulated 3D perspective created by rotating the site horizontally by 60° and elevating it at an angle of 30° from the horizontal. Looking at the site along the long axis of the surface rectangle, the three zones used in sampling are from left to right: Forest, Transition Zone and Cleared. Each cell of the fine black grid represents a square with sides of 2m. The coarse black grid is of a 10m interval. The distortion of these grids reflects the topography of the area (shown using a 20X vertical exaggeration, to highlight micro-relief). The colouring of the surface displays the value of the variable measured. The continuous coloured surface has been interpolated mathematically from the point data gathered in the field, using a bilinear interpolation algorithm. A full interpretation of these diagrams can be found in the accompanying text.



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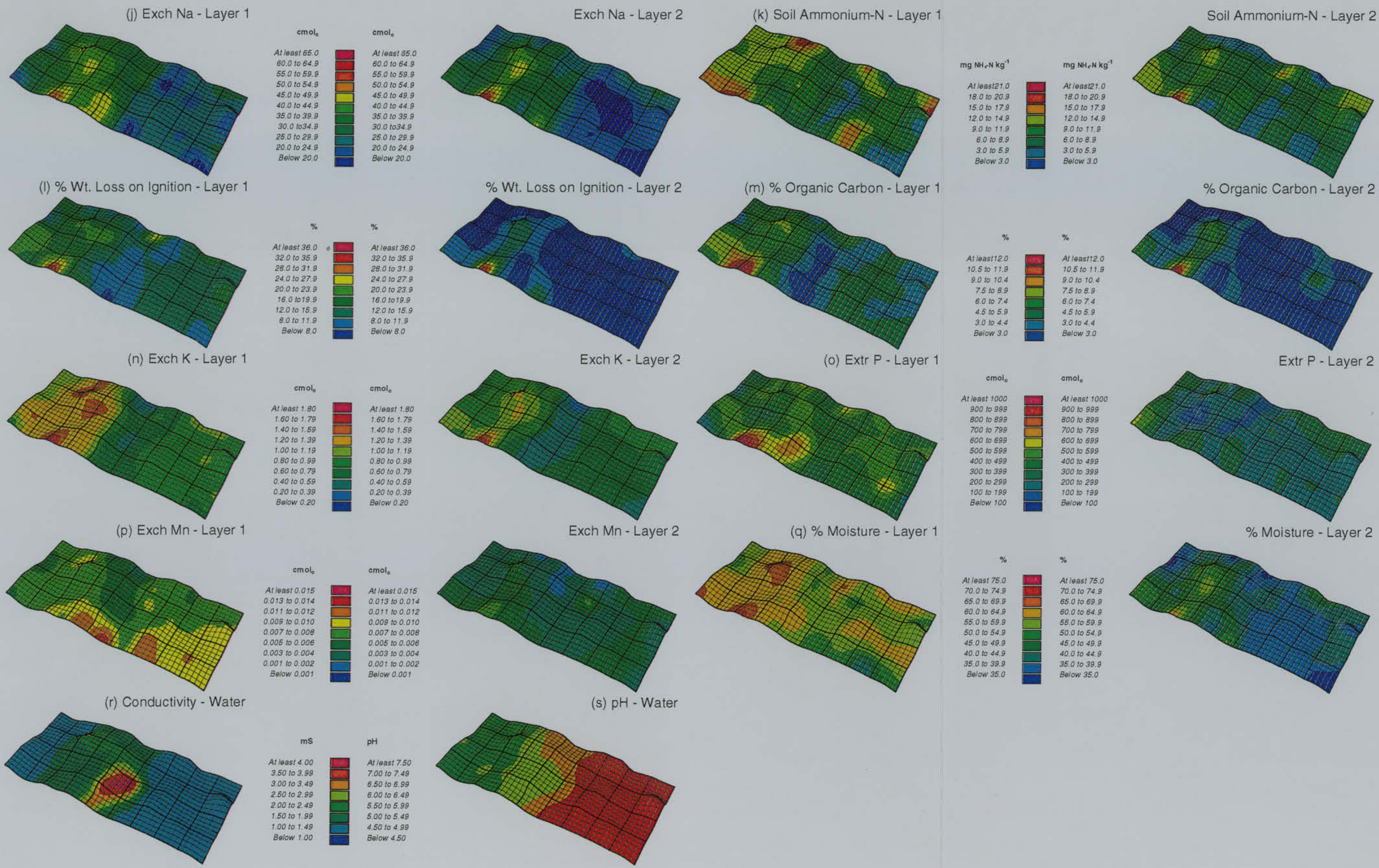


(j) Exch Na - Layer 1
cmol$_c$
At least 65.0
60.0 to 64.9
55.0 to 59.9
50.0 to 54.9
45.0 to 49.9
40.0 to 44.9
35.0 to 39.9
30.0 to34.9
25.0 to 29.9
20.0 to 24.9
Below 20.0
cmol$_c$
At least 65.0
60.0 to 64.9
55.0 to 59.9
50.0 to 54.9
45.0 to 49.9
40.0 to 44.9
35.0 to 39.9
30.0 to34.9
25.0 to 29.9
20.0 to 24.9
Below 20.0
Exch Na - Layer 2
(k) Soil Ammonium-N - Layer 1
mg NH_4-N kg^{-1}
At least21.0
18.0 to 20.9
15.0 to 17.9
12.0 to 14.9
9.0 to 11.9
6.0 to 8.9
3.0 to 5.9
Below 3.0
mg NH_4-N kg^{-1}
At least21.0
18.0 to 20.9
15.0 to 17.9
12.0 to 14.9
9.0 to 11.9
6.0 to 8.9
3.0 to 5.9
Below 3.0
Soil Ammonium-N - Layer 2
(l) % Wt. Loss on Ignition - Layer 1
%
At least 36.0
32.0 to 35.9
28.0 to 31.9
24.0 to 27.9
20.0 to 23.9
16.0 to19.9
12.0 to 15.9
8.0 to 11.9
Below 8.0
%
At least 36.0
32.0 to 35.9
28.0 to 31.9
24.0 to 27.9
20.0 to 23.9
16.0 to19.9
12.0 to 15.9
8.0 to 11.9
Below 8.0
% Wt. Loss on Ignition - Layer 2
(m) % Organic Carbon - Layer 1
%
At least12.0
10.5 to 11.9
9.0 to 10.4
7.5 to 8.9
6.0 to 7.4
4.5 to 5.9
3.0 to 4.4
Below 3.0
%
At least12.0
10.5 to 11.9
9.0 to 10.4
7.5 to 8.9
6.0 to 7.4
4.5 to 5.9
3.0 to 4.4
Below 3.0
% Organic Carbon - Layer 2
(n) Exch K - Layer 1
cmol$_c$
At least 1.80
1.60 to 1.79
1.40 to 1.59
1.20 to 1.39
1.00 to 1.19
0.80 to 0.99
0.60 to 0.79
0.40 to 0.59
0.20 to 0.39
Below 0.20
cmol$_c$
At least 1.80
1.60 to 1.79
1.40 to 1.59
1.20 to 1.39
1.00 to 1.19
0.80 to 0.99
0.60 to 0.79
0.40 to 0.59
0.20 to 0.39
Below 0.20
Exch K - Layer 2
(o) Extr P - Layer 1
cmol$_c$
At least 1000
900 to 999
800 to 899
700 to 799
600 to 699
500 to 599
400 to 499
300 to 399
200 to 299
100 to 199
Below 100
cmol$_c$
At least 1000
900 to 999
800 to 899
700 to 799
600 to 699
500 to 599
400 to 499
300 to 399
200 to 299
100 to 199
Below 100
Extr P - Layer 2
(p) Exch Mn - Layer 1
cmol$_c$
At least 0.015
0.013 to 0.014
0.011 to 0.012
0.009 to 0.010
0.007 to 0.008
0.005 to 0.006
0.003 to 0.004
0.001 to 0.002
Below 0.001
cmol$_c$
At least 0.015
0.013 to 0.014
0.011 to 0.012
0.009 to 0.010
0.007 to 0.008
0.005 to 0.006
0.003 to 0.004
0.001 to 0.002
Below 0.001
Exch Mn - Layer 2
(q) % Moisture - Layer 1
%
At least 75.0
70.0 to 74.9
65.0 to 69.9
60.0 to 64.9
55.0 to 59.9
50.0 to 54.9
45.0 to 49.9
40.0 to 44.9
35.0 to 39.9
Below 35.0
%
At least 75.0
70.0 to 74.9
65.0 to 69.9
60.0 to 64.9
55.0 to 59.9
50.0 to 54.9
45.0 to 49.9
40.0 to 44.9
35.0 to 39.9
Below 35.0
% Moisture - Layer 2
(r) Conductivity - Water
mS
At least 4.00
3.50 to 3.99
3.00 to 3.49
2.50 to 2.99
2.00 to 2.49
1.50 to 1.99
1.00 to 1.49
Below 1.00
pH
At least 7.50
7.00 to 7.49
6.50 to 6.99
6.00 to 6.49
5.50 to 5.99
5.00 to 5.49
4.50 to 4.99
Below 4.50
(s) pH - Water

Opens out →

This corresponds with an unvegetated, locally scoured area. Perhaps this has resulted in the removal of a greater proportion of the fine sediment fraction than the surrounding area, because of a localised root mat loss. Compared with layer 1, the sand content of layer 2 shows a marked drop, which confirms the field observations: a far higher clay and silt content in this lower layer.

6.1.4 Soil exchangeable calcium

Figure 6.1d shows that the level of exchangeable calcium in the upper soil layer is generally consistent across the field site, with values around 2 $cmol_c$. However, similar to the particle size pattern above, in the scoured region of layer 1 there is a definite peak in calcium levels, reaching values approximately three times that of surrounding sites. It is possible that this peak highlights an area of extreme calcium concentration, perhaps from shells dropped by birds, or ash concentration following burning. Alternatively, given the observed scouring in this region, this may be simply a proportional effect. The sample obtained at this site may have had a very low organic content, with more of the mineral fraction yielding a higher total sample calcium concentration.

Calcium levels in layer 2 are generally slightly lower, and the peak seen in layer 1 does not continue into layer 2. This confirms the view of this localised region of extreme values as the result of surface-based effects. A weak calcium gradient can be detected running across the field site, parallel to the cut edge. This gradient shows that calcium levels increase inland, confirming the earlier view that the major source of exchangeable calcium input in the mangroves at this field site is from inland alluvial deposits rather than marine (carbonate) sources.

6.1.5 Soil exchangeable magnesium

Layer 1 magnesium values show a consistent distribution, with typical values around 4 $cmol_c$. Magnesium levels in the lower, layer 2 samples show a slight difference, with samples measured in the forest having higher exchangeable magnesium levels than sites in the cleared area. A similar trend is seen in the potassium data. In studies in tropical montane forests, Clements & Colon (1975) found that significant quantities of both these nutrients were leached from above ground vegetation by rainfall and stemflow. They found that this contributed up to 80% of the total magnesium and potassium returned to the soil by plants, making it more significant than litter input. The high soil values of magnesium and potassium in the forest samples of Figure 6.1e are thought to show that this process is occurring in the mangroves. The accumulation of these soluble cations at depth corroborates the hypothesis that these greater values are the result of vertical dislocation.

There is also a region particularly deficient in magnesium, located 5-10 m from the cut edge. This does not correspond with any obvious surface feature and is thought to be just an area which has a lower magnesium content. Perhaps it corresponds to an opening in the original forest cover at this point.

6.1.6 Soil bulk density

Measurements of soil bulk density were only made for the upper layer. Figure 6.1f shows that over the field site as a whole, bulk density values tend to be in the range 3.5 to 4.0 gcm^{-3}. Small localised regions of much higher bulk density occur in the cleared zone, which may have been compacted during the clearance process. The most compacted regions at the extreme edge of the cleared zone lie near areas where fallen timber was collected into piles for burning, and thus can be expected to have received a greater trampling. Scattered areas of low bulk density values lie in the forest, these may be samples with a large organic content, or areas with intensive crab burrowing and litter turnover.

6.1.7 Water dissolved oxygen content

The amount of dissolved oxygen measured in water from the cleared zone (shown in Figure 6.1g) is generally lower than that found in the forest. This is consistent with the stagnant, reducing conditions found in the cleared zone, exaggerated by the greater volume of dead and decaying material here as a result of clearance. The higher values in the forest may reflect the presence of animal burrows, the photosynthesising activity of algae on mangrove pneumatophores and prop roots, or the physical disturbance that these vegetative projections cause to water flow, helping to aerate the forest waters. The highest values are found near the cut edge of the forest, particularly at sites closest to the coast. This corresponds well with the area which experiences the greatest water movement by offshore winds, waves and impact against the first area rich in aerial plant roots and stems, leading to a higher increased dissolved oxygen content.

6.1.8 Soil pH

Layer 1 soil pH measurements, shown in Figure 6.1h, tend to have a value just below neutral, around pH 6. Whilst not explaining all the pH variation across the field site, there is a discernible pH gradient, seen most clearly at the edges of the field site. Forest values tend to be more acidic, cleared areas more neutral. This may reflect differences in bacterial decomposition activity, redox potential (which at high values could decrease pH by favouring sulphate over sulphide species) and surface soil ammonification. This gradient is even more pronounced in layer 2, with samples in general slightly more acidic. The pattern of greater acidity with depth supports the idea that soil ammonium may be acting to neutralise natural soil acidity. Ammonification is restricted to anaerobic regions which in the mangrove forest soils are most likely below the soil surface, (see the following discussion of soil redox distribution), explaining the lower pH measurements in layer 2. The forest-cleared differences may be the result of plant ammonium-uptake in the forest maintaining soil acidity.

6.1.9 Soil redox

Figure 6.1i shows redox potential values across the field site to be low (negative) reflecting the anaerobic, reducing conditions present. Looking at the values for layer 1 (close to, but not measured at the soil surface), there are two noticeable regions of high values, indicating more oxidising conditions.

One of these is in the middle of the forest, the other is at the edge of the cleared zone. Higher redox potential values in the forest may be the result of animal burrows or the oxygen translocation activity of mangrove roots. The higher value in the cleared zone is more difficult to explain. It lies in a slightly depressed, scoured region and might show more oxidising conditions because of the close proximity of a crab burrow, or live roots from a coppicing *Avicennia* stump.

Looking at layer 2 a marked difference between forest and cleared values is immediately apparent, with sites in the forest having much higher values (more oxidising conditions) than those in the cleared zone. This reflects the presence of many pneumatophores and *Rhizophora* prop root termini in the soil at this depth, each of which create locally oxidised spheres around them through oxygen export. In the cleared zone, the gas translocation of the roots has ceased following forest clearance, resulting in a return to more uniform, reducing soil conditions.

6.1.10 Soil exchangeable sodium

The distribution of exchangeable sodium values in Figure 6.1j shows a marked difference between samples measured in the forest and samples measured in the cleared zone. For both soil layers, exchangeable sodium levels tend to be higher in the forest. This increase in the level of this highly soluble cation may reflect differences in nutrient input, or the number of potential cation sites and the cations occupying the exchange sites in the soil. With its higher organic content, the soils in the forest will have a higher cation exchange capacity than the clay-rich soils of the cleared zone. The large surface area of the forest canopy will act as a more effective interceptor of precipitation and sea spray inputs than the flat, cleared zone. The actions of mangrove trees to exclude and excrete salts will also act to concentrate sodium levels in the soils and in senescent leaves.

6.1.11 Soil ammonium-N

It is difficult to infer any trends from the soil ammonium-N data shown in Figure 6.1k. Values appear very localised, with many small clusters of similar values. It is tempting to argue that there may be a weak pattern showing higher values of ammonium-N across the forest, most clearly seen in the layer 1 data. The difference in forest ammonium-N levels agrees with the pattern which can be inferred from the soil redox potential data. Ammonium-N levels should be greatest in layer 1, as layer 2 samples are approaching redox values high enough to favour nitrification, which would result in a net decrease in ammonium-N. The lower levels of ammonium-N in the cleared soils may be indicative of a lower organic-N content in the cleared zone. However, because of the weakness of the observed patterns their interpretation require further support, using statistical methods.

6.1.12 Soil weight loss on ignition

Sample weight loss on ignition is the result of rapid oxidation of organic and carbonate materials in the sample. It is often used as a crude indicator of organic content. The pattern of weight loss differences in layer 1 seen in Figure 6.1l shows higher values in the forest and low values in the cleared zone. This is the pattern that is predicted in a site of this age, the low organic content of the cleared zone samples reflecting the long absence of litter input. The pattern is maintained, but less distinct in layer 2 which is also as expected, given its more heterogeneous nature and the generally lower organic content of this layer.

6.1.13 Soil organic carbon content

Organic carbon levels, given in Figure 6.1m, closely follow the pattern of soil weight loss on ignition discussed above. This reflects the fact that much of the material lost in the combustion process is composed of organic carbon. The slight trough in organic carbon levels in the centre of the field site is of interest, in that it supports the concept of a transition zone, with a range of values distinct from those in the cleared or forest zone. This loss of organic material around the cut forest edge may be the result of greater water movement in this region.

6.1.14 Soil exchangeable potassium

Across both layers, Figure 6.1n shows that soil exchangeable potassium levels tend to be higher in the forest and lower in the cleared zone. This pattern is most marked in soil layer 1, where the highest soil potassium levels are found. The pattern of soil potassium values is consistent with that of forest cover, suggesting that litter, or the stemflow discussed in Section 6.1.5, are the major sources of potassium for the soil. There is also a marked deficit of potassium values along the cut edge of the forest. The "poverty" of soil potassium in this zone may be a combination of low inputs along the edge and a sustained potassium demand from the roots of nearby trees.

6.1.15 Soil extractable phosphorus

As expected from the many studies of mangrove soils which have reported a low soil phosphorus content and a high rate of phosphorus immobilisation, the measured values of soil extractable phosphorus seen in Figure 6.1o are low and show a very even distribution across all three zones. There is one region of local high values in the forest, readings here may have been affected by the proximity of crab burrows, offering an additional source of phosphorus, not yet immobilised in the soil. The general uniformity of phosphorus values across the site, particularly in the root zone (layer 2), suggests that soil phosphorus values have not really been affected by the clearance process.

6.1.16 Soil exchangeable manganese

Figure 6.1p shows that soil exchangeable manganese values are uniformly low across the field site. The measurements made in layer 1 show a pattern which results from only very small differences in value. This weak pattern shows manganese values to increase slightly inland, indicative of their terrestrial source.

6.1.17 Soil moisture content

Because the soil samples were collected at sites where the height of the water table was at or actually above the soil surface, interpretation of Figure 6.1q which shows the soil moisture content must be made with caution. Under saturated conditions, such a measure will reflect the soil's maximum ability to retain water. Highest values are found in the forest, lower in the cleared zone. This mirrors the distribution of organic matter seen above and it is thought that at this site, soil moisture content is highly correlated with organic content, as the organic material acts to retain water more strongly than the mineral fractions.

6.1.18 Water conductivity

Looking at the overall pattern of conductivity values given in Figure 6.1r, there is no obvious difference which would support a gradient aligned towards the shore. This implies that the marine influence is relatively uniform (uniformly low), across the site. Values are generally around 1.5 mS except for a peak of over 4.0 mS at the edge of the cut line with a possible diffusion effect into the forest behind. The conductivity distribution pattern, a centre of high values surrounded by uniformly low values suggests that some very localised pollution or some other form of contamination effect may have occurred.

6.1.19 Water pH

Water pH values in Figure 6.1s show a very marked zonation, which corresponds well to the cleared, transition and forest zone delineation of the field site. The highest water pH values occur in the cleared zone, similar to the trends observed in soil pH values. The neutral pH of cleared zone waters is thought to be the result of high dissolved ammonium levels. Water pH in the forest remains acidic, because here the ammonium is taken up by plants rather than dissolved in the mangrove waters.

Summary of the patterns seen in the visualisation procedures

Plotting the interpolated values of measured soil and water properties as a continuous surface, draped over a model of topography has proven to be a very simple yet successful way to reveal spatial patterns in the data. For models where the resulting pattern is clear, the figures allow an initial test to be made of the predicted changes in the value of the measured properties in sites following clearance.

Examples of such clear models with discernible differences between values measured in the forest and cleared zones are: water pH, exchangeable sodium, weight loss on ignition, and organic carbon content. Weaker patterns are found in soil pH, soil redox, bulk density, dissolved oxygen, moisture content, exchangeable magnesium, exchangeable potassium and exchangeable manganese. The sign of the differences between forest and cleared zone values are consistent with those predicted in chapter three. Other variables show a near uniform value across the field site, suggesting no discernible clearance effect. These variables are the percentage of soil greater than 2 mm, extractable phosphorus and exchangeable calcium levels.

With figures such as the water pH elevation model, where a predicted pattern is subsequently found, there is little doubt that a real spatial difference has been identified. A second and perhaps more critical question relates to the less clear-cut models such as soil extractable ammonium-N, whether these figures should be used to show that in reality there is no difference between values in the forest and cleared zones. The confusion stems from our inability to differentiate visually between two potential sources of "non-patterning": random data and the sampling interval used. If the variable being mapped shows no spatial autocorrelation then a true random non-pattern should result, with no obvious difference between values in the cleared and forest zones. The second and more difficult source reflects the fact that the spatial pattern of values revealed in every such diagram is also a function of the sampling interval used. Patterns which in reality operate at a scale far finer or far coarser than the field sampling interval may not be adequately revealed in these visual representations. McKee (1993) for example has shown that mangrove soil sulphide concentration varies over a scale of a few millimetres. Attempting to map soil sulphide concentrations using data points separated by a few metres would produce statistically independent sulphide values, rendering their mapping useless. Identifying the scale at which spatial processes operate has received considerable attention from researchers across the earth sciences (e.g. Burgess & Webster 1980; Matheron 1965,1971; Webster & Oliver 1990) and this question and its implications form the focus of a later chapter on semivariogram analysis.

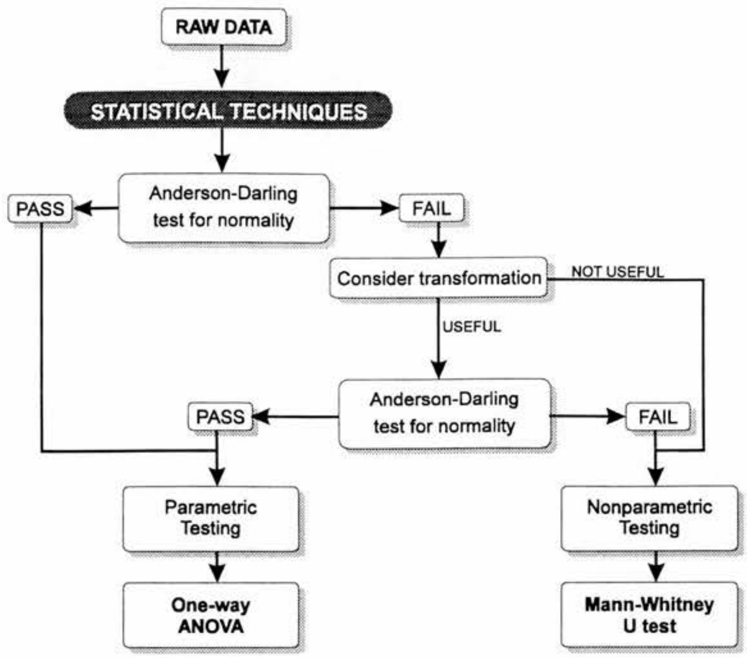
Consequently, the second stage of data investigation uses some of the more traditional methods of data investigation - statistical testing. Statistical methods will be used to quantify any differences between the cleared and forest zones. Such techniques provide a *more* objective method of interpretation than simply looking at the generated maps, though they are still not *truly* objective. The choice of which critical significance level to use is still subjective and the decisions are made based on probability criteria rather than any objective certainty. Despite these limitations, such methods are widely used as an acceptable, repeatable and understandable mechanism for determining the degree of similarity or difference between datasets. Because the resulting algebra can act to separate the user from the data, it is important to ensure that the methods employed are appropriate. Therefore, a discussion of suitable methods proceeds the presentation of the results of the statistical testing.

6.2 Statistical testing

Chapter five has given an outline of the chosen statistical testing rationale. Figure 6.2 shows the key role played by the initial normality tests in determining which comparative test should be used with the data. In order to establish the sensitivity of available normality testing procedures, three possible tests are considered in Section 6.3.1. The wider significance of such a testing logic is addressed in Section

6.4.1, asking whether we should expect data to be normally distributed and discussing how dynamic processes and periods of relative stasis may influence the observed frequency distribution of variables. As well as providing sufficient criteria for test selection, a consideration of the sample's distribution can shed light on the process of change. Appendix 3 contains such an example, comparing measurements of soil ammonium levels in the cleared and forest zones to show how inter-zonal change can be revealed by differences in the sample distributions.

Figure 6.2 Comparative statistical testing procedure



Datasets initially failing normality tests are often mathematically transformed, to allow their later parametric analysis. Section 6.4.2 considers whether transformations are applicable to this piece of research. The results of the parametric and nonparametric tests and their interpretation - deciding which variables do or do not change and why, form Section 6.6.

6.3 The need for normality tests

Measured soil and water properties from the cleared, forest and transition zone must be individually tested for normality to determine which comparative statistical test is most suitable. As detailed in chapter five, variables found to be normally distributed across all three sampling zones can then be compared using the preferred, statistically powerful parametric methods. Those failing the normality tests must be compared using non-parametric methods. These are less powerful, tending not to reject a false null hypothesis as often as parametric tests (Boneau, 1960) because they do not make assumptions about the shape of the variable's distributions (Williams, 1986).

Many methods of normality testing exist, from a simple comparison of a variable's skew and kurtosis (Ebdon, 1985) to more sophisticated probabilistic methods. It is one of the latter techniques which will be used in this work.

6.3.1 Normality testing: the question of method

To investigate whether different statistical methods may yield conflicting decisions concerning the data's distribution function, three common tests of normality were compared, using data from the surface layer of the 1992 Burnt Site. The tests considered are the Kolmogorov-Smirnov test (using the less rigorous Lilliefors version, which does not assume a particular value for the sample mean or standard deviation[2], (SYSTAT Inc., 1993)) the Anderson-Darling test and the Ryan-Joiner test. The latter is very similar to the more common Shapiro-Wilks test (MINITAB Inc., 1993), often used for small sample sizes, (SAS Institute Inc., 1982). Full details of this testing can be found in Appendix 3. The text below contains extracts from the Appendix.

6.3.2 Interpretation: which test to use?

The testing reveals that there is generally remarkably little difference between the conclusions of the three tests. Many apparent minor differences in classification are the result of only very small differences in the reported probability values, which happen to lie either side of a classification boundary. This is particularly true for differences between the Kolmogorov-Smirnov and Anderson-Darling tests, the Ryan-Joiner test shows a slight tendency to retain spuriously the null hypothesis, claiming the data are normally distributed when it actually is not.

Further testing using mathematically generated data sets has shown that the Ryan-Joiner test does not differentiate clearly between binomial and normally distributed datasets. For this reason and the discrepancy noted above, it was not considered suitable for further use, reducing the choice of test to two: the Kolmogorov-Smirnov and the Anderson-Darling tests. Although the Kolmogorov-Smirnov test is more widely employed in geographical literature, for this work the Anderson-Darling test will be used, as it seems to be slightly more critical, rejecting the assumption of normality slightly more often than the other two tests.

6.4 Normality testing and data transformation

Table 6.1 below shows the results of Anderson-Darling normality tests applied to three datasets. The first two datasets give a mixture of water and soil properties measured from two different depths from the 1992 Burnt Site. The third dataset comprises both measured soil and water properties from the Punta del Este Site, collected in 1994. Comparing these results allows us to see whether measured variables have similarly shaped frequency distributions at different locations and at different depths.

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[2] Very rigorous tests of normality compare the distribution against a normal distribution with a mean of zero and a standard deviation of one. For the data given here to pass such a test, it is likely it would have to first undergo a statistical standardisation procedure, such as subtracting the mean from each individual value, then dividing the result by the standard deviation of the population.

The right hand column of Table 6.1 lists which comparative test should be used. If in each case, the variable distribution is found to be "normal" or "near normal" then a parametric test is chosen, indicated by the letter "P". However, if the variable is found to deviate significantly from a normal distribution, then a non-parametric testing routine is selected, shown in this column by the letters "N-P".

Table 6.1 Normality test results

Measured property	Zone	1992 Burnt Site - L1	1992 Burnt Site - L2	1994 Punta del Este - All	
z	Cleared	0.056 - NEAR NORMAL	0.128 - NORMAL	NOT SAMPLED	
	Forest	0.363 - NORMAL	0.140 - NORMAL	NOT SAMPLED	P
	Transition	0.175 - NORMAL	0.554 - NORMAL	NOT SAMPLED	
Layer Thickness	Cleared	0.277 - NORMAL	0.099 - NEAR NORMAL	0.000	
	Forest	0.325 - NORMAL	0.160 - NORMAL	0.006	N-P
	Transition	0.791 - NORMAL	0.040	0.414 - NORMAL	
Mean Layer Depth	Cleared	0.277 - NORMAL	0.026	0.000	
	Forest	0.325 - NORMAL	0.767 - NORMAL	0.006	N-P
	Transition	0.791 - NORMAL	0.104 - NORMAL	0.414 - NORMAL	
Bulk Density	Cleared	0.000	NOT SAMPLED	NOT SAMPLED	
	Forest	0.531 - NORMAL	NOT SAMPLED	NOT SAMPLED	N-P
	Transition	0.438 - NORMAL	NOT SAMPLED	NOT SAMPLED	
% Moisture w/w	Cleared	0.004	0.326 - NORMAL	NOT SAMPLED	
	Forest	0.368 - NORMAL	0.415 - NORMAL	NOT SAMPLED	N-P
	Transition	0.652 - NORMAL	0.336 - NORMAL	NOT SAMPLED	
% Dry Matter w/w	Cleared	0.004	0.326 - NORMAL	NOT SAMPLED	
	Forest	0.368 - NORMAL	0.415 - NORMAL	NOT SAMPLED	N-P
	Transition	0.652 - NORMAL	0.336 - NORMAL	NOT SAMPLED	
% > 2 mm	Cleared	0.000	0.204 - NORMAL	NOT SAMPLED	
	Forest	0.000	0.453 - NORMAL	NOT SAMPLED	N-P
	Transition	0.442 - NORMAL	0.425 - NORMAL	NOT SAMPLED	
% < 2 mm	Cleared	0.000	0.204 - NORMAL	NOT SAMPLED	
	Forest	0.000	0.453 - NORMAL	NOT SAMPLED	N-P
	Transition	0.442 - NORMAL	0.425 - NORMAL	NOT SAMPLED	
% Wt. Loss on Ignition	Cleared	0.407 - NORMAL	0.186 - NORMAL	NOT SAMPLED	
	Forest	0.065 - NEAR NORMAL	0.000	NOT SAMPLED	N-P
	Transition	0.011	0.002	NOT SAMPLED	
% Organic C	Cleared	0.407 - NORMAL	0.000	NOT SAMPLED	
	Forest	0.017	0.000	NOT SAMPLED	N-P
	Transition	0.695 - NORMAL	0.236 - NORMAL	NOT SAMPLED	
Surface Soil pH	Cleared	NOT SAMPLED	NOT SAMPLED	0.086 - NEAR NORMAL	
	Forest	NOT SAMPLED	NOT SAMPLED	0.002	N-P
	Transition	NOT SAMPLED	NOT SAMPLED	1.000 - NORMAL	
Layer 1 Soil pH	Cleared	0.515 - NORMAL	NOT SAMPLED	0.002	
	Forest	0.001	NOT SAMPLED	0.002	N-P
	Transition	0.183 - NORMAL	NOT SAMPLED	1.000 - NORMAL	
Layer 2 Soil pH	Cleared	NOT SAMPLED	0.007	0.001	
	Forest	NOT SAMPLED	0.228 - NORMAL	0.046	N-P
	Transition	NOT SAMPLED	0.254 - NORMAL	1.000 - NORMAL	
Field Water pH	Cleared	0.205 - NORMAL	NOT SAMPLED	0.274 - NORMAL	
	Forest	0.103 - NORMAL	NOT SAMPLED	0.386 - NORMAL	P
	Transition	0.107 - NORMAL	NOT SAMPLED	1.000 - NORMAL	
Surface Redox potential	Cleared	NOT SAMPLED	NOT SAMPLED	0.083 - NEAR NORMAL	
	Forest	NOT SAMPLED	NOT SAMPLED	0.004	N-P
	Transition	NOT SAMPLED	NOT SAMPLED	1.000 - NORMAL	
Layer 1 Soil redox	Cleared	0.000	NOT SAMPLED	0.034	
	Forest	0.000	NOT SAMPLED	0.387 - NORMAL	N-P
	Transition	0.246 - NORMAL	NOT SAMPLED	1.000 - NORMAL	
Layer 2 Soil Redox	Cleared	NOT SAMPLED	0.402 - NORMAL	0.110 - NORMAL	
	Forest	NOT SAMPLED	0.031	0.001	N-P
	Transition	NOT SAMPLED	0.890 - NORMAL	1.000 - NORMAL	
Water Conductivity	Cleared	0.017	NOT SAMPLED	0.158 - NORMAL	
	Forest	0.000	NOT SAMPLED	0.850 - NORMAL	N-P
	Transition	0.173 - NORMAL	NOT SAMPLED	0.461 - NORMAL	
Dissolved Oxygen	Cleared	0.239 - NORMAL	NOT SAMPLED	0.000	
	Forest	0.002	NOT SAMPLED	Identical (all zero)	N-P
	Transition	0.004	NOT SAMPLED	0.000	
Exch Ca	Cleared	0.022	0.000	NOT SAMPLED	
	Forest	0.000	0.097 - NEAR NORMAL	NOT SAMPLED	N-P
	Transition	0.000	0.214 - NORMAL	NOT SAMPLED	
Exch Mg	Cleared	0.042	0.000	NOT SAMPLED	
	Forest	0.896 - NORMAL	0.112- NORMAL	NOT SAMPLED	N-P
	Transition	0.627 - NORMAL	0.507 - NORMAL	NOT SAMPLED	

Measured property	Zone	1992 Burnt Site - L1	1992 Burnt Site - L2	1994 Punta del Este - All	
Exch K	Cleared	0.376 - NORMAL	0.401 - NORMAL	NOT SAMPLED	
	Forest	0.178 - NORMAL	0.002	NOT SAMPLED	N-P
	Transition	0.559 - NORMAL	0.006	NOT SAMPLED	
Exch Na	Cleared	0.440 - NORMAL	0.560 - NORMAL	NOT SAMPLED	
	Forest	0.225 - NORMAL	0.002 - NORMAL	NOT SAMPLED	P
	Transition	0.418 - NORMAL	0.396 - NORMAL	NOT SAMPLED	
Exch Mn	Cleared	0.006	0.000	NOT SAMPLED	
	Forest	0.000	0.059 - NEAR NORMAL	NOT SAMPLED	N-P
	Transition	0.122 - NORMAL	0.504 - NORMAL	NOT SAMPLED	
Extr. P	Cleared	0.332 - NORMAL	0.079 - NEAR NORMAL	NOT SAMPLED	
	Forest	0.180 - NORMAL	0.152 - NORMAL	NOT SAMPLED	P
	Transition	0.502 - NORMAL	0.833 - NORMAL	NOT SAMPLED	
Water React P	Cleared	NOT SAMPLED	NOT SAMPLED	0.031	
	Forest	NOT SAMPLED	NOT SAMPLED	0.000	N-P
	Transition	NOT SAMPLED	NOT SAMPLED	0.000	
Water NO_3-N	Cleared	NOT SAMPLED	NOT SAMPLED	0.037	
	Forest	NOT SAMPLED	NOT SAMPLED	0.000	N-P
	Transition	NOT SAMPLED	NOT SAMPLED	0.503 - NORMAL	
Soil NH_4-N	Cleared	0.015	0.090 - NEAR NORMAL	NOT SAMPLED	
	Forest	0.241 - NORMAL	0.020	NOT SAMPLED	N-P
	Transition	0.018	0.412 - NORMAL	NOT SAMPLED	
Chloride	Cleared	NOT SAMPLED	NOT SAMPLED	0.304 - NORMAL	
	Forest	NOT SAMPLED	NOT SAMPLED	0.061 - NEAR NORMAL	P
	Transition	NOT SAMPLED	NOT SAMPLED	1.000 - NORMAL	
Sulphate	Cleared	NOT SAMPLED	NOT SAMPLED	0.728 - NORMAL	
	Forest	NOT SAMPLED	NOT SAMPLED	0.037	N-P
	Transition	NOT SAMPLED	NOT SAMPLED	0.366 - NORMAL	
Sulphate:Chloride Ratio	Cleared	NOT SAMPLED	NOT SAMPLED	0.581 - NORMAL	
	Forest	NOT SAMPLED	NOT SAMPLED	0.000	N-P
	Transition	NOT SAMPLED	NOT SAMPLED	0.996 - NORMAL	
TDS	Cleared	NOT SAMPLED	NOT SAMPLED	0.134 - NORMAL	
	Forest	NOT SAMPLED	NOT SAMPLED	0.854 - NORMAL	P
	Transition	NOT SAMPLED	NOT SAMPLED	0.398 - NORMAL	
Turbidity	Cleared	NOT SAMPLED	NOT SAMPLED	1.000 - NORMAL	
	Forest	NOT SAMPLED	NOT SAMPLED	1.000 - NORMAL	P
	Transition	NOT SAMPLED	NOT SAMPLED	1.000 - NORMAL	
Suspended Solids	Cleared	NOT SAMPLED	NOT SAMPLED	1.000 - NORMAL	
	Forest	NOT SAMPLED	NOT SAMPLED	1.000 - NORMAL	P
	Transition	NOT SAMPLED	NOT SAMPLED	1.000 - NORMAL	
% Litter Cover	Cleared	NOT SAMPLED	NOT SAMPLED	Identical (All 100%)	
	Forest	NOT SAMPLED	NOT SAMPLED	0.063 - NEAR NORMAL	N-P
	Transition	NOT SAMPLED	NOT SAMPLED	0.175 - NORMAL	

Maximum samples sizes (no missing observations): Burnt Site $n_C = n_F = 35$, $n_T = 8$; Punta del Este $n_C = n_F = 15$, $n_T = 9$.
Punta del Este data taken from three transect lines, using the numbered points as follows C = 1-5; T = 6-8; F = 9-13.

6.4.1 Interpreting the normality results

The normal distribution is a mathematical construct, describing the distribution of an idealised, randomly distributed independent variable. Whether it applies to the soil, water and other environmental variables measured in the field requires some consideration. In a relatively passive area, where ecological systems have obtained an equilibrium position, it seems possible that data values may indeed be at least approximately normally distributed. The mean will have the same value as the equilibrium point, with the distribution of points around the mean representing minor fluctuations around this equilibrium. Variables which show little deviation from this equilibrium point will have a very small variance, and a highly peaked (leptokurtic) distribution.

Variables measured in a zone which has experienced change, may or may not be normally distributed. If sufficient time has elapsed since the disturbance, a new equilibrium position may have established itself, resulting in a new normal distribution (though possibly with a different mean and variance). Alternatively, if a new equilibrium position has not yet been reached, the data could fail a normality test because it is multimodal or skewed. Multimodality (having several very common values) may be indicative of the change process - some values clustered around the old equilibrium value, others grouped around a new, emerging equilibrium. Alternatively, it may indicate that the data are genuinely not normally distributed, perhaps having values which take one of a range of common values (modes) each relating to an ecological threshold. A variable considered earlier to be likely to show a multimodal distribution is redox potential, where the reported voltage relates to the particular substance being used in the soil as an oxygen donor, each of which has its own characteristic range of redox potential values. Deciding whether multimodality is a characteristic of the measured variable, or transient and thus indicative of change, can be achieved by comparing frequency distributions from a range of sites at different stages in the clearance process.

Data may also fail the normality tests because of skew. A skewed distribution occurs when a variable shows an unequal distribution of values around the mean, often with one side of the distribution having a long tail, and the other being rapidly truncated. Disturbance to an area may produce a skewed distribution. For example, removal of the forest cover and thus litter input, can be expected to reduce the level of organic carbon in soils from the cleared zone and thus the mean organic carbon level in these areas. However, it is likely that at least in the period shortly after clearance, areas will remain which still have relatively high organic carbon levels (e.g. where a fallen branch lay) providing a long tail of low-frequency but high magnitude organic carbon levels: a positively skewed distribution. A negatively skewed distribution could occur where clearance results in a sudden single high magnitude input of material, e.g. the release of large quantities of nutrients from the ash of burnt trees, effectively swamping the previous distribution of these variables. Values would show a distribution with a high mean, reflecting the magnitude of this recent input, but may show a negative skew (a long tail of low values) reflecting a combination of uneven distribution of the ash giving rise to relatively unaffected areas and the lower previous levels of these nutrients in this area.

Another factor which can affect the shape of a variable's frequency distribution is the combination of its range of expected values and the scale of measurement. For variables measured in the centre of a bounded distribution (e.g. percentages, which have a minimum of zero and a maximum of 100) or those without attainable limits (e.g. soil temperature in the tropics measured in degrees Celsius, or soil pH where hydrogen ion concentration is unlikely to be so high or low as to lie outwith the range 1-14) these arguments do not apply. However, in other cases they may result in a skewed distribution. For example, consider a soil with a very low calcium level and thus a low mean value. If soil samples show considerable variance around this mean, then a flat (platykurtic) distribution should be found. With a large variance, some measured calcium levels should lie far above and below the mean. Values lying well above the mean are possible, but those below the mean are limited by the measurement scale used, in this case to a minimum value of zero percent calcium. This effective truncation of the lower levels of the distribution results in an asymmetrical distribution with a long "high" value tail - positive skew. Similarly, variables near their upper limits (e.g. 100%) may result in a negatively skewed distribution.

An example of how an understanding of the processes affecting a variable's frequency distribution pattern can aid in the interpretation of the process of change is given in Appendix 3 (Interzonal differences in the distributions).

6.4.2 Assessing the need for data transformation

Whilst visual comparisons of the untransformed distributions of the measured variables can provide some illumination, as shown in the production of 3D surfaces of Section 6.2 and the consideration of soil ammonium-N levels in Appendix 3, for many less clear-cut situations, determining whether two datasets differ *significantly* requires the use of a comparative statistical test. Such comparative testing forms the remainder of this chapter, providing the mechanism for the "search for difference". Data found to be normally distributed are evaluated using a parametric test: analysis of variance (ANOVA). Data failing the normality assumption can either be tested using a non-parametric test which doesn't require normally distributed data, e.g. the Mann Whitney-U test, or the data can be transformed mathematically, to produce a new, normally distributed dataset. The decision whether to transform data or not requires further consideration.

Parametric tests compare distributions by measuring differences in two descriptors of a variable's distribution: the sample mean and variance. If a dataset is skewed, and thus not normally distributed, then the accuracy of these measures of centre is in doubt, notably the fact that value of the sample variance is strongly influenced by the position of the mean (Webster & Oliver, 1990). For strongly skewed data, parametric tests cannot be used directly. However, mathematical modifications can be applied to the data as a whole (e.g. taking the square root or natural logarithm of sample values) in an attempt to produce a new, normally distributed dataset. This process is known as transforming data.

Mathematically, such a process is quite acceptable, and because soil and water data are often slightly positively skewed (Webster & Oliver, 1990) many published works present the analysis of *transformed* datasets. For example, McKee (1993) uses log transformed mangrove soil data from Florida; Carlson & Yarbro (1988) use a log 10 transformation to stabilise their iron measurements.

However, the validity of such data manipulation has not gone unquestioned, with concern being expressed as to how such transformed data should then be interpreted. Typical of these criticisms are those offered by Gould (1970, p442):

> "...too often we end up relating the value of one variable to the log of another, with the square root of the third, the arc sine of a fourth, and the log of a fifth. Everything is

normal, statistically significant at the one percent level - except that we have not the faintest idea what it means".

Whilst such criticisms of what Webster & Oliver (1990) refer to as statistical "cookery" have some value, all transformations cannot simply be rejected out of hand. Furthermore, some of the "raw data", the properties measured, have already been transformed, for example the reported field soil pH values in this piece of work are in fact a log transformation of soil hydrogen ion concentration. In this case, data transformation has not rendered its interpretation meaningless as Gould claimed above. Indeed, this example merely draws attention to a wider point, exposing the arbitrary nature of all the chosen soil, water and other environmental variables used here and by other researchers in an attempt to measure and model the real world.

Applying transformations to some soil data

The success of transformations depends upon how similar the shapes of the forest and cleared data distributions are. This is most easily explained graphically. Appendix 3 (Applying transformations to some soil data) shows the effects of different transformations upon a property's frequency distribution.

Because transformations arc mathematical processes, which change the value of each sample, their use inevitably adds another "layer" of interpretation. Therefore, they should only be applied when there is an obvious benefit, such as allowing the use of a more powerful statistical test. Applying some standard transformations to abnormally distributed variables from the field data has shown that this process is only advantageous if the samples from the cleared and forest areas have very similarly shaped distributions. This is rarely the case and where it does apply, the data are unlikely to be different anyway. Therefore, transformations have not been used in the comparative tests which follow.

This decision not to transform the data, and the resulting loss in statistical power is not thought to be serious. Each dataset found above to be normally distributed and thus tested using a one-way analysis of variance technique in Table 6.2 below was retested using the non-parametric Mann Whitney-U test. In every case, (a total of 36 comparisons), the same decision to reject or retain the null hypothesis was given by the two tests.

6.5 Comparative testing

Table 6.2 below, gives the results of individual variable comparative testing applied to the same three datasets tested for normality above. Differences between the values of each variable are tested as a series of couples: cleared vs. forest values (C vs. F); cleared vs. transition zone values (C vs. TZ); forest vs. transition zone values (F vs. TZ). The tests consider the null hypothesis that there is no difference between the datasets compared. The results reported below are the probability thresholds for rejection of the null hypothesis. They have been classified as follows: "highly significant" where the null hypothesis can be rejected at $\alpha = 0.05$; "significant" where the null hypothesis can be rejected at $\alpha = 0.10$, but not at $\alpha = 0.05$; and "not significant" where the null hypothesis is retained. For clarity, the "not significant" result is reported in Table 6.2 as a blank. Immediately beneath the name of the measured property is an indication of the test used.

Table 6.2 Comparative statistical test results

Measured property	Zone	1992 Burnt Site - L1	1992 Burnt Site - L2	1994 Punta del Este - All
z	C vs. F	0.581	0.063 - H. SIGNIF	NOT SAMPLED
One-way ANOVA	C vs. TZ	0.089 - SIGNIF	0.001 - H. SIGNIF	NOT SAMPLED
	F vs. TZ	0.294	0.083 - H. SIGNIF	NOT SAMPLED
Layer Thickness	C vs. F	0.0018 - H.SIGNIF	0.1786	0.6783
Mann Whitney-U	C vs. TZ	0.0021 - H.SIGNIF	0.8505	1.0000
	F vs. TZ	0.0858 - SIGNIF	0.3875	0.4798
Mean Layer Depth	C vs. F	0.0018 - H. SIGNIF	0.0085 - H. SIGNIF	0.6729
Mann Whitney-U	C vs. TZ	0.0021 - H.SIGNIF	0.0116 - H. SIGNIF	1.0000
	F vs. TZ	0.0858 - SIGNIF	0.3484	0.4798
Bulk Density	C vs. F	0.0002 - H. SIGNIF	NOT SAMPLED	NOT SAMPLED
Mann Whitney-U	C vs. TZ	0.0309 - H. SIGNIF	NOT SAMPLED	NOT SAMPLED
	F vs. TZ	0.2606	NOT SAMPLED	NOT SAMPLED
% Moisture w/w	C vs. F	0.0004 - H. SIGNIF	0.000 - H. SIGNIF	NOT SAMPLED
Mann Whitney-U	C vs. TZ	0.5222	0.1953	NOT SAMPLED
	F vs. TZ	0.2546	0.3256	NOT SAMPLED
% Dry Matter w/w	C vs. F	0.0004 - H. SIGNIF	0.0000 - H. SIGNIF	NOT SAMPLED
Mann Whitney-U	C vs. TZ	0.5222	0.1953	NOT SAMPLED
	F vs. TZ	0.2546	0.3256	NOT SAMPLED
% > 2 mm	C vs. F	0.3013	0.1883	NOT SAMPLED
Mann Whitney-U	C vs. TZ	0.4537	0.5850	NOT SAMPLED
	F vs. TZ	0.9751	0.1467	NOT SAMPLED
% < 2 mm	C vs. F	0.3013	0.1883	NOT SAMPLED
Mann Whitney-U	C vs. TZ	0.4537	0.5850	NOT SAMPLED
	F vs. TZ	0.9751	0.1467	NOT SAMPLED
% Wt. Loss on Ignition	C vs. F	0.0005 - H. SIGNIF	0.0000 - H. SIGNIF	NOT SAMPLED
Mann Whitney-U	C vs. TZ	0.0155 - H. SIGNIF	0.0100 - H. SIGNIF	NOT SAMPLED
	F vs. TZ	0.0043 - H. SIGNIF	0.6509	NOT SAMPLED
% Organic C	C vs. F	0.0003 - H.SIGNIF	0.0000 - H. SIGNIF	NOT SAMPLED
Mann Whitney-U	C vs. TZ	0.0749 - SIGNIF	1.0000	NOT SAMPLED
	F vs. TZ	0.0029 - H. SIGNIF	0.0408 - H. SIGNIF	NOT SAMPLED
Surface Soil pH	C vs. F	NOT SAMPLED	NOT SAMPLED	1.0000
Mann Whitney-U	C vs. TZ	NOT SAMPLED	NOT SAMPLED	0.0244 - H. SIGNIF
	F vs. TZ	NOT SAMPLED	NOT SAMPLED	0.0887 - SIGNIF
Layer 1 Soil pH	C vs. F	0.0381 - H. SIGNIF	NOT SAMPLED	0.0025 - H. SIGNIF
Mann Whitney-U	C vs. TZ	0.5635	NOT SAMPLED	0.0174 - H. SIGNIF
	F vs. TZ	0.4260	NOT SAMPLED	0.5081
Layer 2 Soil pH	C vs. F	NOT SAMPLED	0.0000 - H. SIGNIF	0.0075 - H. SIGNIF
Mann Whitney-U	C vs. TZ	NOT SAMPLED	0.0493 - H. SIGNIF	0.0128 - H. SIGNIF
	F vs. TZ	NOT SAMPLED	0.6847	0.0548 - SIGNIF
Field Water pH	C vs. F	0.000 - H. SIGNIF	NOT SAMPLED	0.055 - SIGNIF
One-way ANOVA	C vs. TZ	0.000 - H. SIGNIF	NOT SAMPLED	0.793
	F vs. TZ	0.001 - H. SIGNIF	NOT SAMPLED	0.101
Surface Redox potential	C vs. F	NOT SAMPLED	NOT SAMPLED	0.1522
Mann Whitney-U	C vs. TZ	NOT SAMPLED	NOT SAMPLED	0.0390 - H. SIGNIF
	F vs. TZ	NOT SAMPLED	NOT SAMPLED	0.0864 - SIGNIF
Layer 1 Soil redox	C vs. F	0.0045 - H. SIGNIF	NOT SAMPLED	0.1709
Mann Whitney-U	C vs. TZ	0.2481	NOT SAMPLED	0.2274
	F vs. TZ	0.5532	NOT SAMPLED	0.1103
Layer 2 Soil Redox	C vs. F	NOT SAMPLED	0.0000 - H. SIGNIF	0.3724
Mann Whitney-U	C vs. TZ	NOT SAMPLED	0.0289 - H. SIGNIF	0.5593
	F vs. TZ	NOT SAMPLED	0.1696	0.6126
Water Conductivity	C vs. F	0.0000 - H. SIGNIF	NOT SAMPLED	0.0023 - H. SIGNIF
Mann Whitney-U	C vs. TZ	0.0000 - H. SIGNIF	NOT SAMPLED	0.3553
	F vs. TZ	0.0004 - H. SIGNIF	NOT SAMPLED	0.0369 - H. SIGNIF
Dissolved Oxygen	C vs. F	0.0002 - H. SIGNIF	NOT SAMPLED	Forest values all identical
Mann Whitney-U	C vs. TZ	0.0000 - H.SIGNIF	NOT SAMPLED	0.9174
	F vs. TZ	0.0004 - H. SIGNIF	NOT SAMPLED	Forest values all identical
Exch Ca	C vs. F	0.7025	0.0226 - H. SIGNIF	NOT SAMPLED
Mann Whitney-U	C vs. TZ	0.5120	0.6285	NOT SAMPLED
	F vs. TZ	0.6734	0.4260	NOT SAMPLED
Exch Mg	C vs. F	0.0190 - H. SIGNIF	0.0002 - H. SIGNIF	NOT SAMPLED
Mann Whitney-U	C vs. TZ	0.0011 - H. SIGNIF	0.0000 - H. SIGNIF	NOT SAMPLED
	F vs. TZ	0.0245 - H. SIGNIF	0.0300 - H. SIGNIF	NOT SAMPLED

Measured property	Zone	1992 Burnt Site - L1	1992 Burnt Site - L2	1994 Punta del Este - All
Exch K	C vs. F	0.0000 - H. SIGNIF	0.0000 - H. SIGNIF	NOT SAMPLED
Mann Whitney-U	C vs. TZ	0.0002 - H. SIGNIF	0.0000 - H. SIGNIF	NOT SAMPLED
	F vs. TZ	0.0000 - H. SIGNIF	0.0000 - H. SIGNIF	NOT SAMPLED
Exch Na	C vs. F	0.000 - H. SIGNIF	0.000 - H. SIGNIF	NOT SAMPLED
One-way ANOVA	C vs. TZ	0.000 - H. SIGNIF	0.000 - H. SIGNIF	NOT SAMPLED
	F vs. TZ	0.673	0.786	NOT SAMPLED
Exch Mn	C vs. F	0.0856 - SIGNIF	0.2802	NOT SAMPLED
Mann Whitney-U	C vs. TZ	0.0880 - SIGNIF	0.8094	NOT SAMPLED
	F vs. TZ	0.4094	0.5257	NOT SAMPLED
Extr. P	C vs. F	0.847	0.708	NOT SAMPLED
One-way ANOVA	C vs. TZ	0.107	0.541	NOT SAMPLED
	F vs. TZ	0.365	0.845	NOT SAMPLED
Water React P	C vs. F	NOT SAMPLED	NOT SAMPLED	0.0098 - H. SIGNIF
Mann Whitney-U	C vs. TZ	NOT SAMPLED	NOT SAMPLED	0.0941 - SIGNIF
	F vs. TZ	NOT SAMPLED	NOT SAMPLED	0.6936
Water NO_3-N	C vs. F	NOT SAMPLED	NOT SAMPLED	0.0000 - H. SIGNIF
Mann Whitney-U	C vs. TZ	NOT SAMPLED	NOT SAMPLED	0.0008 - H. SIGNIF
	F vs. TZ	NOT SAMPLED	NOT SAMPLED	0.1182
Soil NH_4-N	C vs. F	0.0012 - H. SIGNIF	0.3977	NOT SAMPLED
Mann Whitney-U	C vs. TZ	0.5223	0.4825	NOT SAMPLED
	F vs. TZ	0.0237 - H. SIGNIF	0.9378	NOT SAMPLED
Chloride	C vs. F	NOT SAMPLED	NOT SAMPLED	0.731
One-way ANOVA	C vs. TZ	NOT SAMPLED	NOT SAMPLED	0.876
	F vs. TZ	NOT SAMPLED	NOT SAMPLED	0.743
Sulphate	C vs. F	NOT SAMPLED	NOT SAMPLED	0.0000 - H. SIGNIF
Mann Whitney-U	C vs. TZ	NOT SAMPLED	NOT SAMPLED	0.5696
	F vs. TZ	NOT SAMPLED	NOT SAMPLED	0.0016 - H. SIGNIF
Sulphate:Chloride Ratio	C vs. F	NOT SAMPLED	NOT SAMPLED	0.2058
Mann Whitney-U	C vs. TZ	NOT SAMPLED	NOT SAMPLED	0.2045
	F vs. TZ	NOT SAMPLED	NOT SAMPLED	0.9438
TDS	C vs. F	NOT SAMPLED	NOT SAMPLED	0.003 - H. SIGNIF
One-way ANOVA	C vs. TZ	NOT SAMPLED	NOT SAMPLED	0.579
	F vs. TZ	NOT SAMPLED	NOT SAMPLED	0.014 - H. SIGNIF
Turbidity	C vs. F	NOT SAMPLED	NOT SAMPLED	0.000 - H. SIGNIF
One-way ANOVA	C vs. TZ	NOT SAMPLED	NOT SAMPLED	0.169
	F vs. TZ	NOT SAMPLED	NOT SAMPLED	0.158
Suspended Solids	C vs. F	NOT SAMPLED	NOT SAMPLED	0.006 - H. SIGNIF
One-way ANOVA	C vs. TZ	NOT SAMPLED	NOT SAMPLED	0.303
	F vs. TZ	NOT SAMPLED	NOT SAMPLED	0.201
Water redox potential	C vs. F	NOT SAMPLED	NOT SAMPLED	0.0380 - H. SIGNIF
Mann Whitney-U	C vs. TZ	NOT SAMPLED	NOT SAMPLED	0.0645 - SIGNIF
	F vs. TZ	NOT SAMPLED	NOT SAMPLED	0.3106
% Litter Cover	C vs. F	NOT SAMPLED	NOT SAMPLED	Cleared values all identical
Mann Whitney-U	C vs. TZ	NOT SAMPLED	NOT SAMPLED	Cleared values all identical
	F vs. TZ	NOT SAMPLED	NOT SAMPLED	0.0112 - H. SIGNIF

6.6 Interpretation of the results

The results of the statistical tests confirm the findings of the visualisation procedures. Variables which show a marked spatial pattern, such as water pH, weight loss on ignition and exchangeable potassium all report highly significant differences in Table 6.2 above. Similarly, variables which the visualisation procedures had shown to have relatively uniform values across the site, such as the percent greater than 2 mm, exchangeable calcium and extractable phosphorus, all return no significant difference. The statistical testing allows a more specific comparison of the zonal data, comparing samples from each zone with the other two. This forms the next stage of the analysis.

6.6.1 Comparing the forest and cleared zones

The greatest zonal differences are expected to arise from the comparison of values from the cleared and forest zones. These comparisons are given below, grouping the measured variables together using the classification developed in the predictive work of chapter three. In the tables that follow, for each variable, values measured in the forest are statistically compared with those in the cleared zone, using the method given in Table 6.2 above. The result of the test: whether or not a significant difference is found is given under the heading "Significance Test". The results of comparing the two dataset means is given in the next column labelled "Highest", which gives the first letter of the zone with the highest mean value. When this difference is not considered statistically significant, the letter is shown in parentheses.

Rapidly released soluble cations

Table 6.3 Comparing rapidly released cation values in the cleared and forest zones

Site	Burnt Site '92 Layer 1			Burnt Site '92 Layer 2			Punta del Este '94	
Variable	Significance Test		Highest	Significance Test		Highest	Significance Test	Highest
Soil Exch K	C vs. F	H. SIG	**F**	C vs. F	H. SIG	**F**	NOT SAMPLED	
Soil Exch Na	C vs. F	H. SIG	**F**	C vs. F	H. SIG	**F**	NOT SAMPLED	
Soil Exch Mn	C vs. F	SIG	**F**	C vs. F	-	***(F)***	NOT SAMPLED	
Soil Exch Ca	C vs. F	-	***(F)***	C vs. F	H. SIG	**F**	NOT SAMPLED	
Soil Exch Mg	C vs. F	H. SIG	**F**	C vs. F	H. SIG	**F**	NOT SAMPLED	

H. SIG = significant at a = 0.05; SIG = significant at a = 0.10; Highest - the higher of the cleared and forest mean values is printed in bold typeface. Points in italics and parentheses represent those accepted as probably not significantly different.

All the labile exchangeable cations in Table 6.3 show a higher mean value when measured in the forest. With the exception of exchangeable calcium, this difference has been found to be significant, and except for exchangeable manganese values, continues in the lower, more clay-rich second soil layer. These patterns match the predicted trends and suggest that the cation levels measured in the cleared zone have fallen from the initial peak following clearance, whilst those in the forest are maintained at their high level through litterfall and stemflow.

Organic carbon

Table 6.4 Comparing organic carbon values in the cleared and forest zones

Site	Burnt Site '92 Layer 1			Burnt Site '92 Layer 2			Punta del Este '94	
Variable	Significance Test		Highest	Significance Test		Highest	Significance Test	Highest
% Wt LoI	C vs. F	H. SIG	**F**	C vs. F	H. SIG	**F**	NOT SAMPLED	
% Organic C	C vs. F	H. SIG	**F**	C vs. F	H. SIG	**F**	NOT SAMPLED	

Both these measures of soil organic carbon content show that sites in the forest have significantly higher levels than those in the cleared zone. This pattern is repeated at depth and can be explained by the sustained litter input in the forest zone.

Extractable phosphorus

Table 6.5 Comparing extractable phosphorus values in the cleared and forest zones

Site	Burnt Site '92 Layer 1			Burnt Site '92 Layer 2			Punta del Este '94		
Variable	Significance Test		Highest	Significance Test		Highest	Significance Test		Highest
Soil Extr. P	C vs. F	-	***(F)***	C vs. F	-	***(C)***	NOT SAMPLED		
Water Rea. P	NOT SAMPLED			NOT SAMPLED			C vs. F	H. SIG	**C**

The levels of soil extractable phosphorus given in Table 6.5 do not show significantly different values in the cleared and forest sites. This confirms the predicted uniformly low values because of the very high immobilisation rates expected at the field site. However, the amount of reactive phosphorus (orthophosphate) measured in the waters of the Punta del Este field site contradicts this uniform picture, with reactive phosphorus levels significantly higher in the cleared zone. This is attributed to sample contamination. At the time of measurement, a few of the dipwells in the cleared zone were found to contain small drowned crabs. These are thought to be the source of the higher phosphorus levels.

Inorganic forms of nitrogen

Table 6.6 Comparing ammonium-N and nitrate-N values in the cleared and forest zones

Site	Burnt Site '92 Layer 1			Burnt Site '92 Layer 2			Punta del Este '94		
Variable	Significance Test		Highest	Significance Test		Highest	Significance Test		Highest
Soil NH_4-N	C vs. F	H. SIG	F	C vs. F	-	*(F)*	NOT SAMPLED		
Water NO_3-N	NOT SAMPLED			NOT SAMPLED			C vs. F	H. SIG	C

Soil ammonium-N values are found to be higher in the forest for both layer 1 and layer 2 samples, although this difference is only significant for the upper samples. The pattern predicted in chapter three expected ammonium-N levels to be higher in the cleared area, only tailing off to a level below that of the forest once the organic material from the fallen litter had been ammonified. The results obtained question the timescale used in the prediction. It is possible that the time elapsed is sufficient for the pattern to be that predicted long after clearance. In this case, the continual litter input in the forest would be providing a sustained source of organic nitrogen for ammonification, whilst that in the cleared zone is eventually consumed. Alternatively, soil ammonium-N production may truly be greater in the cleared zone, but more of this ammonium-N may be converted to other forms, resulting in a lower net ammonium-N level than in the forest. It is possible that some of the ammonium-N may undergo nitrification, suggesting that conditions in the cleared site are favourable for the bacteria involved - i.e. oxidised pockets remain in the soil. In the cleared zone, ammonium-N loss via ammonia volatilisation is also possible, this is likely to be greater in the cleared zone because of the more favourable near-neutral water and soil pH conditions. The fact that the observed difference is not statistically significant at greater depth is consistent with the redox data which shows these samples to have values indicating far more homogeneous reducing soil conditions.

Soil nitrate-N values measured at the burnt site in 1992 were found to be uniformly zero, in common with many other mangrove soil studies. Measurement of nitrate-N levels in the porewater collected from the more recently cleared Punta del Este site, however, reveals a different picture. Nitrate-N levels in the cleared zone are significantly higher than those in the forest. This result also initially appears to contradict the predictions given in chapter three: it was expected that root death in the cleared zone would result in a decrease in the proportion of the subsoil which is oxidised. Thus, the number of potential sites for nitrification to occur would drop, and so the concentration of nitrate-N falls accordingly. However, this anticipated decrease in soil nitrification in the cleared zone may be less than the volume of nitrate-N lost through plant uptake from soils in the remaining forest. If this is the case then the net effect may be higher soil nitrate-N values in the cleared zone, despite a greater nitrification rate in the forest. The Punta del Este site has very dense vegetation cover (see PCQM results in Appendix 1) and the soil samples were found to contain a high proportion of roots, both these observations corroborate the idea of a large requirement for nitrate-N in the forest.

Measurements of nitrous oxide flux were only taken along the fieldwork transect lines because of the difficulty of obtaining comparable results over large areas with only a small field team[3]. This means that the resulting datasets are too small for the statistical comparisons of this chapter. Patterns in these measurements are considered in chapter nine, which looks at all the transect data.

Other vegetation cover influenced processes

Most of the litter dependent variables (such as organic carbon content and exchangeable cation levels) have already been considered above. Ground level insolation measurements were restricted to the smaller, transect sampling programme to minimise differences due to cloud movements during the sampling period. These are, therefore, considered in chapter nine. Litter cover measurements were taken at the Punta del Este site in 1994. Samples in the cleared zone showed a complete (100%) litter cover arising from the recent clearance and pneumatophore damage. Values recorded in the forest were slightly lower, because the dense carpet of pneumatophores meant that fallen leaves did not completely cover the soil surface. The uniformity of the cleared zone sample values prevents the application of statistical tests, but nevertheless, the pattern of litter cover can be seen to differ markedly between the forest and cleared zones.

Marine and drainage processes

Table 6.7 Comparing the values of marine and drainage influenced variables in the cleared and forest zones

Site	Burnt Site '92 Layer 1			Burnt Site '92 Layer 2			Punta del Este '94		
Variable	Significance Test		Highest	Significance Test		Highest	Significance Test		Highest
% Moisture	C vs. F	H. SIG	F	C vs. F	H. SIG	F	NOT SAMPLED		
Conductivity	C vs. F	H. SIG	F	SAMPLE AS LAYER 1			C vs. F	H. SIG	C
Soil Exch Na	C vs. F	H. SIG	F	C vs. F	H. SIG	F	NOT SAMPLED		
Soil Exch Mn	C vs. F	SIG	F	C vs. F	-	(F)	NOT SAMPLED		
Water SO_4	NOT SAMPLED			NOT SAMPLED			C vs. F	H. SIG	F
Soil NH_4-N	C vs. F	H. SIG	F	C vs. F	-	(F)	NOT SAMPLED		
Water TDS	NOT SAMPLED			NOT SAMPLED			C vs. F	H. SIG	F
Turbidity	NOT SAMPLED			NOT SAMPLED			C vs. F	H. SIG	F
Susp. Solids	NOT SAMPLED			NOT SAMPLED			C vs. F	H. SIG	F
% Dry Matter	C vs. F	H. SIG	C	C vs. F	H. SIG	C	NOT SAMPLED		
Water Cl^-	NOT SAMPLED			NOT SAMPLED			C vs. F	-	(C)

3 To be truly comparable, samples should be collected at the same time of day to eliminate differences in flux due to changes in soil temperature.

Variable	Significance Test		Highest	Significance Test		Highest	Significance Test		Highest
Surface pH	NOT SAMPLED			NOT SAMPLED			C vs. F	-	*(C)*
Layer 1 pH	C vs. F	H. SIG	C	NOT SAMPLED			C vs. F	-	*(C)*
Layer 2 pH	NOT SAMPLED			C vs. F	H. SIG	C	C vs. F	H. SIG	C
Surface redox	NOT SAMPLED			NOT SAMPLED			C vs. F	-	*(C)*
Layer 1 redox	C vs. F	H. SIG	F	NOT SAMPLED			C vs. F	-	*(C)*
Layer 2 redox	NOT SAMPLED			C vs. F	H. SIG	F	C vs. F	-	*(C)*
Water pH	C vs. F	H. SIG	C	SAMPLE AS LAYER 1			C vs. F	SIG	C
Water redox	NOT SAMPLED			NOT SAMPLED			C vs. F	H. SIG	C
Dissolved O_2	C vs. F	H. SIG	F	SAMPLE AS LAYER 1			C vs. F	*	C
Water NO_3-N	NOT SAMPLED			NOT SAMPLED			C vs. F	H. SIG	C

** Forest dissolved oxygen values were all zero. Redox and pH values are measured in the soil unless otherwise stated. Comparisons as before, e.g. C vs. F is a comparison between points from the cleared and forest zones.*

The soil and water variables listed in Table 6.7, which are affected by the water level and potential flushing action of the tides, can be separated into two. One group show higher values in the forest, the second higher values in the cleared zone. Soil moisture content is significantly higher in forest samples. This is thought to be due to the greater organic content of these soils. The pattern of conductivity values is less clear. In the 1992 Burnt site, conductivity values are higher in the forest, but in the better drained 1994 Punta del Este site they are higher in the cleared zone. These higher cleared values could be the result of greater evaporation rates acting to concentrate salt levels in the soil. The higher conductivity in the Burnt site may be because of significantly higher exchangeable cation levels in the forest. Because the cleared portion of this site was covered by standing water at the time of sampling, soil salt concentration through evaporation is expected to be far lower here.

Higher forest values of ions such as sodium, manganese and sulphate, suggests that the marine contribution to the level of these nutrients has either not been affected by clearance and drainage, or any change is acting uniformly across the site. Indicators of the suspended load of the porewater and surface waters of the mangrove, such as turbidity, dissolved and suspended solids measurements all show higher values in the forest.

Variables which are water level dependent such as redox potential, and thus soil pH and the value of reduced ion species, do not show a consistent pattern of higher values in one zone. This is attributed to the fact that in 1992 the Burnt field site was covered in standing water. Higher redox values in forest samples taken below the soil surface are a result of the oxygen translocation activity of the live roots.

Terrestrial sedimentation processes

All the metal cations listed above in Table 6.3 show higher values in the forest, most of which are statistically significant. This differs from the predicted pattern for alluvial deposited material, which is not expected to change significantly following clearance. There are two possible reasons for this. Either alluvium is not an important source of these cations in the mangrove, or else it could be that if the timing and volume of alluvial deposition is highly irregular, adequate time has not elapsed to restore samples across the field site as a whole. However, if the latter explanation was correct, then higher cation levels should be expected in the cleared zone, because of greater cation uptake by plants in the forest zone. This is not the case, and thus we must conclude that at least over the short term, there is only very minimal alluvial input of cations across the site and so terrestrial inputs of these nutrients do not seem to play a major role in localised mangrove nutrient cycling. Therefore, terrestrial sedimentation processes will not be considered further in this chapter.

Geological processes

Table 6.8 Comparing the values of variables likely to alter because of geological processes acting in the cleared and forest zones

Site	Burnt Site '92 Layer 1			Burnt Site '92 Layer 2			Punta del Este '94		
Variable	Significance Test		Highest	Significance Test		Highest	Significance Test		Highest
% > 2 mm	C vs. F	-	***(C)***	C vs. F	-	***(F)***	NOT SAMPLED		
% < 2 mm	C vs. F	-	***(F)***	C vs. F	-	***(C)***	NOT SAMPLED		
Soil Exch Ca	C vs. F	-	***(F)***	C vs. F	H. SIG	**F**	NOT SAMPLED		
Soil Exch Mg	C vs. F	H. SIG	**F**	C vs. F	H. SIG	**F**	NOT SAMPLED		

Comparing the value of variables which may be influenced by geological processes, a very weak pattern emerges: generally there is no significant difference between forest and cleared sites, as expected. This leads us to confirm the earlier view that geology does not seen to play a major role in short term nutrient cycling in the mangrove. The changes noted in the levels of calcium and magnesium seem to match trends noted in other cations, which are attributed to litter input rather than geological processes. Therefore, geological processes will not be considered as a cause of change in the remainder of this work.

Compaction effects

Table 6.9 Comparing the values of variables indicative of physical compaction in the cleared and forest zones

Site	Burnt Site '92 Layer 1			Burnt Site '92 Layer 2			Punta del Este '94		
Variable	Significance Test		Highest	Significance Test		Highest	Significance Test		Highest
Thickness	C vs. F	H. SIG	**F**	C vs. F	-	***(F)***	C vs. F	-	***(C)***
Mean Depth	C vs. F	H. SIG	**C**	C vs. F	H. SIG	**F**	C vs. F	-	***(F)***
Bulk Density	C vs. F	H. SIG	**C**	NOT SAMPLED			NOT SAMPLED		

The thickness, depth and bulk density patterns confirm a picture of localised compaction in the cleared zone, resulting from trampling during clearance.

6.6.2 Reconsidering the transition zone: is a third class valid?

Comparing the zonal averages of measured variables individually will show the pattern of values in the transition zone. It allows us to consider statistically whether samples from this zone are showing a similar pattern of values to those of another zone, or whether the transition zone samples are actually different from them both, in a significant statistical way. This results of such tests are given in the tables below:

Rapidly released soluble cations

Table 6.10 Comparing rapidly released cation values in the transition zone

Site	Burnt Site '92 Layer 1			Burnt Site '92 Layer 2			Punta del Este '94	
Variable	Significance Test		Highest	Significance Test		Highest	Significance Test	Highest
Soil Exch K	C vs. TZ	H. SIG	C	C vs. TZ	H. SIG	C	NOT SAMPLED	
	TZ vs. F	H. SIG	F	TZ vs. F	H. SIG	F		
Soil Exch Na	C vs. TZ	H. SIG	TZ	C vs. TZ	H. SIG	TZ	NOT SAMPLED	
	TZ vs. F	-	(TZ)	TZ vs. F	-	(F)		
Soil Exch Mn	C vs. TZ	SIG	TZ	C vs. TZ	-	(TZ)	NOT SAMPLED	
	TZ vs. F	-	(TZ)	TZ vs. F	-	(F)		
Soil Exch Ca	C vs. TZ	-	(TZ)	C vs. TZ	-	(TZ)	NOT SAMPLED	
	TZ vs. F	-	(TZ)	TZ vs. F	-	(F)		
Soil Exch Mg	C vs. TZ	H. SIG	TZ	C vs. TZ	H. SIG	TZ	NOT SAMPLED	
	TZ vs. F	H. SIG	TZ	TZ vs. F	H. SIG	TZ		

The most striking feature of Table 6.10 is the frequency of measures where the most consistently high values are found in the transition zone. This pattern supports the conceptualisation of a three zone classification. The fact that many exchangeable cation values are higher in the transition zone than either the forest or cleared areas means that this zone is not merely a combination of values from the other two, but is actually a distinct third zone. The higher values in the transition zone may be a result of this area benefiting from two sources of nutrient input: fallen material in the cleared zone and continuous litterfall at the forest edge. If this is the case, then these zonal differences will decay over time, as the nutrient supply from cleared zone litter decomposition and mineralisation becomes exhausted.

Organic carbon

Table 6.11 Comparing organic carbon values in the transition zone

Site	Burnt Site '92 Layer 1			Burnt Site '92 Layer 2			Punta del Este '94	
Variable	Significance Test		Highest	Significance Test		Highest	Significance Test	Highest
% Wt LoI	C vs. TZ	H. SIG	C	C vs. TZ	H. SIG	TZ	NOT SAMPLED	
	TZ vs. F	H. SIG	F	TZ vs. F	-	F		
% Organic C	C vs. TZ	SIG	C	C vs. TZ	-	TZ	NOT SAMPLED	
	TZ vs. F	H. SIG	F	TZ vs. F	H. SIG	F		

The pattern of organic material deposition shown above is initially rather contradictory. Samples from Layer 2 show the expected pattern: organic levels are highest in the forest, and higher in the transition zone than in cleared areas. This follows the long term pattern of litter input. However, samples from the upper layer show the reverse: organic levels are highest in the cleared zone and higher in the transition zone than in the forest. This pattern of organic matter distribution is a result of the large surface litter input after clearance. The fact that the clearance-altered pattern of layer 1 does not continue in lower samples shows that little of the additional surface organic material has as yet been incorporated into the lower regions of the soil.

Extractable phosphorus

Table 6.12 Comparing extractable phosphorus values in the transition zone

Site	Burnt Site '92 Layer 1		Burnt Site '92 Layer 2		Punta del Este '94	
Variable	Significance Test	Highest	Significance Test	Highest	Significance Test	Highest
Soil Extr. P	C vs. TZ - TZ vs. F -	***(TZ)*** ***(TZ)***	C vs. TZ - TZ vs. F -	***(C)*** ***(F)***	NOT SAMPLED	
Water Rea. P	NOT SAMPLED		NOT SAMPLED		C vs. TZ SIG TZ vs. F -	**C** ***(TZ)***

Soil extractable phosphorus levels do not really show significant differences across any of the three zones. This uniformity reflects the great ability of mangrove soils to immobilise soil phosphorus. The significantly higher water reactive phosphorus levels seen in the cleared-transition zone comparison at the Punta del Este site is again thought to be due to sample contamination (drowning crabs) in the cleared zone.

Inorganic forms of nitrogen

Table 6.13 Comparing inorganic nitrogen values in the transition zone

Site	Burnt Site '92 Layer 1		Burnt Site '92 Layer 2		Punta del Este '94	
Variable	Significance Test	Highest	Significance Test	Highest	Significance Test	Highest
Soil NH_4-N	C vs. TZ - TZ vs. F H. SIG	***(TZ)*** **F**	C vs. TZ - TZ vs. F -	***(TZ)*** ***(F)***	NOT SAMPLED	
Water $N0_3$-N	NOT SAMPLED		NOT SAMPLED		C vs. TZ H. SIG TZ vs. F -	**C** ***(TZ)***

Soil ammonium-N values generally show little difference between the zones, the only exception being higher ammonium-N values in the forest from layer 1 samples. Here the transition zone appears to show a range of values very similar to the cleared zone, rather than being a separate zone itself.

Water nitrate-N values support a view of the site where values are significantly higher in the cleared zone (as a result of the large organic-N input) with a transition in values, decreasing towards the forest. For this variable samples in the transition zone appear to be behaving more like those in the forest, than the cleared zone. This is thought to be because of the presence of live mangrove roots in the transition zone, creating a greater volume of oxidising soil conditions, which act to decrease ammonium-N levels by favouring nitrification.

Other vegetation cover influenced processes

Table 6.14 Comparing litter cover values in the transition zone

Site	Burnt Site '92 Layer 1		Burnt Site '92 Layer 2		Punta del Este '94	
Variable	Significance Test	Highest	Significance Test	Highest	Significance Test	Highest
%Litter Cover	NOT SAMPLED		NOT SAMPLED		C vs. TZ failed TZ vs. F H. SIG	**C** **TZ**

The only other variable affected by vegetation cover influenced processes which has not yet been discussed is litter cover. The uniform 100% litter cover in the cleared zone means that values in this zone are the highest, but cannot be compared using the tests employed above. Values from the transition zone are found to be significantly higher than those in the forest. This is because many of the transition sites have no forest cover and show properties very similar to the cleared zone. Sites beyond the cut line show litter cover figures very similar to the forest sites. This suggests that in the case of litter cover, the transition zone is not particularly useful and a two zone model would suffice. The only case for maintaining the three zone classification is if samples in the transition zone showed higher litter levels than those of the cleared zone, because of additional litter input from the remaining forest. However this cannot be tested using the percentage scale of the litter cover data because the soil surface in the cleared zone is already fully covered with litter.

Marine and drainage processes

Table 6.15 Comparing the value of marine and drainage influenced variables in the transition zone

Site	Burnt Site '92 Layer 1			Burnt Site '92 Layer 2			Punta del Este '94		
Variable	Significance Test		Highest	Significance Test		Highest	Significance Test		Highest
% Moisture	C vs. TZ	-	*(TZ)*	C vs. TZ	-	*(TZ)*	NOT SAMPLED		
	TZ vs. F	-	*(F)*	TZ vs. F	-	*(F)*			
Conductivity	C vs. TZ	H. SIG	**TZ**	SAMPLE AS LAYER 1			C vs. TZ	-	*(C)*
	TZ vs. F	H. SIG	**TZ**				TZ vs. F	H. SIG	**F**
Soil Exch Na	C vs. TZ	H. SIG	**TZ**	C vs. TZ	H. SIG	**TZ**	NOT SAMPLED		
	TZ vs. F	-	*(TZ)*	TZ vs. F	-	*(F)*			
Soil Exch Mn	C vs. TZ	SIG	**TZ**	C vs. TZ	-	*(TZ)*	NOT SAMPLED		
	TZ vs. F	-	*(TZ)*	TZ vs. F	-	*(F)*			
Water SO_4	NOT SAMPLED			NOT SAMPLED			C vs. TZ	-	*(TZ)*
							TZ vs. F	H. SIG	**F**
Soil NH_4-N	C vs. TZ	-	*(TZ)*	C vs. TZ	-	*(TZ)*	NOT SAMPLED		
	TZ vs. F	H. SIG	**F**	TZ vs. F	-	*(F)*			
Water TDS	NOT SAMPLED			NOT SAMPLED			C vs. TZ	-	*(TZ)*
							TZ vs. F	H. SIG	**F**
Turbidity	NOT SAMPLED			NOT SAMPLED			C vs. TZ	-	*(TZ)*
							TZ vs. F	-	*(F)*
Susp. Solids	NOT SAMPLED			NOT SAMPLED			C vs. TZ	-	*(TZ)*
							TZ vs. F	-	*(F)*
% Dry Matter	C vs. TZ	-	*(C)*	C vs. TZ	-	*(C)*	NOT SAMPLED		
	TZ vs. F	-	*(TZ)*	TZ vs. F	-	*(TZ)*			
Water Cl^-	NOT SAMPLED			NOT SAMPLED			C vs. TZ	-	*(TZ)*
							TZ vs. F	-	*(F)*
Surface pH	NOT SAMPLED			NOT SAMPLED			C vs. TZ	H. SIG	**C**
							TZ vs. F	SIG	F
Layer 1 pH	C vs. TZ	-	*(C)*	NOT SAMPLED			C vs. TZ	-	*(C)*
	TZ vs. F	-	*(TZ)*				TZ vs. F	-	*(F)*
Layer 2 pH	NOT SAMPLED			C vs. TZ	H. SIG	**C**	C vs. TZ	H. SIG	**C**
				TZ vs. F	-	*(TZ)*	TZ vs. F	H. SIG	**F**
Surface redox	NOT SAMPLED			NOT SAMPLED			C vs. TZ	H. SIG	**C**
							TZ vs. F	SIG	**F**
Layer 1 redox	C vs. TZ	-	*(TZ)*	NOT SAMPLED			C vs. TZ	-	*(C)*
	TZ vs. F	-	*(TZ)*				TZ vs. F	-	*(F)*
Layer 2 redox	NOT SAMPLED			C vs. TZ	H. SIG	**TZ**	C vs. TZ	-	*(C)*
				TZ vs. F	-	*(TZ)*	TZ vs. F	-	*(F)*
Water pH	C vs. TZ	H. SIG	**C**	SAMPLE AS LAYER 1			C vs. TZ	-	*(C)*
	TZ vs. F	H. SIG	**TZ**				TZ vs. F	-	*(F)*

continued overleaf

Site	Burnt Site '92 Layer 1			Burnt Site '92 Layer 2			Punta del Este '94		
Variable	Significance Test		Highest	Significance Test		Highest	Significance Test		Highest
Water redox	NOT SAMPLED			NOT SAMPLED			C vs. TZ	SIG	**TZ**
							TZ vs. F	-	***(TZ)***
Dissolved O_2	C vs. TZ	H. SIG	**TZ**	SAMPLE AS LAYER 1			C vs. TZ	-	***(TZ)***
	TZ vs. F	H. SIG	**TZ**				TZ vs. F	?	**TZ**
Water NO_3-N	NOT SAMPLED			NOT SAMPLED			C vs. TZ	H. SIG	**C**
							TZ vs. F	-	***(TZ)***

The marine and drainage influenced variables show a very mixed pattern, reflecting the large number of variables considered. Most of the measured properties do not show significant differences between samples measured in the transition zone and the other two areas. This reflects the fact that the dominant freshwater-marine gradient is aligned perpendicular to the cleared-forest gradient, and thus will act to suppress zonal differences. An exception to this are the levels of the exchangeable cations and conductivity, which support the concept of a separate transition zone. For these properties the highest values are found around the cut line. The peak in conductivity may reflect the higher cation levels or the possible contamination effect discussed in Section 6.1.18. The behaviour of the cation levels and possibly conductivity is thought to be due to differences in litter deposition, rather than water-transported materials. Another contradictory variable is dissolved oxygen, which shows significantly higher values in the transition zone, compared with both the forest and cleared areas. This may be because in this region, the greater water movement found in the open waters of the cleared zone, combines with the greater number of obstacles to water movement in the forest, to create a zone of "turbulence" oxygenating the waters.

Terrestrial sedimentation processes

The pattern for variables which might be influenced by terrestrial sediment distribution, matches that of the labile cations considered above. These patterns can be satisfactorily explained by nutrient release from litterfall and thus sediment influence is not thought to contribute significantly to the level of these variables across the field site and thus an investigation of transition zone values is not repeated here.

Geological processes

Because of their generally uniform values, the patterns arising from the geologically influenced variables do little to support the idea of a transition zone. Again, the significantly higher magnesium levels in the transition zone are thought to be due to higher litter input, rather than geological processes.

Compaction effects

Some of the other physical measures show their highest values in the transition zone. Samples from layer 1 in the Burnt site are thickest in the transition zone. This is thought to be because of a greater accumulation and retention of organic input in this zone, sheltered from high winds by the forest, which may also provide additional litter sources.

Table 6.16 Comparing the value of variables indicative of physical compaction in the transition zone

Site	Burnt Site '92 Layer 1			Burnt Site '92 Layer 2			Punta del Este '94		
Variable	Significance Test		Highest	Significance Test		Highest	Significance Test		Highest
Thickness	C vs. TZ	H. SIG	**TZ**	C vs. TZ	-	***(C)***	C vs. TZ	-	***(C)***
	TZ vs. F	SIG	**TZ**	TZ vs. F	-	***(F)***	TZ vs. F	-	***(F)***
Mean Depth	C vs. TZ	H. SIG	**C**	C vs. TZ	H. SIG	**TZ**	C vs. TZ	-	***(TZ)***
	TZ vs. F	SIG	**F**	TZ vs. F	-	***(TZ)***	TZ vs. F	-	***(TZ)***
Bulk Density	C vs. TZ	H. SIG	**C**	NOT SAMPLED			NOT SAMPLED		
	TZ vs. F	-	***(TZ)***						

The variables associated with trampling such as soil bulk density and mean layer depth (particularly of layer 1 samples) might have been expected to match this pattern, because of the intensive clearance activity required to create the straight cut edge. However, cleared sites tend to show the greatest compaction. This may actually be the case, or sites in felled regions of the transition zone may actually be more compacted, but this is masked by the lower values obtained for transition zone sites within the standing forest.

6.6.3 Summary

This analysis has been able to show that there are many statistically significant differences between environmental properties measured at different locations in the field sites, which are the result of mangrove clearance and drainage. As expected, the most consistent difference between the zones is one between samples from forest and cleared zones. This statistical analysis also provides a suitable arena to test the utility of the variable classifications developed in chapter three. The variables affected by litter input generally show very clear trends, such as those seen in the values of the exchangeable cations. The marine and drainage process-influenced variables encompass a wide range of measures. The initial conceptualisation seems to have been too wide ranging, in the sense that it contains many variables where the resulting pattern is better explained by a more specific grouping. An example of this is the level of exchangeable sodium, which seems to be explained by variation in litter input. Geological and terrestrial sedimentation processes have been shown to exert only a very minor influence upon the value of soil and water properties at the field sites. The value of many of these variables such as calcium, seem to be more influenced by litter input.

In general, the data strongly support the existence of differences between environmental properties measured in the forest and cleared zones. Samples from the transition zone vary in their behaviour. For some properties, e.g. dissolved oxygen and organic carbon content, they are distinctly higher than the other two zones. For others they seem to represent intermediate values, or a mosaic of alternating forest and cleared properties. This can be interpreted as showing the highly variable-specific shape and nature of the transition zone.

6.7 Conclusions: Trends at different sites

The discussion above has primarily been concerned with a search for zonal differences. However, because this chapter uses the randomly sampled areal data from the 1992 Burnt site and the intensive three transect sampling data from the 1994 Punta del Este site it is also possible to compare these two areas[4]. The changes predicted in chapter three can be detected in the field sites, with the 1992 Burnt site showing values characteristic of a recently cleared but undrained site. The other site, Punta del Este shares some of these characteristics, but is probably better considered as a site experiencing surface drainage, because of features such as a higher redox in the cleared zone. This is consistent with the drainage activity seen at this site, which contrasts with the standing water saturating the soils of the Burnt site in 1992.

Patterns resulting from similarities and differences between the field sites examined in this work are investigated further in the next few chapters. The pattern of change in measured properties is considered transect by transect in chapter nine, with a particular focus on the 1994 fieldwork. This is proceeded by a holistic ordination analysis of the data in chapter seven, to complement the reductionist work considered to date. It also extends the consideration of the transition zone, elaborating on the patterns found in this chapter. Finally, it brings in the 1994 transect work, comparing the trends found at all the field sites.

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[4] Although this is hindered slightly by the difference in variables measured at these two sites.

7

Ordination: investigating site variation in more detail

The need for ordination

The previous chapter tested a series of hypothesised differences between cleared and forested areas by comparing the values of measured soil and water properties. The fact that many variables did show statistically significant differences in their values when measured in these two zones, corroborates the first research hypothesis. This shows that because of selected clearance, the soil and water properties in these two zones are different, in measurable ways. This conclusion is given greater weight as the number of variables showing such a difference increases.

However, such a comparison adopts a reductionist approach, assuming that the essential overall difference in these two zones will be retained if we analyse it "by dissection" - using a series of single variable comparisons. The nutrient budget development in chapter three has shown the interdependence of many processes and thus measurable variables in the mangrove ecosystem. Therefore, the research programme (shown earlier in Figure 5.16) was designed to complement the individual analyses of the previous chapter with a more holistic perspective, one which looks at interactions of all the variables *together*. A technique which allows this is ordination, and its application to the mangrove data is the subject of this chapter.

Ordination techniques will be used to answer the following questions:

1. To investigate whether there are environmental gradients (spatial patterns of difference) extending across the 1992 field site which are expected because of the selected mangrove clearance.
2. To see whether similar gradients can be detected across the 1994 field sites, given that they are in different locations and different stages in the clearance process.
3. By combining ordination analysis with related mathematical classificatory techniques, it is also possible to assess the validity of the cleared, transition zone and forest field site classification, used in previous chapters.

7.1 The principles of ordination

Ordination, a graphical method, has been widely used in ecological studies as a means of detecting relationships between plant species (or communities) located at sample "sites". Many studies also include measurements of environmental data (primarily soil properties) e.g. Purata (1986); ter Braak (1987); Birks *et al.* (1990). A general definition is given below:

> "Ordination is the collective term for multivariate techniques that arrange sites along axes on the basis of data on species composition."
>
> ter Braak (1987, p91)

Ordination includes methods such as multidimensional scaling, component analysis, factor analysis, and latent structure analysis, all of which have a common mathematical approach:

> "In ordination, sites and species are arranged along axes that represent theoretical variables in such a way that these arrangements optimally summarise the species data"
>
> Jongman (1987, p5)

> "The result of ordination in two-dimensions (two axes) is a diagram in which sites are represented by points in two dimensional space. The aim of ordination is to arrange the points such that points that are close together correspond to sites that are similar in species composition, and points that are far apart correspond to sites that are dissimilar in species composition. The diagram is a graphical summary of data."
>
> ter Braak (1987, p91)

This powerful technique has also been applied in other fields by substituting different factors in place of the ecologists' "species", "site" and/or "environmental" variables[1]. Examples of such applications include those of Hassink *et al.* (1991) who studied microbial populations in reclaimed polder soils; Odeh *et al.* (1991) who used canonical correspondence analysis to investigate soil-landform relationships; and ter Braak & Wiertz (1994) who analysed vegetation change following drainage and soil acidification.

Ordination studies of mangroves are rare, one of the few authors using ordination techniques is the Nigerian Imoh Ukpong (Ukpong, 1992; Ukpong 1995; Ukpong & Areola, 1995). In these studies, principal component analysis techniques are used to show relationships between soil measurements and vegetational characteristics. In one study (Ukpong, 1992) this is taken a step further and canonical

[1] In the case of the data considered in this work, the zonal classification of "cleared", "transition" and "forest" is equivalent to the term "species"; and the soil, water and other environmental properties measured at each sampling point (a "site") are considered "environmental data". Ordination of these data should allow the separation of sites into the three zones, by mathematically combining the values of the measured environmental variables in such a way as to maximise any difference between these zones.

correspondence analysis is used to show that salinity and nutrient variations are the primary controlling factors in a soil-vegetation relationship (mangrove zonation) for *Avicennia* dominated mangroves in Nigeria.

7.2 The choice of ordination method

The term ordination can be applied to a *suite* of statistical techniques. The choice of exactly which technique is most appropriate depends upon two factors: the purpose of the investigation (the type of gradient analysis) and the nature of the data relationships expected.

Gradient analysis

Ordination methods are used in ecology for gradient analysis - to reveal changes in properties over space. Gradient analyses can be subdivided into two approaches: indirect and direct. Indirect gradient analysis involves simply studying the changes in plant species over a range of sites distributed in space. Whilst such work infers an underlying environmental gradient, actual environmental properties are not measured, or included in the analysis. In such applications, the true cause of the gradient cannot be unequivocally identified. Direct gradient analysis is a method of ecological interpretation where the focus is not just on for instance, the plants, but where

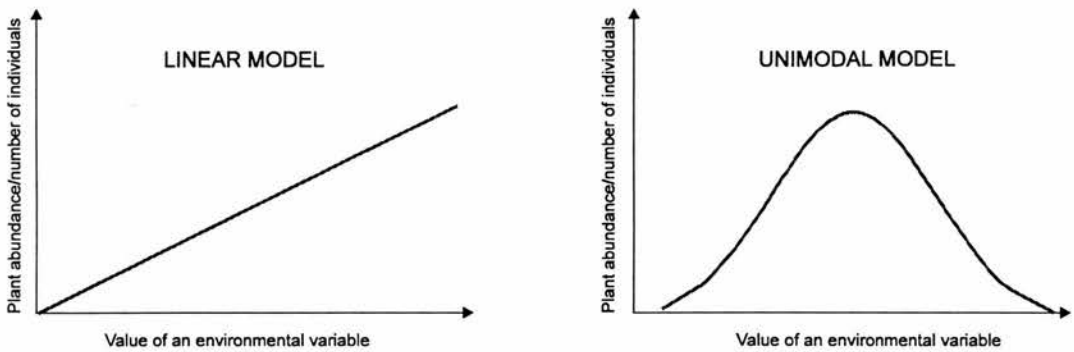
> "...one is interested from the beginning in particular environmental variables, i.e. either in their influence on the species as in a regression analysis... or in their values at particular sites..."
>
> ter Braak (1987, p93).

Both these techniques can be applied to this study. Indirect gradient analysis of the environmental data alone, without any indication of which vegetation zone the sample points belong, can be used to evaluate the three zone (forest, cleared and transition) field site classification. Secondly, direct gradient analysis can be used to investigate specific vegetation soil relationships at the field sites. There are very few published direct gradient analyses of mangrove plant-soil relationships. Ukpong (1995) attributes this absence to the complex hydrology of many mangrove areas. The tidal inflow, outflow and seepage act to obscure any environmental gradients present at the sites. Yet most of the published studies have been located in estuarine mangrove areas, where these effects are likely to be most acute. The Burnt field site considered in this study is effectively ponded at both the landward and seaward ends, which will severely curtail water movement across the site. The Texaco field site examined in 1994 is located some distance inland, and hydrological movements around the 1994 Punta field site will be dampened by the terrestrial drainage and the nearby canal. Therefore, the hydrology of these areas is expected to be more stable, allowing the use of direct gradient methods.

Assumed plant species-environmental relationships

The second factor influencing the choice of ordination method concerns the form of the relationships expected between the measured environmental variables and the plant species. These can be divided into two types: linear and unimodal, which are shown below in Figure 7.1.

Figure 7.1 Assumed relationships between plant species and environmental variables

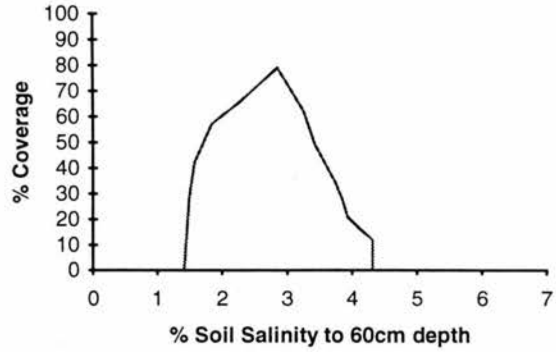


The linear model in Figure 7.1 shows a positive relationship, but a negative one is equally possible. For a finite range, changes in the value of the influencing environmental variable are matched by an appropriate change in the number of the affected plant species at a site. An example of such a relationship would be the number of acid loving plants, such as heathers, found at temperate sample sites increasing as the soil pH fell, where the pH range across the sites was such that the relationship was effectively linear. The linear model is essentially unbounded, in that it assumes that such relationships theoretically continue in a linear pattern.

The unimodal model also shows the relationship between the number of a given plant species and the value of an environmental variable, but assumes that the plant shows a varying tolerance to the environmental property. For example, too much of a nutrient and the plants will suffer from toxicity, too little and the plants will be under-nourished. This latter unimodal model fits well with mangroves' known tolerance response to properties such as salinity, pH and redox potential discussed in chapter four, therefore in this investigation a unimodal model is assumed for the plant-environmental relationships.

This assumption is supported by the work of Ukpong (1991), who examined the distribution of mangrove species along a salinity gradient. His work shows that mangroves' responses to salinity gradients are generally unimodal, with a few bimodal exceptions. Figure 7.2 below shows one of his response curves for *Rhizophora mangle*.

Figure 7.2 Salinity tolerance of Rhizophora mangle



This figure shows how the percentage red mangrove cover at sites varies with soil salinity. Salinity was measured as an average value from soil samples taken to a depth of 60 cm. The pattern of variation seems to follows a unimodal pattern.
Source: From Figure 2a in Ukpong (1991).

Table 7.1 below, groups the choice of available techniques according to the type of gradient analysis required and the assumed response. The table excludes common gradient analysis methods based upon regression and calibration techniques such as generalised linear modelling (GLM) and weighted averaging of environmental variables (WAE) because their limited capacity for dealing with more than one environmental variable at once renders them unsuitable for this application. In addition to the traditional ordination techniques, the table also contains references to *canonical* ordination techniques, which are somewhat of an intermediate:

> "Between regression analysis and ordination (in the strict sense) stands the canonical ordination techniques. They are ordination techniques converted into multivariate direct gradient analysis techniques; they deal simultaneously with many species and many environmental variables. *The aim of canonical ordination is to detect the main pattern in the relations between the species and the observed environment.*"
>
> ter Braak (1987, p93), emphasis added.

Table 7.1 Gradient analysis techniques

	indirect gradient	direct gradient
linear	PCA	RDA
unimodal	CA DCA	CCA DCCA

PCA: principal components analysis; RDA: redundancy analysis;
CA: correspondence analysis; CCA: canonical correspondence analysis;
DCA: detrended correspondence analysis; DCCA: detrended canonical correspondence analysis.
Source: ter Braak (1987-1992).

This shows that two techniques are suitable for indirect gradient analysis of unimodal data: correspondence analysis (CA) and detrended correspondence analysis (DCA). Detrending removes the so-called "arch effect" which is a result of polynomial relationships between the ordination axes (discussed more fully in Hill & Gauch (1980)). Detrended correspondence analysis is the more widely used indirect gradient technique and for this reason will be applied to the sample data.

It is interesting to note that the linear based PCA method employed in the studies of Ukpong & Areola (1995) and Ukpong (1995) seems an unusual choice given the unimodal response models demonstrated in earlier work (Ukpong, 1991).

For direct gradient analysis, the choice lies between canonical correspondence analysis (CCA) and detrended canonical correspondence analysis (DCCA). Detrending in direct gradient analysis is far less common, particularly in applications looking at mangrove plant-soil relationships. Therefore, CCA was selected as the technique for use in direct gradient analysis. Canonical ordination techniques have been found to be superior to normal ordination techniques for applications (such as this one), where it is important that the ordination axes correspond to the environmental variables. It is able to achieve this using the regression techniques contained within its computative algorithms (ter Braak, 1987-1992).

> "Canonical ordination techniques are designed to detect the patterns of variation in the species data that can be explained 'best' by the observed environmental variables. The resulting ordination diagram expresses not only a pattern of variation in species composition but also the main relations between the species and each of the environmental variables. Canonical ordination thus combines aspects of regular ordination with aspects of regression."
>
> ter Braak (1987, p137)

The two strand approach of indirect gradient analysis followed by direct gradient analysis may at first seem unnecessarily repetitive. However, this two step analysis was chosen to ensure that the differences identified in the species data, resulting from ordination with environmental data correspond to sensible patterns which can be identified in the field. This approach therefore seeks to avoid one of the potential failings of ordination focusing on environmental data:

> "Ordination of environmental data will reveal the main variation in it, this may <u>not</u> correspond well with the major variation in plant species. If a single environmental variable is important for the species and many more variables are included in the analysis, the first few axes of the environmental ordination mainly represent the relations amongst the unimportant variables and the relation of the important environmental variable with the species data wouldn't be found. It is therefore better to search for the largest variation in the species data first and to find out afterwards which of the environmental variables is influential."
>
> ter Braak (1987, p136)

7.3 Preparing the data

Several datasets were produced from the field site measurements, each one tailored to a particular ordination investigation. These datasets can be divided into two, those containing environmental variables and those containing data about the vegetation cover at each sampling point. For the direct gradient analysis, these datafiles are commonly referred to as the "environmental data" and the "species data", respectively. Confusingly, these terms are not consistent with those used in this implementation of indirect gradient analysis. This stems from the fact that these latter techniques, originally designed for ecological analysis focusing on the plant variables ("species" data), are in this case being applied to a study focusing on soil and water data. This means that the indirect gradient analysis "species" data actually contains the soil and water variable measurements. In an attempt to maintain clarity, in this work regardless of the ordination technique used, datasets of vegetation cover information will always be referred to as "species" data, and datasets containing the environmental properties measured at each sample site will be referred to as "environmental" data.

The "species" dataset was generated for each field site using the three unit nominal classification for each sampling point, assigning it a value of one for the zone in which it is found, and zero for the other two, as shown below:

Sample point location	C1	C2	..	C35	TZ1	TZ2	..	TZ8	F1	F2	..	F35
Cleared Zone	1	1		1	0	0		0	0	0		0
Transition Zone	0	0		0	1	1		1	0	0		0
Forest Zone	0	0		0	0	0		0	1	1		1

For the first data column, sample C1 lies in the cleared zone and so a 1 is placed in this row, the other "species" categories, the forest and transition zones are therefore filled with zeroes. This pattern continues until sample TZ1 is reached. This lies in the transition zone, so a 1 is placed in the transition zone "species" row and a zero is placed in each of the others. When F1, the first forest zone sample is reached, a one is placed in the forest zone species column and the cleared and transition zones are each given a score of zero.

Whilst crude in comparison with the true plant species lists of many other ecological applications of ordination, this classification does still highlight differences between the measured soil and water properties in the three zones. Whilst recording the individual plant species found at each of the sampling points was theoretically possible, such an approach was rejected for two reasons:

1. In cleared areas and much of the transition zone, there are very few live plants to record. Even in the forest, in most cases the list of recorded species would not extend beyond *Rhizophora mangle* and *Avicennia germinans*, and thus this approach would not produce significantly more classes.
2. Secondly, this approach was thought to be misleading. Because of the small sampling interval used, points were often located below the same plants, which would result in a duplicated reporting of individuals. Also in many cases, even if there was only one of the mangrove species directly overhead, the ground in which the sample was taken contained roots from both species.

The validity of this three zone species classification is considered further in Section 7.4.

Environmental variable datasets were prepared for each field site, listing each of the soil, water and other environmental properties in a form similar to that shown below[2]. Properties measured on an interval and ratio scale were included in the analysis, with the exception of obviously redundant pairs (e.g. only one of the percent soil greater than 2 mm e.p.s. and percent soil lower than 2 mm e.p.s. were included). The redox potential values also required modification to remove negative values which cannot be used with these techniques. This was achieved by adding 400 mV to all values, which merely altered the mean redox value but not the shape of the distribution of the redox measurements.

Sample point location	C1	C2	..	C35	TZ1	TZ2	..	TZ8	F1	F2	..	F35
Soil pH	6.90	6.81		5.98	6.78	6.79		6.74	8.12	8.02		7.87
Exch. Magnesium	0.03	0.01		0.08	0.00	0.01		0.01	0.03	0.04		0.08
.												
.												
Bulk Density	0.9	0.7		0.1	1.0	1.6		0.8	1.2	1.3		1.3

In a similar manner to the creation of datasets for the 4D models of chapter six, the datasets used for CCA were not screened for potential "extreme" values. Such screening would require assumptions to be made about the data[3] which earlier descriptive statistical analysis had shown could not always be justified.

The list of potential variables which could be included in an ordination diagram is effectively infinite, but it should be restricted to the ones which actually make a significant contribution to the classification. The number of variables used to generate the diagrams was reduced using two criteria - considering whether they duplicate other variables already included, and through comparison of their explanatory power. Two sets of routines were employed for these purposes. Duplication of effect was detected using a correlation matrix and tests for covariance carried out automatically during the process of ordination axes determination. Measures of the strength of the relationship between the ordination axes and a given environmental property (their explanatory power) can be determined using tests of significance. Such testing can be carried out within the ordination program using a student's *t* test. The results of CCA using such reduced datasets are considered in Section 7.5.

During the ordination analyses, the environmental data are automatically standardised, so that the ordination plots are not distorted by the units of measurement used. For example, without

[2] All the files used in the analysis are of the "Cornell Condensed Ecology" format. For clarity in these illustrative examples, many of the formatting requirements (such as variable naming conventions, file headers, FORTRAN input instructions, etc.) have been omitted. Full details of this format can be found in ter Braak (1987-92).

[3] For example techniques such as excluding values greater than ± 2 SD assume that the data are normally distributed. This becomes more complicated when the samples are classified - should the sample mean refer to the entire dataset, or just the sub-set of a given classification? Decisions such as this introduce bias into the sampling that would hinder the testing of the zonal categories later in this chapter.

standardisation, differences in the value of soil exchangeable manganese which has a range of 0.002 to 0.017 $cmol_c\ kg^{-1}$ in the upper layer of samples from the 1992 Burnt Site would otherwise be completely swamped by differences in properties such as exchangeable calcium (range 1.47 to 11.23 $cmol_c\ kg^{-1}$) and soil redox potential (range -264 to 326 mV NHE). This standardisation is achieved using the mathematical transformation:

$$\text{standardised datapoint} = \frac{\text{raw datapoint - mean}}{\text{standard deviation}}$$

The analyses considered below are discussed in chronological order. The first analyses look at the results of the 1992 fieldwork, which measured a very wide range of environmental properties at a single site. Indirect gradient analysis is applied first, to investigate the validity of the vegetation zone classification used at this site. From this, direct gradient analysis of both the soil and vegetation data is possible, revealing the causes of environmental gradients present across the field site. This process is then repeated for the three sites looked at in 1994, revealing differences in these gradients because of their different stages in the process of clearance.

7.4 1992 Fieldwork: Indirect gradient analysis of the Burnt site

Up until this point, the field sites have been classified using a simple zonal classification. This arose from two sources: vegetation cover differences observed in the field (giving the forest and cleared categories), combined with sampling considerations (the attempt to introduce a third, transition zone). It was felt to be useful at this point to test this "visual" classification against more objective numerical approaches. The success of such classifications can be tested by applying divisive and agglomerative classification methods to the results of an indirect gradient analysis.

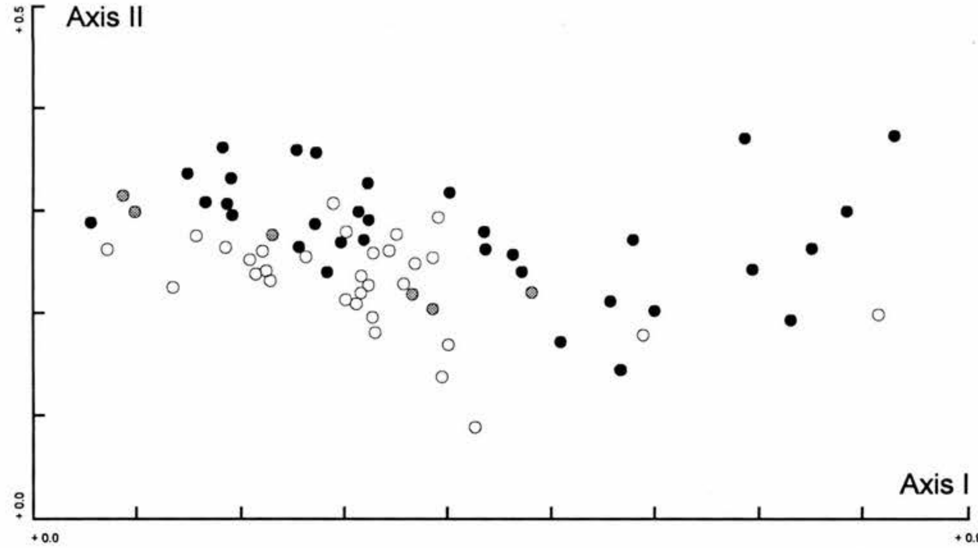
A detrended correspondence analysis is first applied to the environmental variables measured across the Burnt 1992 field site, without reference to the vegetation cover at each sampling point. This results in an ordination, separating the sample points according to differences in the combined values of the measured environmental properties. Sample points with similar ranges of environmental properties will lie close together in this ordination space. Assuming that the vegetation cover is influenced by the value of these environmental properties, we can use the distribution of these sample sites in the resulting ordination space to test the original classification scheme against mathematical classifications generated using measures of sample similarity and difference to define groups (clusters) of samples. This process begins with a detrended correspondence analysis of the layer 1 data from the 1992 Burnt field site.

Detrended correspondence analysis was carried out using the program CANOCO version 3.10 (ter Braak, 1987-1992), which incorporates the DCA routines used in the DECORANA program of Hill (1979). It offers a range of options to tailor the analysis to the user's requirements. For this simple analysis, the default options were accepted, which included no (further) transformation[4] of the sample data.

7.4.1 Detrended correspondence analysis - Burnt site layer 1 data

The diagrams below show the results of applying DCA techniques to the environmental variable data for samples collected from the upper soil layer. Figure 7.3 shows the position of the sampling points in the resulting ordination space, and Figure 7.4 shows the way the measured environmental properties were combined to create this ordination space.

Figure 7.3 Detrended correspondence analysis: 1992 Burnt site layer 1 - sample sites



Ordination Axis I - the horizontal axis - has an eigenvalue of 0.043, Axis II has an eigenvalue of 0.004. Together they account for 80.7% of the variation in the environmental data shown. The ordination axes have been created from linear combinations of the environmental variables which maximise the dispersion of dissimilar points.
The three zone classification has been applied to each sampling point after the DCA. Samples in the cleared zone are represented by open circles and show a tighter clustering than those in the transition zone (grey-shaded circles) and those in the forest (solid black circles).

Looking first at the position of the environmental variables, the detrended correspondence analysis shows an arrangement along two axes. The horizontal axis (Axis I) in Figure 7.4 is difficult to interpret, many of the measured properties show very similar values for positive regions of the diagram. For negative values, an increase in soil extractable phosphorus (orthophosphate) can be seen. Therefore, this axis is thought to represent changes in soil phosphorus levels, possibly as a result of changes in the feeding habits of birds and crustaceans. The pattern along the vertical axis (Axis II) is clearer: a gradient with high values of dissolved oxygen, ammonium-N, organic material, and exchangeable cations for positive values, and low values of soil redox potential, water pH and bulk density for negative values. This gradient seems to relate to high litter and atmospheric nutrient inputs for positive values, consistent with an undisturbed, anaerobic mangrove forest. Negative values reflect the properties of the cleared area - increased soil compaction, a decrease in acidity and increased oxidation of the soil. Thus this gradient can be thought of as indicating site disturbance.

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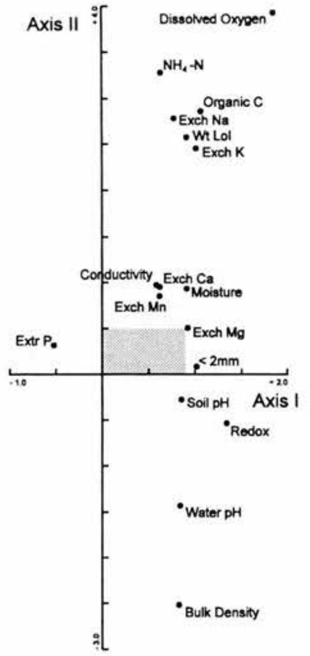
[4] The program automatically standardises the datavalues.

Figure 7.4 Arrangement of environmental variables in DCA ordination space: layer 1 data



This diagram shows the position of the environmental variables in the ordination space. Values near an ordination axis are used to identify the environmental gradient that this axis measures. Increasing distance from the origin shows environmental variables to have a greater influence upon these inferred gradient(s). The shaded area represents the portion of the diagram shown in Figure 7.3 above. The axes are interpreted in the accompanying text.

Returning to Figure 7.3 the detrended correspondence analysis can be seen to have separated the sampling sites in such a way that their grouping is similar to the existing cleared, forest and transition zone classification. Sites located in the forest tend to lie high up Axis II, those in the cleared zone lie further down this axis, reinforcing the idea from the interpretation of Figure 7.4 that this axis corresponds to disturbance. Samples in the cleared zone also tend to be located at low values along Axis I, indicating higher levels of extractable phosphorus. Interpretation of soil phosphorus values is notoriously difficult because of this variable's high inherent variability. This caveat is even more relevant given the one off nature of these measurements. However, this trend in phosphorus values is thought to be the result of higher number of wading birds exploiting the lack of cover for crabs feeding in the cleared zone. As might be expected, dispersion along this axis is far greater, indicating a high degree of variability in extractable phosphorus all over the field site.

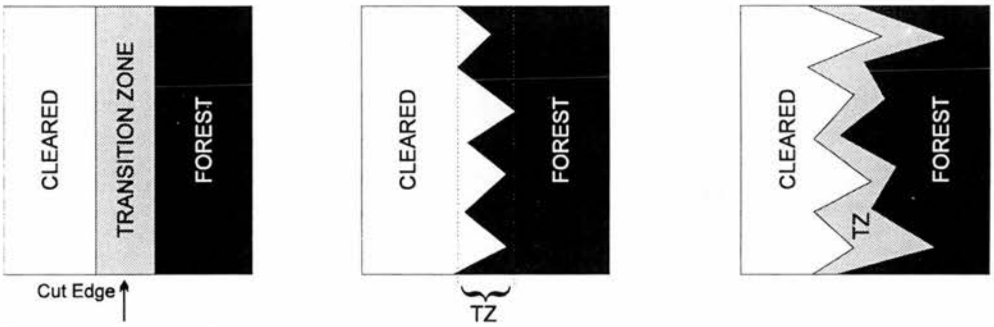
The sample sites in the cleared zone show the tightest clustering, those in the forest show the greatest dispersion. The position of samples considered to be in the third sampling unit - the transition zone - is less clear. This can be interpreted in one of two ways:

1. Some sites, e.g. TZ5, TZ6, TZ7, seem to lie in an area of overlap between the forest and cleared zones, suggesting that the transition zone is really just a subset of the two other sample units, with no characteristics unique to itself.

2. Alternatively, these points could be used to support the idea of a completely separate third zone, possibly containing more points, some of which are presently classified as either forest or cleared.

These differing interpretations suggest that the shape of the transition zone may need further thought. In the earlier, statistical conception it was represented by a simple rectangular zone, centred on the cut forest edge and overlapping areas in both the cleared and forest zones. Upon reflection, this appears rather simplistic. If the critical difference between the cleared and forest sites is the presence or absence of vegetation, then the shape of any intermediate zone must take into account the pattern of change dictated by the distribution and form of the trees. Applied to a transition zone, this means that such a zone may have a highly irregular outline, occupying an interleaved area between the cleared and forest zones, whose shape results from the pattern of root distribution, litter fall, shade, etc. As such, there is not really one universal transition zone, but rather a series of variable-specific transitions. These different conceptualisations of the transition zone applied to the field site are illustrated in plan view in Figure 7.5 below:

Figure 7.5 Three possible conceptualisations of the field site



1. The conceptualisation of the three zones used in chapter five. The transition zone is essentially a buffer, with an even, rectangular shape centred on the forest cut edge.

2. In this example the edges of the cleared and forest zones have been redrawn, in a manner considered more representative of the distribution of measured values. The transition zone occupies the intermediate area of fluctuating values.

3. This figure uses a similar conceptualisation of the forest and cleared edge to the previous example. However, it considers the transition zone as completely separate, distinct from the other two.

Models 1 and 3 assume that values within the transition zone are relatively uniform, allowing it to be given the status of a third class. In model 2 values in the transition zone fluctuate wildly and are more properly thought of as being either forest or cleared values. Models 2 and 3 view the effective edges of the forest and cleared zone to be highly irregular, possibly different for each variable measured. Model 1 represents the edges as linear. Which of these three conceptualisations best represents the field site is considered below.

7.4.2 Methods of classification

These three different possible interpretations highlight the subjective nature of classification. Several mathematical techniques have been developed in an attempt to assist in this process. These use numerical measures of similarity or difference between the properties of samples to provide a multilevel classification. Yet, they remain subjective because the number of classes selected, i.e. the level of classification chosen, is still defined by the user. These multilevel classifications are often termed hierarchical and can be divided into two: agglomerative and divisive methods (van Tongeren, 1987). Agglomerative methods begin by assuming all the data points are effectively individual classes and attempt to combine them using measures of similarity, reducing the number of classes with each iteration. Divisive methods take the opposite approach, they begin assuming all the datapoints are similar and use measures of difference (more properly referred to as measures of dissimilarity) to divide the data creating multiple classes, the number of which increases with each iteration. In order to consider the validity of the vegetation cover sampling schemes in a more quantitative way, methods reflecting both these classificatory approaches have been applied to the field site data.

Agglomerative methods

Two factors are important in this process and divide the range of available methods. These are differences in the way individual similarity comparisons are measured mathematically (often referred to as the similarity indice) and the way an approach compares the similarity of groups. Most of the similarity derived indices have been developed by ecologists and botanists (e.g. Jaccard, 1912; Sørensen, 1948) and many of these have been designed for abundance data, often on a nominal scale of measurement. Looking at possible methods suitable for applications using soil data, Webster & Oliver (1990) have shown that Gower's similarity coefficient (Gower, 1971) is a suitable measure. It can be used with a wide range of data, measured on both continuous and discrete measurement scales. Therefore, this method was used to calculate a similarity index for the fieldwork data.

The selection of a particular agglomerative method for use with soil and water data is far less clear-cut. Webster & Oliver (1990) state that no one particular method is suitable for all applications and advocate the trial of several methods A range of standard agglomerative methods available in the multivariate statistical programme MVSP Plus (Kovach, 1993) were applied to the sample data. The output of these analyses were generally poor, with the resulting classification dividing the sample sites into classes which seemed to bear little resemblance to the known distribution of vegetation cover across the site. Of these poor classifications, the best classification was that resulting from the use of the weighted centroid (median) method. This general lack of classification can be interpreted as revealing that when all the variables are examined together, the pattern of their variation is effectively continuous, rather than resulting in discrete zones in the soil and water which have very similar properties.

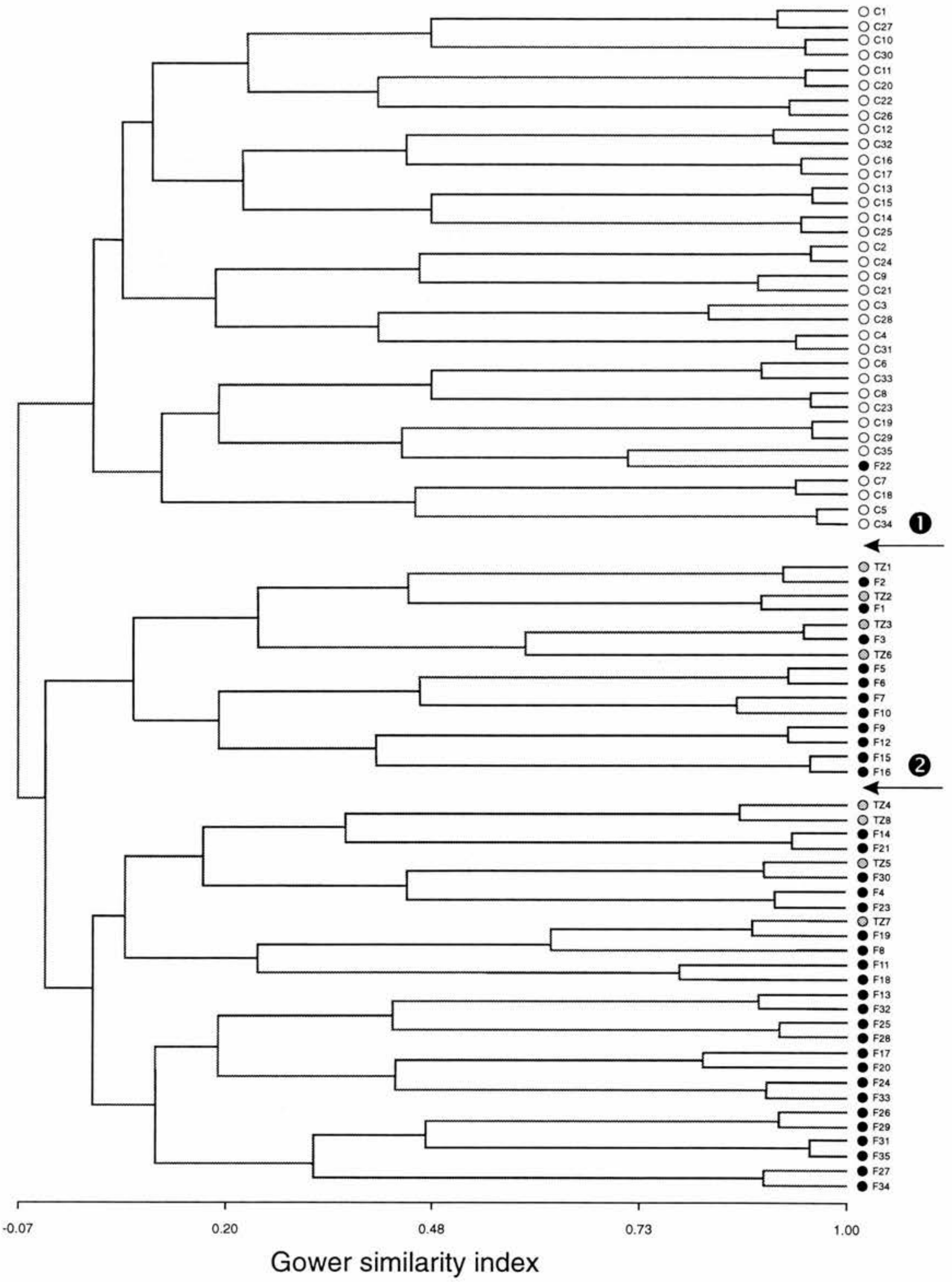
Before rejecting this analytical technique outright, the decision was made to repeat the analyses for a reduced environmental property dataset, in case a discrete pattern of change amongst some variables was being obscured by continuous change amongst the others. Thus, a new environmental dataset was created, containing only those variables which the detrended correspondence analysis had found to have a strong influence on the environmental gradient(s). These are bulk density, percent organic carbon, water pH, dissolved oxygen content, exchangeable calcium, soil ammonium-nitrogen and extractable phosphorus. Again, the weighted centroid (median) method was found to produce the best classification. This time, however, the resulting classification was found to correspond fairly closely to that used already in the field. The results of this analysis, expressed in the form of a dendrogram can be seen in Figure 7.6.

The sample sites in the dendrogram have been shown slightly separated to emphasise the two-group and three-group classifications of the data. At the final agglomeration (marked with arrow 1) the sites have been combined into two groups which show a very strong differentiation into samples from the cleared zone and those from both the forest and transition zone. Such a grouping suggests that soil properties in the transition zone are more similar to those in the forest than they are to those in the cleared zone. In some cases, soil conditions at sampling locations in the transition zone (e.g. TZ1) are more similar to another point in the forest (F2) than others in the transition zone. Looking at the earlier three group classification (arrow 2 on the dendrogram), it can be seen that two of these classes later combine to form the final "forest" class. This analysis, therefore, supports a view of the sampling units most similar to that shown in model 2 of Figure 7.5. Superimposing the two group agglomerative derived classification upon a detrended correspondence analysis of the seven selected environmental properties (not shown) resulted in a pattern broadly similar to Figure 7.3. The samples in the defined cleared zone (i.e. the upper subset of values shown in Figure 7.6) are slightly more tightly clustered, reflecting their greater similarity of values.

Divisive methods

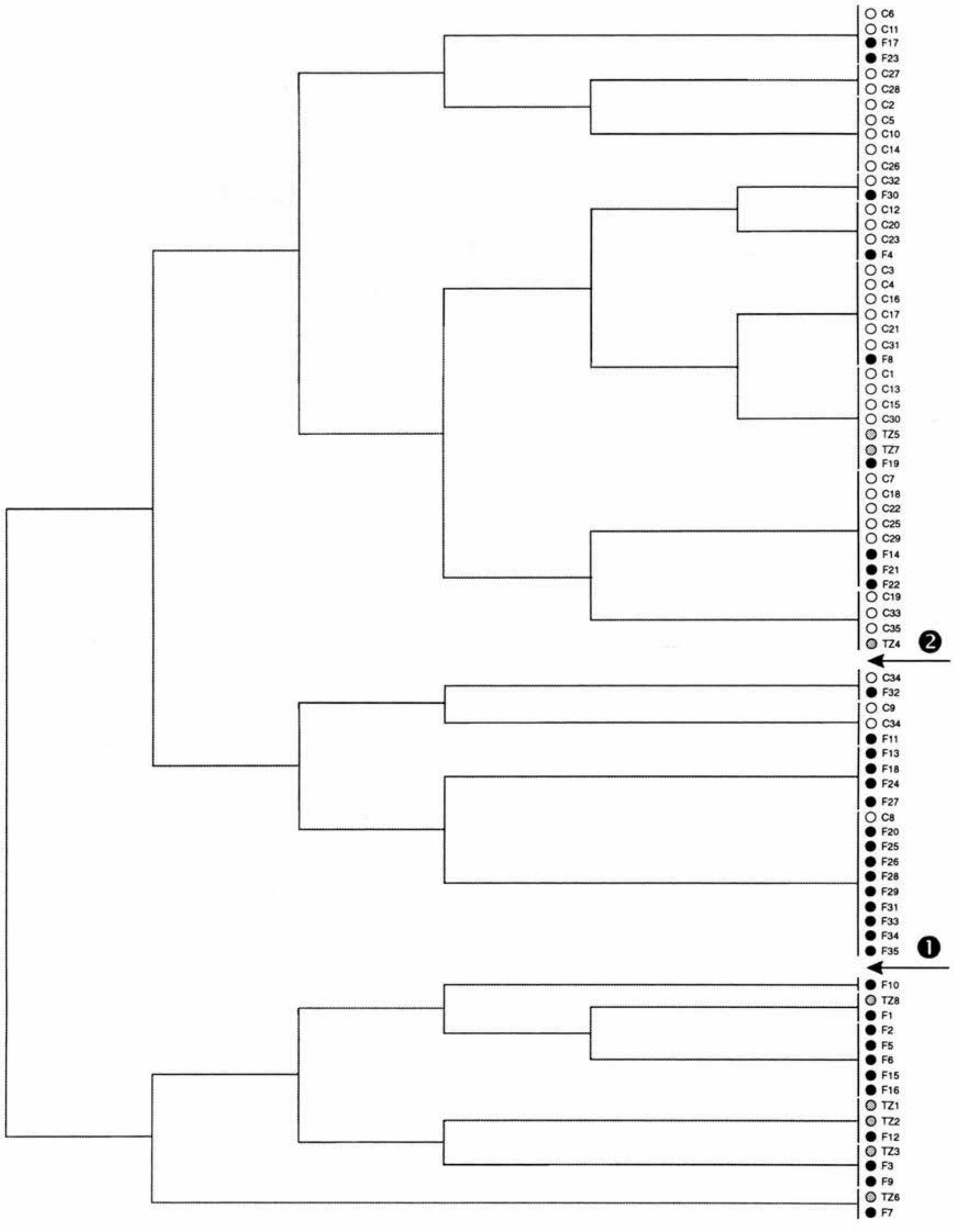
Divisive methods of classification are *not* commonly used in studies of soil mainly because they often result in groups which are rather heterogeneous with respect to the properties not used in the particular discrimination, (Webster & Oliver, 1990). This risks splitting weaker clusters actually present in the data. In the wider field of ecology one method has been very widely applied: two way indicator species analysis. This uses regression analysis techniques to establish the major sources of variation between groups of samples (Kershaw & Looney, 1985). For completeness, therefore, this divisive classificatory method was cautiously applied to the field site data using a revised version of the program TWINSPAN (Hill, 1994). Several TWINSPAN program configurations were tried, altering the values of the cut-off levels and the number of pseudo-species used to determine the classes. The most satisfactory results were obtained using the default options. Similar to the agglomerative methods, the results of TWINSPAN analysis of the complete soil property dataset were poor, with the classes identified having no obvious vegetational counterpart in the field. The analysis was repeated for the seven environmental variables selected above, which resulted in a slightly better classification. The results of this analysis are given below in Figure 7.7.

Figure 7.6 Dendrogram showing a weighted centroid classification of 7 selected environmental variables



The numbered arrows indicate the boundaries between possible classification groups discussed in the text. The dendrogram shows how individual samples are combined to form larger groups. The classification proceeds from right to left in this figure. Samples are shown as circles along the right hand side of the figure and have been coloured according to the three zone classification developed earlier. Samples from the forest are shown as solid circles, those in the transition zone as grey and the cleared zone samples are represented by open circles.

Figure 7.7 Dendrogram showing a TWINSPAN classification of seven selected environmental variables



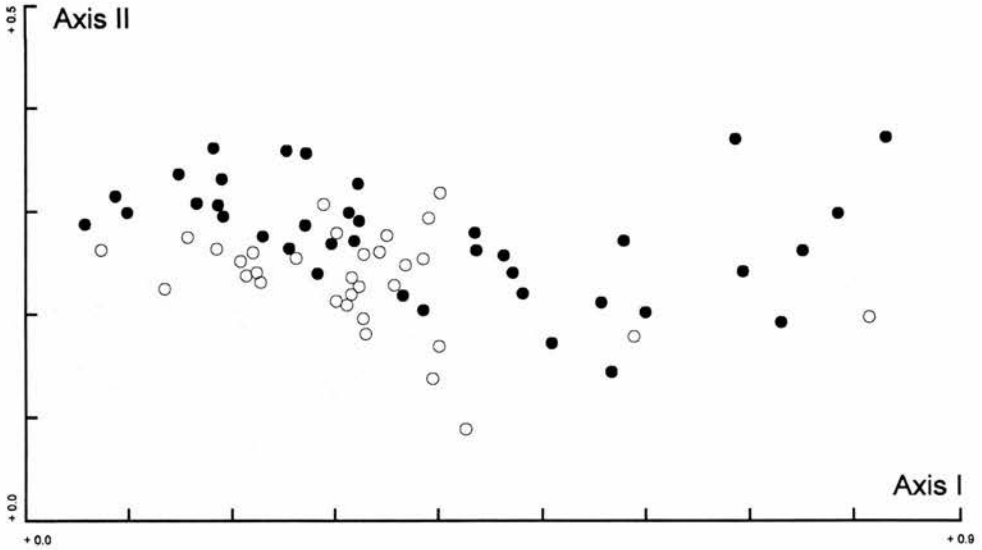
This dendrogram shows a divisive classification, which proceeds from left to right. The numbered arrows indicate boundaries between classes discussed in the text. The sample sites are coloured as before.

The TWINSPAN classification differs from that produced using agglomerative methods in that the division of samples occurs at regular intervals, corresponding to each iteration of the analysis. This means that the resulting dendrogram has evenly spaced branches. For this application, attention should be focused upon the first few divisions of the field site data, at the left hand side of Figure 7.7. These early classifications can be seen to produce a separation of the sites (listed along the right hand side of the diagram) such that one group contains samples predominantly from the cleared zone, and the other group samples predominantly located in the forest. The classification is slightly less able to separate forest and cleared sites than the agglomerative method considered above, doing so in three classes, rather than two. The most applicable classification seems to be considering the upper class in Figure 7.7 as a "cleared" class, and combining the lower two classes to give a "forest" class. It splits samples from the transition zone into groups dominated by both cleared and forest samples, justifying an extension of the transition zone in both directions. This division of sites from the transition zone weakly corresponds with the placement of these sites relative to the cut forest edge. Superimposing the TWINSPAN derived two group classification upon a detrended correspondence analysis of the seven selected environmental variables produced a pattern very similar to both that seen in Figure 7.3 and the ordination diagram constructed using the agglomerated classification.

Both classification methods show that the greatest difference between the collective environmental properties of the field site corresponds to the presence or absence of vegetation cover. This supports the general cleared-forest vegetation zone classification used in the field. Neither of these two approaches produce a definitive evaluation of the transition zone's validity. The TWINSPAN analysis seems to suggest reallocating these points between the two other zones, whilst the agglomerative methods suggest that the transition zone points could be subsumed completely by the forest class in a simple two zone classification. Neither method produces a three zone classification where the third zone seems to be predominantly composed of samples from the transition zone.

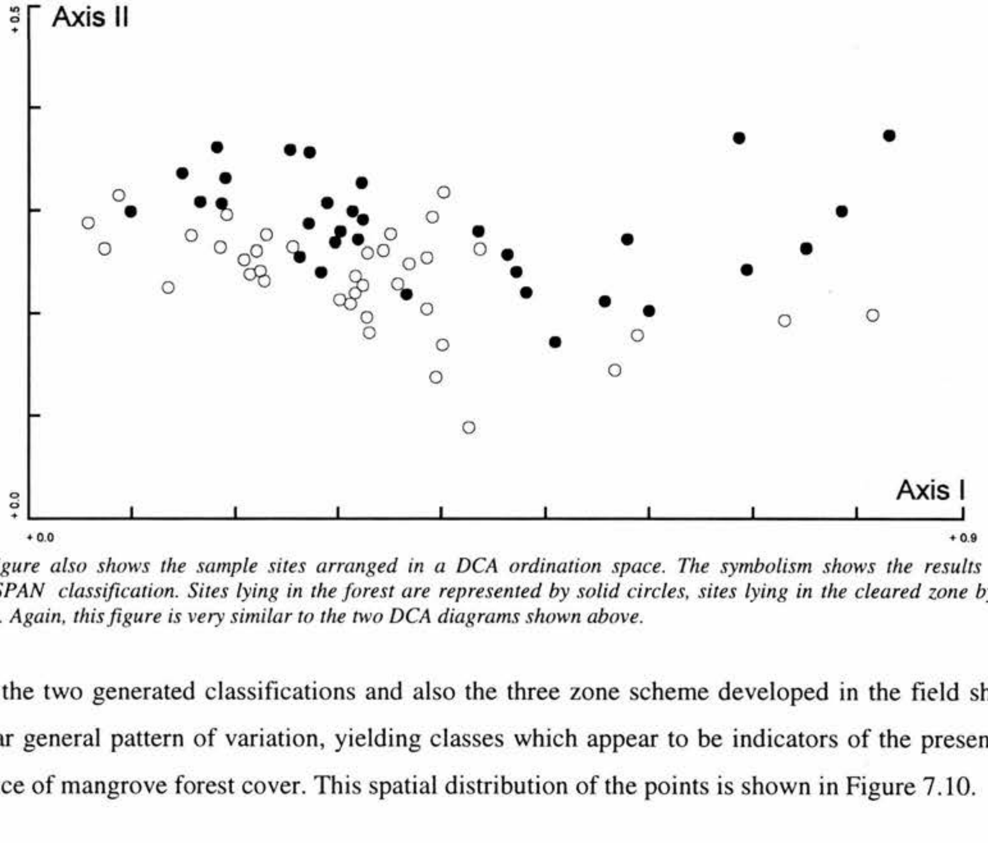
As a further comparison of classificatory methods, the two new classifications derived from the seven selected variables were applied to the detrended correspondence analysis ordination diagram produced using all the layer 1 environmental data. This allows the fit of the suggested classes to the data arranged in ordination space to be determined by eye. This is seen in Figure 7.8 and Figure 7.9.

Figure 7.8 Detrended correspondence analysis: 1992 Burnt site layer 1 - agglomerative classification



This figure shows the sample sites arranged in a DCA ordination space. The sample symbolism shows the results of the weighted centroid (median) classification. Sites lying in the forest are represented by solid circles, sites lying in the cleared zone by open circles. It can be seen to be very similar to the earlier DCA diagram given in Figure 7.3 above.

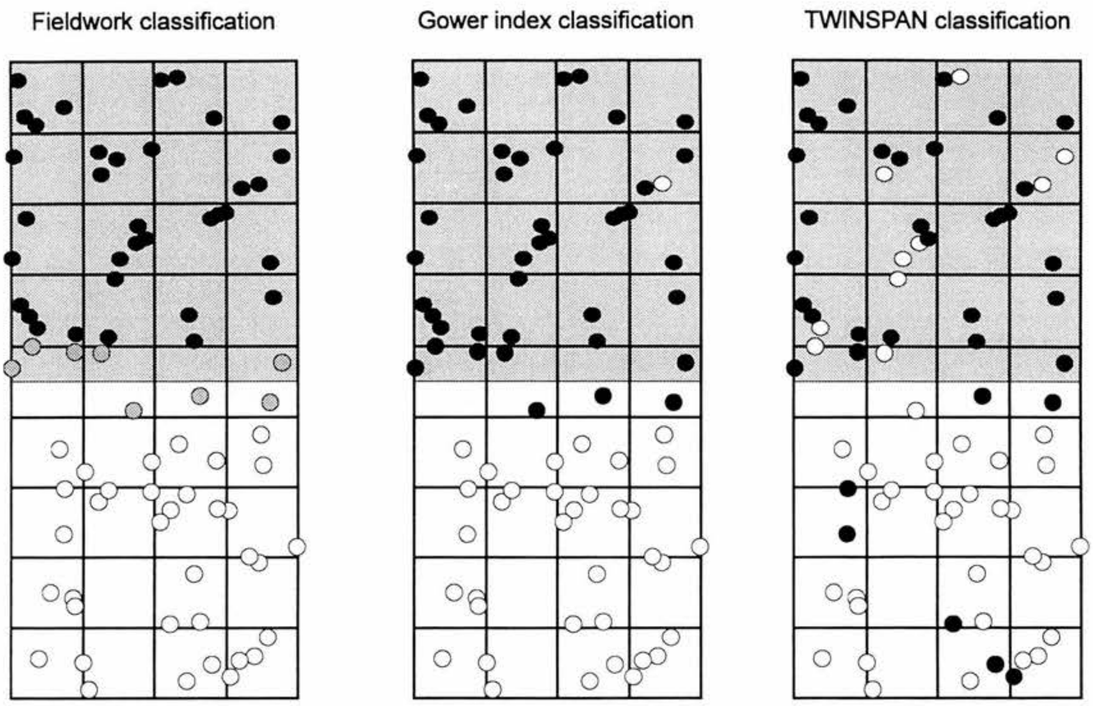
Figure 7.9 Detrended correspondence analysis: 1992 Burnt site layer 1 - divisive classification



This figure also shows the sample sites arranged in a DCA ordination space. The symbolism shows the results of the TWINSPAN classification. Sites lying in the forest are represented by solid circles, sites lying in the cleared zone by open circles. Again, this figure is very similar to the two DCA diagrams shown above.

Both the two generated classifications and also the three zone scheme developed in the field show a similar general pattern of variation, yielding classes which appear to be indicators of the presence or absence of mangrove forest cover. This spatial distribution of the points is shown in Figure 7.10.

Figure 7.10 The spatial distribution of the classified sampling points



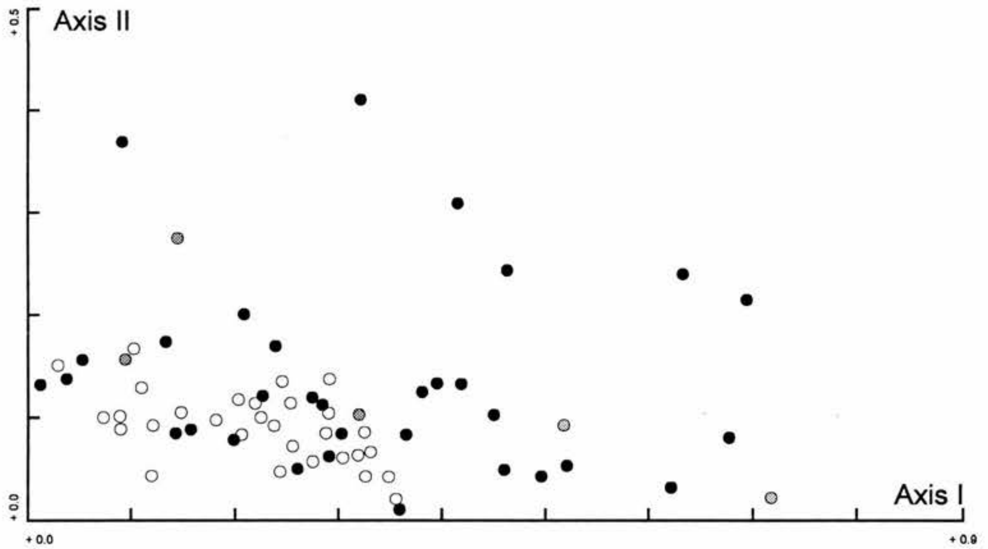
These diagrams show the field site in plan view, with the shaded area corresponding to the portion covered by mangrove. The left hand figure shows the three zone classification developed in the field. Points in the forest zone are shown as solid black circles, points in the transition zone are shown in grey, and points in the cleared zone by open circles. The centre and right hand diagrams show the sample points classified using the mathematically generated routines. For the Gower classification, points represented by open circles correspond to the first (upper) class shown on Figure 7.6, solid black circles the second. For the TWINSPAN generated classification, points shown as open circles represent the upper class from the second split on Figure 7.7, points shaded in black represent an amalgamation of the lower two classes.

Whilst a few differences exist between the allocation of some points to either the forest or cleared zones, this is not felt to detract significantly from the clarity of the classification. The important difference is in the number of groups they use, notably the lack of evidence from the mathematically derived classifications to support a distinct third zone. The most applicable models of the field site seems to be those which treat the cleared forest boundary as an irregular edge. Yet, there is still a case for retaining a third central zone - the earlier statistical comparisons of chapter six have shown that many of the environmental properties measured in the transition zone differ in value both from those in the forest and the cleared zones. This suggests that model 3 from Figure 7.5 probably describes the pattern most effectively, with the exact shape of the transition zone varying from variable to variable. For some measured variables the width of a distinct transition zone may be very small, or effectively zero, making it appear similar in shape to model 2. The fact that the transition zone did not figure strongly in the mathematically derived classifications is attributed to its heterogeneous nature. As it spans the cut edge, it is likely to show a wide range of values, at times spanning those from both the cleared and forested areas. Its small size may also mean that it is more prone to the effects of one or two extreme values affecting its representation in the resulting classification scheme.

7.4.3 Variations at depth

In order to investigate whether the observed differences continued below the soil surface, particularly in soils with a lower organic content, the detrended correspondence analysis was repeated for the environmental data collected at this site pertaining to soil layer two. The results of this analysis (shown in Figure 7.11 and Figure 7.12) can be seen to be very similar to that for the upper soil layer. The detrended correspondence analysis diagram again shows a pattern of tightly clustered sites in the cleared zone, surrounded by more widely scattered points lying in the forest. Between and at the edges of these two zones are the points from the transition zone. This distribution, therefore, supports retaining the chosen classification scheme for samples from surface and subsurface horizons.

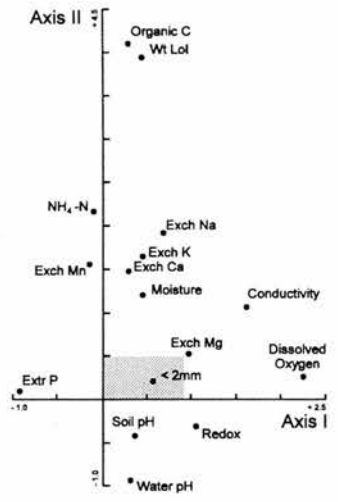
Figure 7.11 Detrended correspondence analysis: 1992 Burnt site layer 2 - sample sites



Ordination Axis I - the horizontal axis - has an eigenvalue of 0.033, Axis II has an eigenvalue of 0.010. Together they account for78.2% of the variation in the environmental data shown.
The (original) three zone classification has been applied to each sampling point after the DCA. Samples in the cleared zone are represented by open circles, those in the transition zone by grey-shaded circles and those in the forest by solid black circles.

The arrangement of the environmental variables in ordination space is shown in Figure 7.12. It is very similar to the layer 1 arrangement of environmental variables (seen in Figure 7.4). Again, the two axes can be interpreted as differences in faunal activity (Axis I) and forest disturbance (Axis II). Because bulk density samples were only collected at the soil surface, this variable was not included in the layer 2 environmental data. Its omission from the resulting ordination is responsible for the shorter negative extent of axis two in this diagram.

Figure 7.12 Arrangement of environmental variables in DCA ordination space: layer 2 data



This diagram shows the position of the environmental variables in the ordination space calculated for the layer 2 data. The shaded area represents the portion of the diagram shown in Figure 7.11 above.

In summary, the indirect gradient analysis of the 1992 field site environmental data reveals that environmental properties at the individual sample sites show a pattern of variation which appears to be related to differences in the vegetation cover. The two principal axes of variation have been identified as an axis indicating disturbance and one of faunal activity. This pattern of variation, first identified in the environmental properties measured in the organic-rich layer 1 has been shown to extend into the second (clay-rich) soil layer.

7.5 1992 Fieldwork: Direct gradient analysis of the Burnt site

The results of the indirect gradient analysis has revealed an inferred pattern of change in the vegetation cover. As these changes are the direct result of mangrove clearance they merit further investigation. With the validity of a three zone site vegetation classification established, these inferred changes can now be substantiated using the direct gradient analysis technique of canonical correlation analysis.

7.5.1 Configuring the canonical correlation analysis

Any ordination is a complex process, and the exact method of calculation can be tailored to the desired application. The program used to carry out the canonical correlation analysis (CANOCO Version 3.10) offers a range of options, two of which require consideration here: pre-selection of environmental variables and repressing the effects of rare species in the ordination.

Pre-selecting environmental variables

Pre-selecting the environmental variables is effectively a Monte Carlo simulation "bootstrapping" routine (ter Braak, 1990): it compares the effect of an environmental variable upon the species distribution with that of a set of randomly generated ordination weights. Whilst initially attractive, in that this method provides a quasi-objective method for selecting environmental variables, it was eventually rejected because the underlying stochastic model is not thought to be applicable to all the field sites, (notably the Burnt 1992 transects, whose irregular sampling interval seriously compromises the assumption of randomly distributed sampling points).

Repressing the effects of rare species

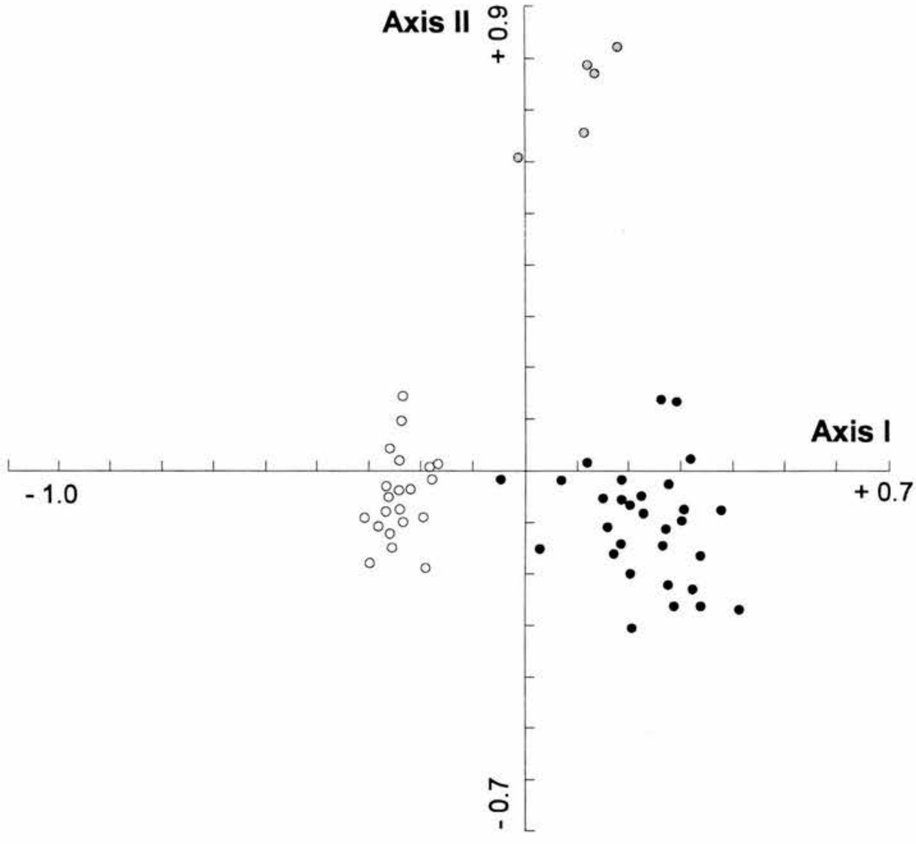
Another option available which affects the calculated weightings is to repress the effect of rare species upon the resulting ordination diagram. This option was experimented with, and found to have no effect upon the resulting diagrams. There was no difference between the generated ordination diagrams, nor in the reported canonical correlation coefficients and eigenvalues. This suggests that although the number of samples of each "species" (i.e. in each of the three sampling zones) is not equal, the number of points in the smallest "species" category (the transition zone) is sufficiently high to not skew the ordination diagram. Thus, the transition zone with eight sample points is not sufficiently rare a "species" class to create an effect upon the resulting ordination diagram disproportional to its true influence.

7.5.2 Results of the canonical correspondence analysis - layer 1

The figures below show the results of a canonical correspondence analysis of the 1992 Burnt field site species data and layer 1 environmental data. The diagrams show graphically the main relationships between the pattern of vegetation cover and the values of the soil, water and other environmental properties measured at the site. For clarity of representation, the analysis results are shown in two diagrams. Figure 7.13 shows the arrangement of the sampling sites in ordination space, grouped according to the zone in which they lie. Figure 7.14 shows the position of the environmental variables in the same ordination space, together with three points which mark the position of the three vegetation class (zone) centroids.

The ordination diagrams show the sample sites are arranged in the order (from left to right), cleared - transition zone - forest along the first (horizontal) canonical axis, Axis I. Table 7.2 shows that this axis is significantly correlated with water pH, exchangeable sodium and soil moisture content. From Figure 7.14, it can be seen that soil pH, redox potential, ammonium-nitrogen and both measures of organic content also show a strong alignment along this axis. These variables are those which earlier analysis of the 1992 field site data has shown to have significantly different values between these three zones. This suggests that this axis indicates a gradient of forest disturbance (clearance, compaction and possibly partial drainage).

Figure 7.13 Canonical correspondence analysis: 1992 Burnt site layer 1 - sample sites



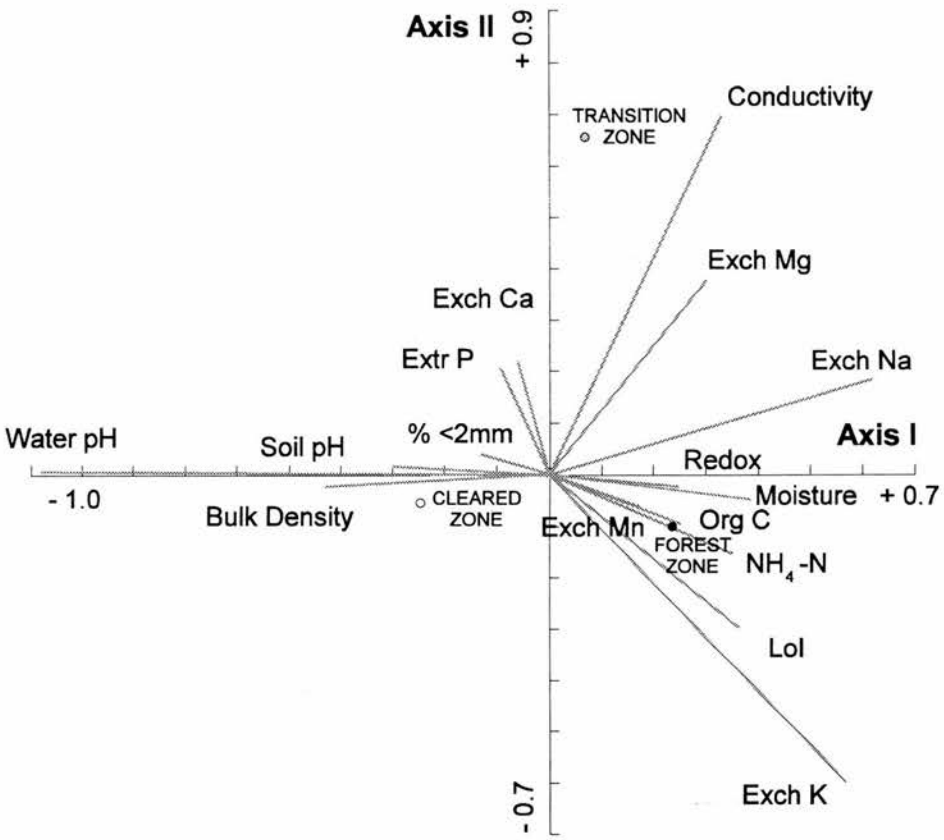
This diagram shows the sample sites arranged in CCA ordination space. Samples in the cleared zone are represented by open circles, those in the transition zone by grey-shaded circles and those in the forest by solid black circles. It can be seen that the ordination has clustered the samples into three groups, corresponding to the three sampling zones. Ordination Axis I - the horizontal axis - has an eigenvalue of 0.914, Axis II has an eigenvalue of 0.861. Together they account for 100.0% of the variation in the species-environment relationships and 88.7% of the variation in the site data shown.

Table 7.2 Summary of CCA results - Burnt 1992 site layer 1 environmental data

	Axis I	**Axis II**	**Axis III**	**Axis IV**
Eigenvalues	0.914	0.861	0.110	0.069
Species-environment correlation	0.956	0.928	0.000	0.000
Cumulative percent variance of species data	45.7%	88.7%	95.7%	100.0%
Cumulative percent variance of species-environment relationship	51.5%	100.0%	-	-
	Environmental variable-axis relationships, significant at t=1.96			
Water pH	-0.94	-0.02	n.s.	n.s.
Exch. K	n.s.	-0.55	n.s.	n.s.
Exch. Mg	n.s.	+0.35	n.s.	n.s.
Conductivity	n.s.	+0.65	n.s.	n.s.
Exch. Na	+0.59	n.s.	n.s.	n.s.
%Moisture	+0.37	n.s.	n.s.	n.s.

The first section of this table lists the numerical parameters generated by canonical correspondence analysis. These values are those used in Figure 7.13 to allow an assessment of the effectiveness of the ordination. The significant environmental variable-canonical axis coefficients listed in the lower part of the table indicate the rate and direction of change in the measured property along the given canonical axis. Their value is expressed on a scale of between -1.00 and 1.00, in a manner similar to regression coefficients.

Figure 7.14 Arrangement of environmental variables in CCA ordination space: layer 1 data



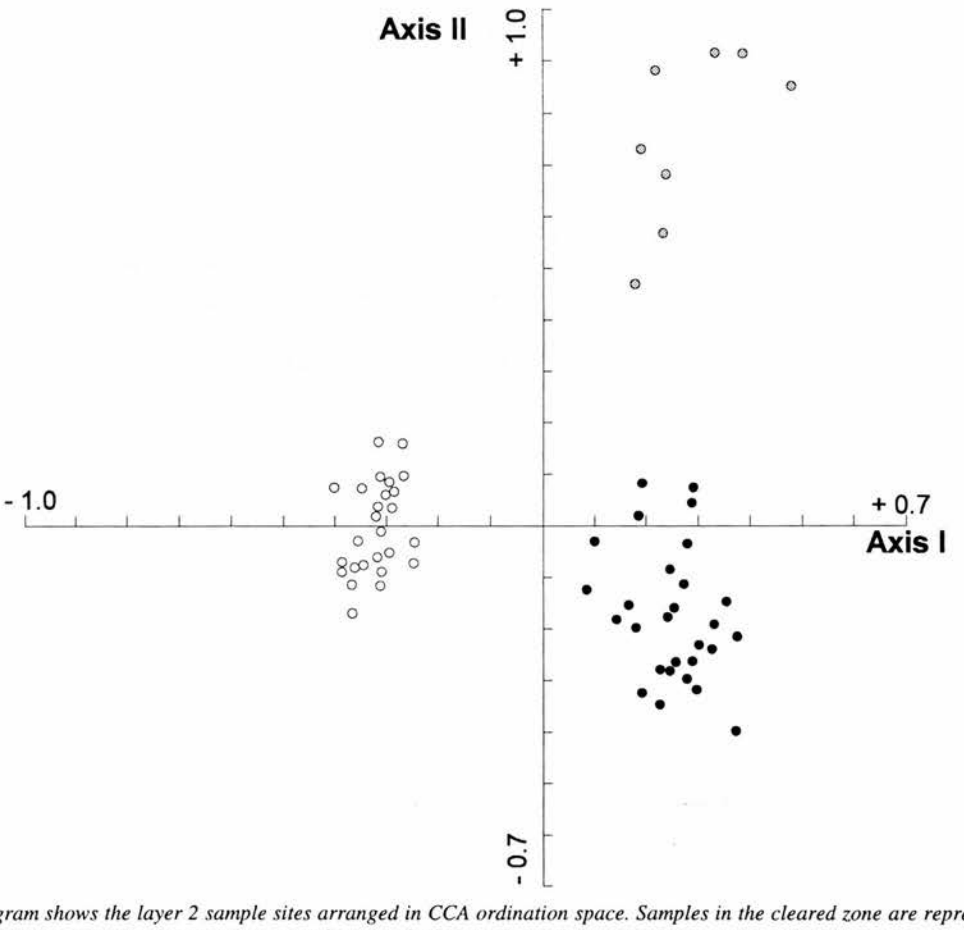
This diagram shows the position of the environmental variable vectors in ordination space. The three circles mark the calculated positions of the cleared, forest and transition zone class centroids. The axes are interpreted in the accompanying text. The influence of dissolved oxygen values are not shown in this diagram because during analysis this variable was found to be highly correlated (show strong covariance) with variables already selected for use in the ordination.

Conductivity, exchangeable potassium and exchangeable magnesium show a significant relationship with Axis II. Extractable phosphorus also seems from Figure 7.14 to be aligned along this vertical axis. The presence of conductivity in this list of variables suggests that this axis may represent a gradient arising from the influence of the sea. Sources of exchangeable potassium and magnesium are likely to be from stemflow, the decomposition of soil litter, and inputs from terrestrial sediment bearing waters. Variation in extractable phosphorus is harder to pin down, and may again relate to differences in the faunal activity across the site. The most sensible interpretation of this axis would seem to be as a freshwater-saltwater gradient.

7.5.3 Results of the canonical correspondence analysis - layer 2

Canonical correspondence analysis was repeated using surface species data and environmental measurements from the second soil layer of the Burnt field site. The resulting ordination diagrams are given below. Figure 7.15 shows that the ordination has again successfully separated the sample sites into the three vegetation zones.

Figure 7.15 Canonical correspondence analysis: 1992 Burnt site layer 2 - sample sites

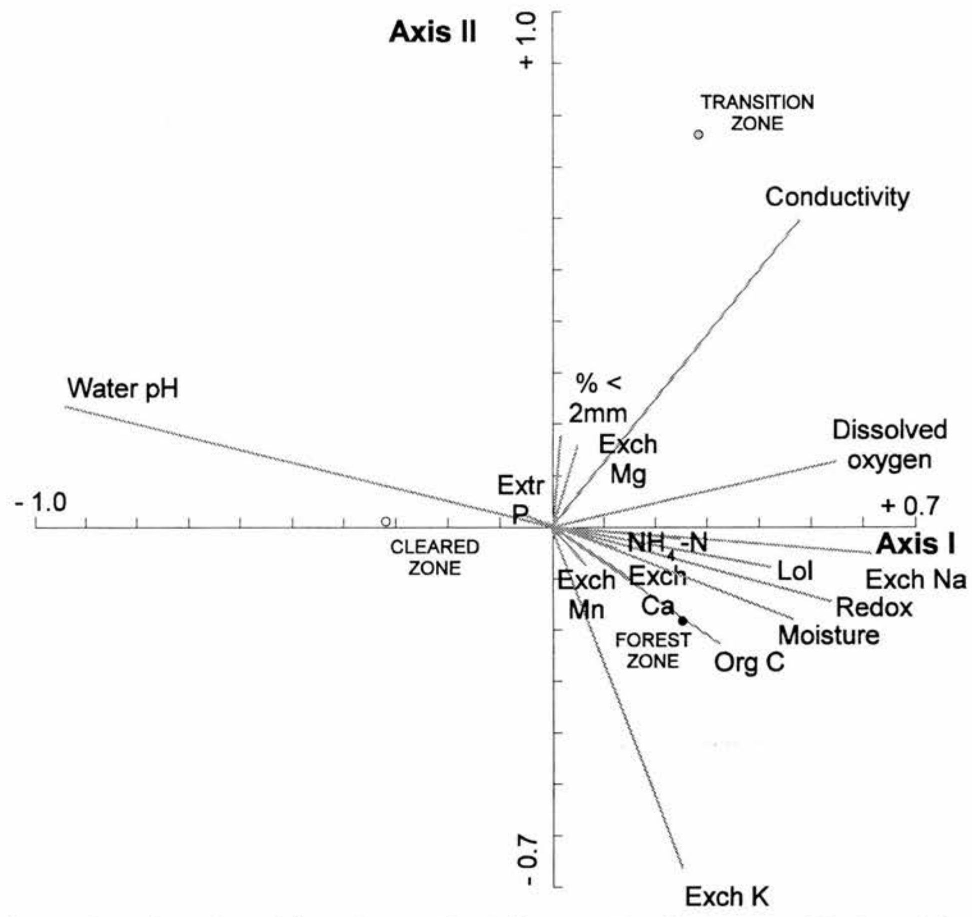


This diagram shows the layer 2 sample sites arranged in CCA ordination space. Samples in the cleared zone are represented by open circles, those in the transition zone by grey-shaded circles and those in the forest by solid black circles. It can be seen that the ordination has successfully clustered the samples into three groups, corresponding to the three sampling zones. Ordination Axis I - the horizontal axis - has an eigenvalue of 0.950, Axis II has an eigenvalue of 0.853. Together they account for 100.0% of the variation in the species-environment relationships and 90.2% of the variation in the site data shown.

The clustering of sites shows as before that cleared zone sites can be separated from those in the forest zone by Axis I values. However, this diagram differs from Figure 7.13 (layer 1 data) in that the transition zone Axis I values are very similar to the forest. This suggests that, at depth, transition zone sites retain the properties of forest soils.

The arrangement of the environmental variables seen in Figure 7.16 and the significant relationships detailed in Table 7.3 are broadly similar to those observed for the layer 1 data, above. The secondary (vertical) Axis II shows high measured water conductivity, soil exchangeable magnesium and to a lesser extent coarse sand content for positive axis positions. Points plotting in negative Axis II positions show high exchangeable potassium values. This pattern still fits the inferred freshwater-saltwater gradient used above. The primary (horizontal) axis, also fits the interpretation given in the layer 1 ordination - a gradient of forest disturbance. Sites lying in the forest are located in the positive region of this axis. These areas have higher levels of soil nutrients such as potassium, sodium and calcium. Areas in the cleared zone (negative Axis I scores) have the highest water pH values.

Figure 7.16 Arrangement of environmental variables in CCA ordination space: layer 2 data



This diagram shows the position of the environmental variable vectors in ordination space. The three circles mark the calculated positions of the cleared, forest and transition zone class centroids. The axes are interpreted in the accompanying text. The variables shown in this figure differ from those shown above in Figure 7.14 in three ways. Bulk density measurements were not made for the layer 2 data and so are not shown in this figure. Dissolved oxygen values were found to contribute a unique aspect to the ordination and so are included in this ordination, but soil pH was excluded instead, because of high correlation and covariation.

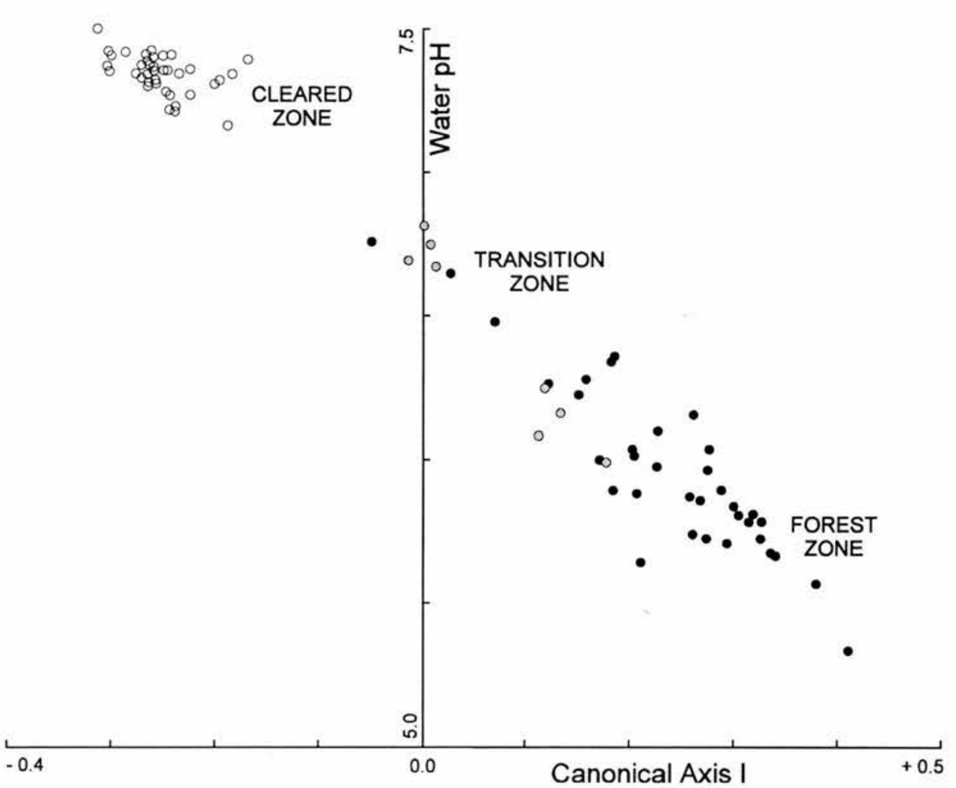
Table 7.3 Summary of CCA results - Burnt 1992 site layer 2 environmental data

	Axis I	Axis II	Axis III	Axis IV
Eigenvalues	0.950	0.853	0.147	0.050
Species-environment correlation	0.975	0.924	0.000	0.000
Cumulative percent variance of species data	47.5%	90.2%	97.5%	100.0%
Cumulative percent variance of species-environment relationship	52.7%	100.0%	-	-
	Environmental variable-axis relationships, significant at t=1.96			
Water pH	-0.93	+0.22	n.s.	n.s.
Exch. K	+0.24	-0.63	n.s.	n.s.
Dissolved oxygen	+0.53	n.s.	n.s.	n.s.
Weight Loss on Ignition	n.s.	-0.08	n.s.	n.s.
Conductivity	n.s.	+0.55	n.s.	n.s.

7.6 Conclusions from the 1992 fieldwork

The results of the canonical correspondence analysis of the 1992 Burnt site data show a similar pattern for the two datasets considered, gathered at different depths. The ordination has successfully arranged the sample sites in a manner which clusters them in an arrangement which matches the three zone vegetation classification (cleared, transition zone and forest) apparent from the field survey. This is confirmed by the high eigenvalues and proportion of the species data variance explained by these axes. The arrangement of the environmental variables in the constructed ordination space also seems logical - similar measures are grouped together, e.g. weight loss on ignition and percent organic carbon, both measures of soil organic matter content. Moreover, examining the numerical parameters listed in Table 7.2 and Table 7.3, their arrangement has been found to successfully account for the variance present in the species-environmental variable relationship.

Figure 7.17 Scattergram of water pH against canonical axis I - layer 1 data

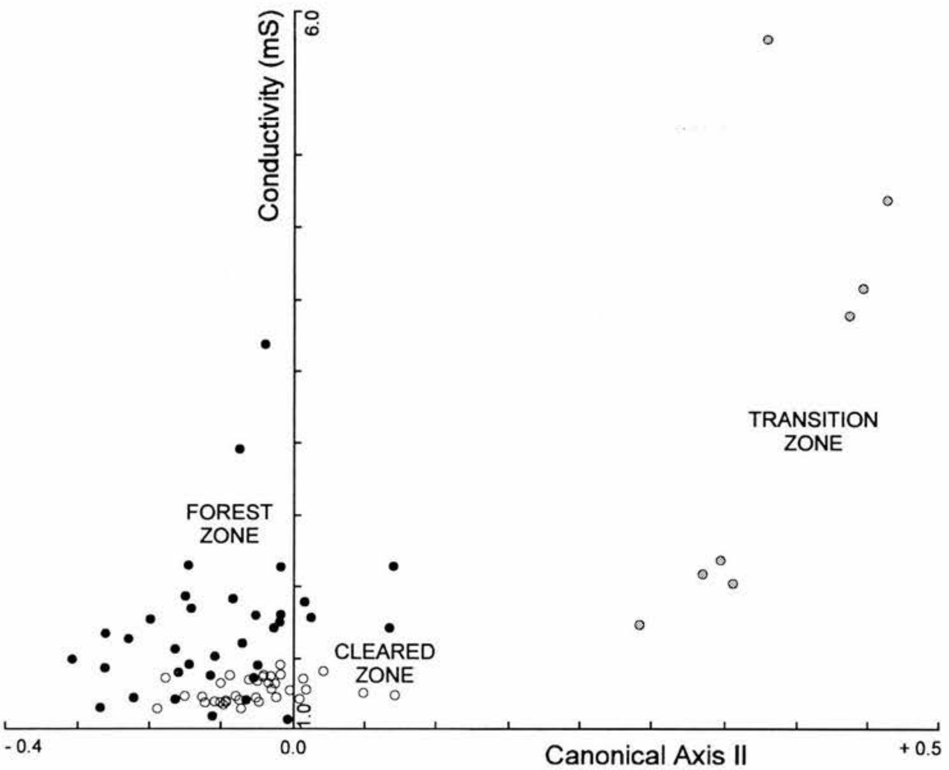


This figure shows the linear relationship between water pH and the first canonical axis. The separation between groups of samples lying in the cleared, forest and transition zones can be clearly seen. Sample points are shaded as before.

Two environmental gradients have been identified, corresponding to the two principal canonical axes. The first of these is interpreted as a "disturbance gradient" aligned along Axis I. This axis clearly picks out the variables which change as a result of forest removal - an increase in water pH, a loss of soil organic matter content, and decreases in the levels of nutrients in samples from the cleared area. The variables found to be responsible for this gradient are those which the earlier statistical analysis showed to display significant differences. This gradient acts in a linear fashion, with increasing differences in sample properties in the order forest-transition-cleared zone. This ordering can be clearly seen in Figure 7.17 below, which shows a scatterplot of water pH against canonical Axis I values. Water pH was selected because it consistently shows the strongest correlation with Axis I.

The second gradient running along Axis II is more difficult to interpret. The clearest variable-axis relationships are increasing conductivity, a rise in the proportion of soil greater than 2 mm, a slight increase in water pH, coupled with a decrease in exchangeable potassium and organic carbon content. The range of variables are consistent with water movement across the site. Seawater penetration would result in a higher field site water conductivity, and may act to neutralise the acidic soil pH. The increase in the coarser sediment fraction may be a combination of wave action - washing away the finer fractions and depositing coarse material during storms. The differences in organic content and some soluble nutrients such as potassium may reflect variations in stemflow or the deposition of alluvial material transported from the interior. This axis acts to separate sites lying in the transition zone from those in the two other zones. This can be seen in Figure 7.18 below.

Figure 7.18 Scattergram of water conductivity against canonical axis II - layer 1 data



This figure shows the how the second canonical axis seems to separate the samples measured in the transition zone from those in the cleared and forest zone. The relationship chosen to illustrate this is that between conductivity and the second canonical axis. Sample points are shaded as before.

There are two possible reasons for this different grouping of the transition zone sites. It could reflect a real difference between the measured property values in this zone and the two others. Alternatively, it could be a function of failings in the vegetation classification - Axis II might be an artificial construct of the ordination process, required to separate the transition zone from the other two areas. This question is most easily resolved by returning to the 4D models developed in chapter six. The conductivity model peaks distinctly in the transition zone. Both layer 1 organic carbon and weight loss on ignition figures show a distinct depleted zone around the cut edge. Dissolved oxygen values (which show an increase in value with Axis II) also seem highest around the transition zone. The fact that "unique" transition zone values can be detected in these figures corroborates the view of this second canonical axis as representing a real aspect of the spatial data pattern. This then also reinforces the earlier conclusion, supporting the choice of the three zone vegetation classification.

7.7 1994 Fieldwork: Indirect gradient analysis of the three sites

After the detailed examination of the Burnt site in 1992, the 1994 fieldwork aimed to extend the area of interest. The number of field sites was increased to three, with the two new sites being the Punta del Este and Texaco field areas. Ordination techniques were applied to the field data to answer two questions:

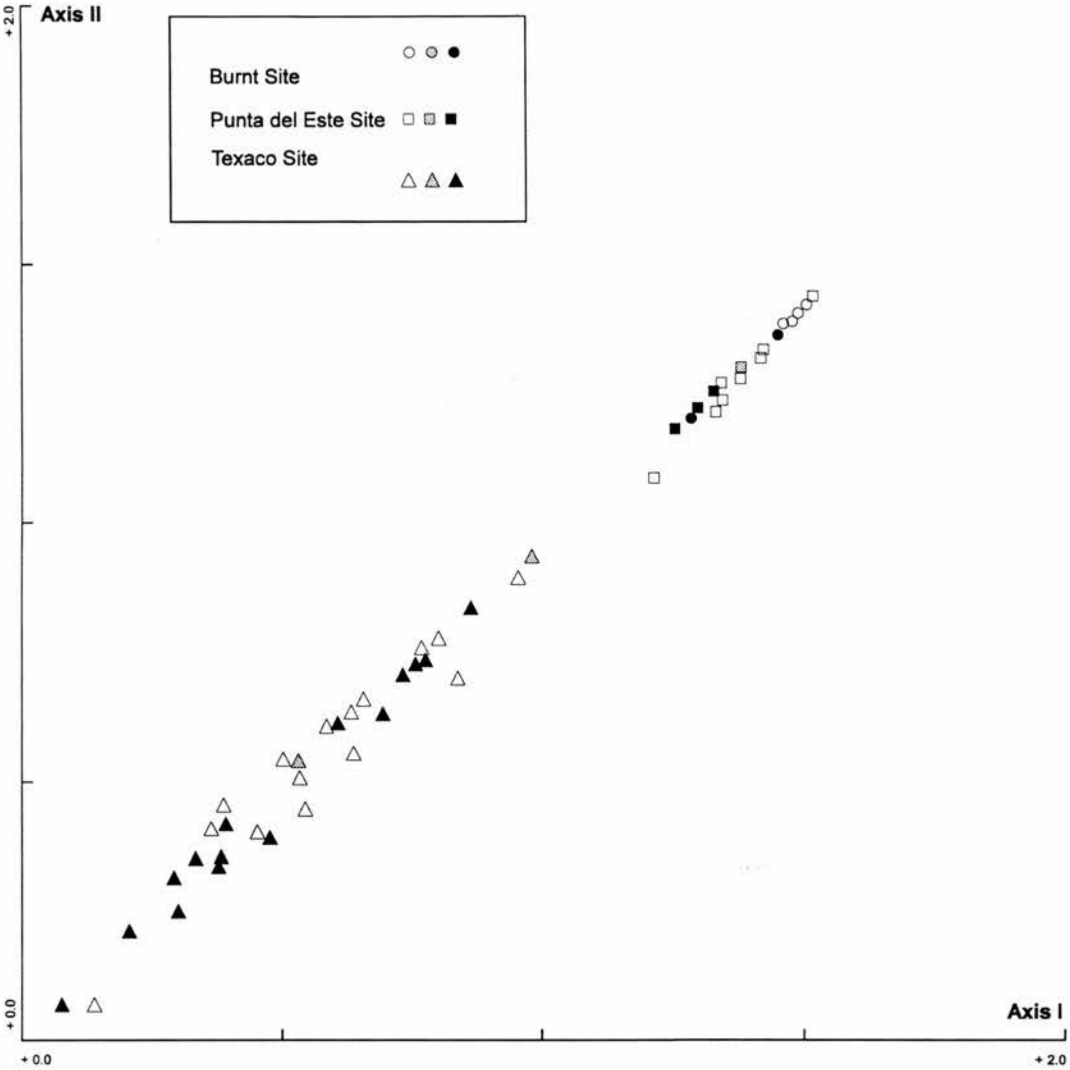
1. To compare these three sites. If the forested areas and cleared areas in the three field sites are alike, then they should plot in similar regions of the ordination diagram.
2. To see whether the environmental gradients found in 1992 are also present in the 1994 sites. If the field sites are indeed similar, then the disturbance and freshwater-salinity gradients may be revealed in the data. However, if the sites are dissimilar, then these gradients may be obscured by other plotted differences.

The first approach was to carry out an indirect gradient analysis of the three sites.

Data from the three sites were combined, so that the sample points could be displayed on a single ordination diagram. This is shown below in Figure 7.19. Because most of the properties recorded in 1994 were measured from water rather than soil samples, the ordination analyses are not repeated at depth.

This figure shows the sample sites arranged in a linear fashion. Samples from the Punta del Este field site lie at one end of this gradient and samples from the Texaco and 1994 Burnt site lie at the other. The samples from the Burnt site appear to be more tightly clustered than those from the Texaco site. It does not separate the sample sites into two forest and cleared groups similar to those seen in the 1992 analysis. Instead, this arrangement of the sampling points seems to correspond with differences in the standing vegetation observed at the three sites.

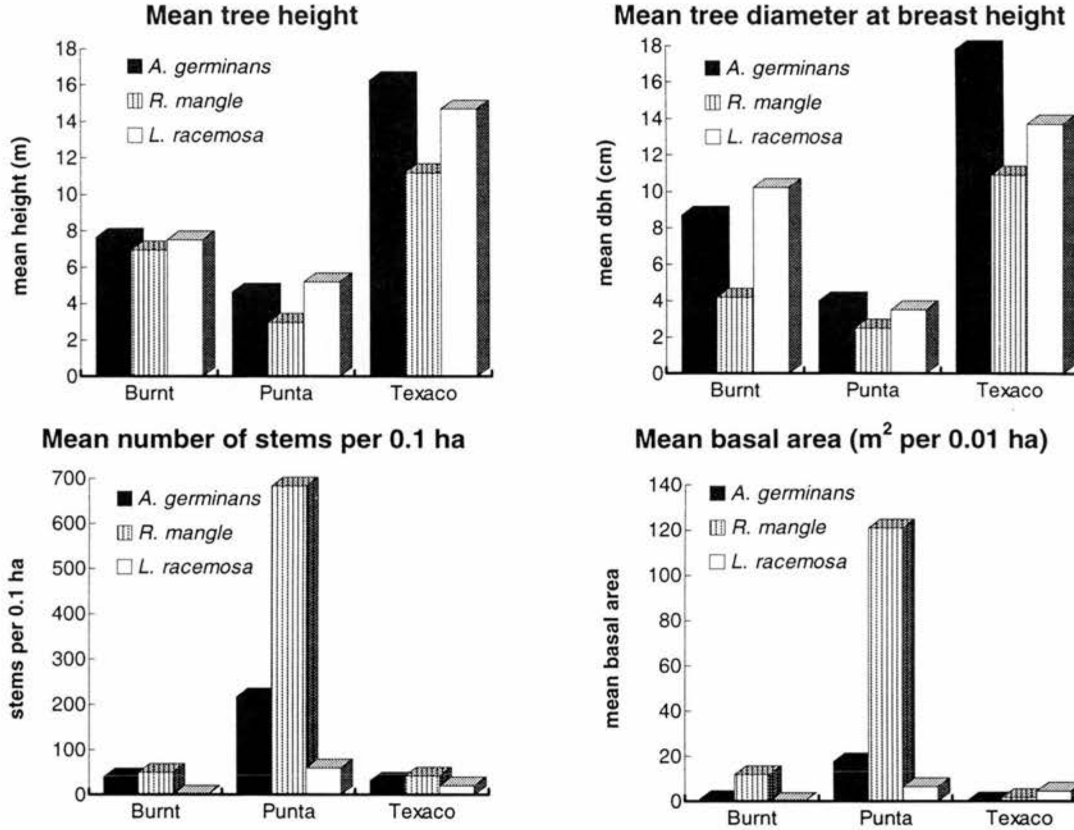
Figure 7.19 Detrended correspondence analysis: All three 1994 field sites - sample sites



Ordination Axis I - the horizontal axis - has an eigenvalue of 0.245, Axis II has an eigenvalue of 0.005. Together they account for 98.2% of the variation in the environmental data shown. As in previous diagrams, samples in the cleared zone are represented by open polygons, those in the transition zone by grey-shaded polygons and those in the forest by solid black polygons. The shape of the polygons indicates the field site in which they were sampled. A key, listing the field sites is given above.

As detailed in the earlier field site descriptions and enumerated in the PCQM vegetation analysis contained in appendix one, the mangrove forest vegetation differs at the three field sites. The Punta del Este mangrove is typically short and dense at ground level. The twisted tree shapes, low number of leaves, their yellow colour and steep angle all indicate vegetative stress. The mangrove of the Burnt site is far taller and healthier looking, although it does not appear quite as luxurious as that seen at the Texaco site. At this third site some of the largest mangroves around Belize City can be found - very tall, straight, and widely spaced. The healthy condition of these trees and the presence of numerous epiphytes on their branches and roots indicates a rich nutrient supply. These differences are shown below in Figure 7.20:

Figure 7.20 Quantitative botanical descriptors of the mangrove forest found at the three field sites



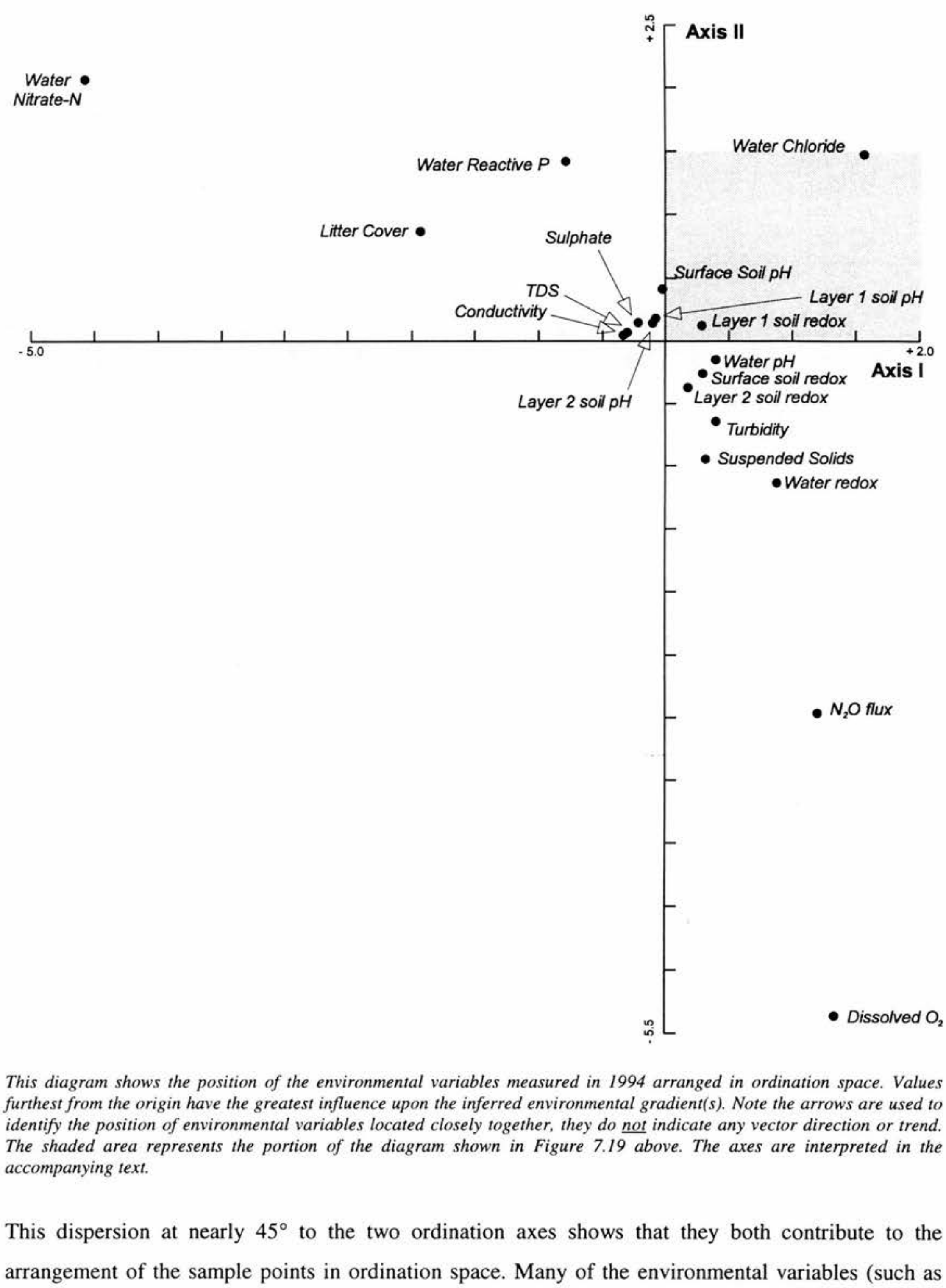
Compiled from vegetation data gathered in the field.

These graphs confirm the field observations. The Punta del Este site can be seen to differ considerably from the other two, with a far higher stem density and basal area, particularly for *Rhizophora mangle*. Individuals at the other two sites, are less densely packed, but taller and wider. The largest individual trees are some of the *Avicennia germinans* and *Laguncularia racemosa* specimens found at the Texaco site. The gradient seen in the detrended correspondence analysis seems to be detecting these botanical differences. Trees at the Punta site are densely packed but small, which means that a great deal of the nutrients will be held in the biomass rather than the soil. Trees at the other two sites are larger, but their lower density and greater size will result in a greater litter return to the soil, maintaining soil (and water) nutrient levels.

Figure 7.21 shows the arrangement of the environmental variables in the ordination space. This allows the identification of which underlying soil and water conditions are important in the inferred vegetation gradient.

The arrangement of sample points along the environmental gradient seen in Figure 7.19 lies within the shaded portion of Figure 7.21, stretching from the origin almost to the position of the chloride value.

Figure 7.21 Arrangement of environmental variables in DCA ordination space: All three 1994 sites



This diagram shows the position of the environmental variables measured in 1994 arranged in ordination space. Values furthest from the origin have the greatest influence upon the inferred environmental gradient(s). Note the arrows are used to identify the position of environmental variables located closely together, they do not indicate any vector direction or trend. The shaded area represents the portion of the diagram shown in Figure 7.19 above. The axes are interpreted in the accompanying text.

This dispersion at nearly 45° to the two ordination axes shows that they both contribute to the arrangement of the sample points in ordination space. Many of the environmental variables (such as layer 2 pH and total dissolved solids) lie in positions very close to the origin. This indicates that they may have their optima at the centre of the calculated ordination space, or else are relatively unrelated to the ordination axes (ter Braak, 1987).

However, water nitrate-N levels and the percentage litter cover can be seen to decrease in value along Axis I. This is accompanied by increases in chloride levels and water pH. The changes in water pH and litter cover are consistent with the changes identified in earlier chapters which occur following forest clearance. Axis I is, therefore, interpreted to be a clearance gradient.

Dissolved oxygen values, the volume of nitrous oxide evolved from the soil surface,[5] a drop in water pH and various measures of turbidity and suspended materials, all decline along Axis II. High turbidity and dissolved oxygen levels are found around the transition zone, which is thought to be the result of the greatest water movement in this area. Near neutral water pH values and high nitrous oxide flux are more typical of the cleared zone. This pattern of values is again consistent with the clearance process, with this axis giving greater emphasis to sub-soil processes.

The general orientation of the samples suggests that water chloride concentration is the variable most strongly influencing the vegetation differences. This agrees with the findings of other workers. Strogonov (1964) studied plants exposed to water with a high salt concentration and suggested that their growth might be affected by toxic compounds formed in reactions between proteins and chloride ions. Ukpong (1992) found that mangrove tree basal area, density, coverage and several other vegetation characteristics were negatively correlated with soil chloride content. Yet he was unable to isolate a mechanism for this gradient and chloride concentration is not recognised as being a limiting factor in the major ecological processes. Chloride itself may not be directly responsible for the gradient, acting instead as an indicator for another highly-correlated variable. The latter conclusion is given weight by a study which has shown that mangrove growth rates are insensitive to chloride levels (Rabinowitz, 1978b). The data gathered in this work are not sufficiently detailed to resolve this question, identifying the true causal process behind this gradient requires further research.

In order to investigate these differences in more detail, further direct correspondence analysis was carried out with the 1994 field site data. This time the dataset was split into two, one containing only samples from the cleared zone and the other only samples from the forest. The resulting ordination diagrams (not shown) were very similar to those already generated. The arrangement of the sample sites from the cleared areas was almost exactly the same as that seen for the combined sites shown in Figure 7.19. The pattern of forest sites was also very similar, with only a slight difference at the positive end of the gradient. Here samples from the Texaco and Burnt sites were separated because of a tighter clustering, with the Burnt site samples located at the furthest end of the gradient. The arrangement of the cleared sites' environmental variables in the ordination space was also very similar to that for the combined datasets. The forest sites pattern was slightly different, notably the movement of reactive phosphorus to a position nearer that of chloride, indicating that it was playing a greater role

[5] Indicating denitrification is occurring.

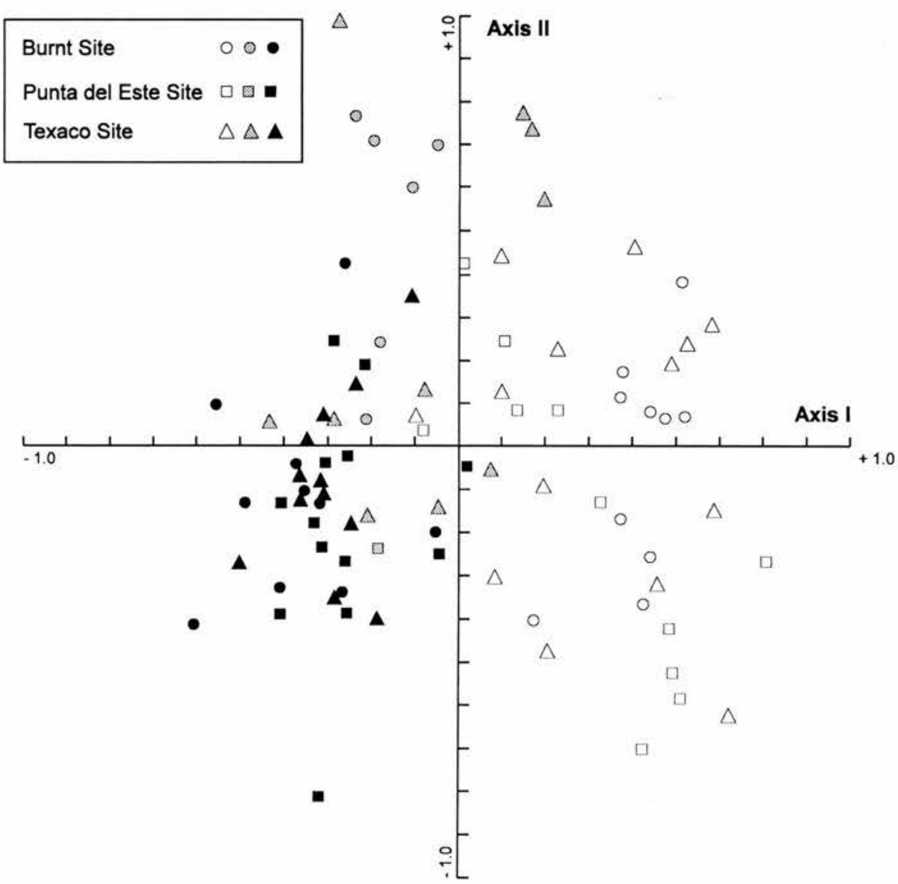
in the forest gradient. Small differences in phosphorus availability may be responsible for the separation of the Texaco and Burnt sites in the forest ordination. The fact that this separation is not maintained when all the sample sites are considered together suggests that the magnitude of this difference is not very great.

Indirect gradient analysis of the 1994 sites' environmental data has suggested that there may be differences in the density and vitality of the mangrove forest found at the three sites. Knowledge of this difference will help to interpret the vegetation-environment relationships which direct gradient methods can reveal.

7.8 1994 Fieldwork: Direct gradient analysis of the three sites

Given the inferred differences in the vegetation at the three sites, the datasets were combined for a single canonical correspondence analysis. Plotting the sample points in a single ordination space will reveal whether this inferred vegetation difference is so great that it obscures the disturbance and saltwater-freshwater gradients found at the Burnt field site in 1992. The arrangement of the sample sites in the ordination space from the direct gradient analysis is shown below in Figure 7.22.

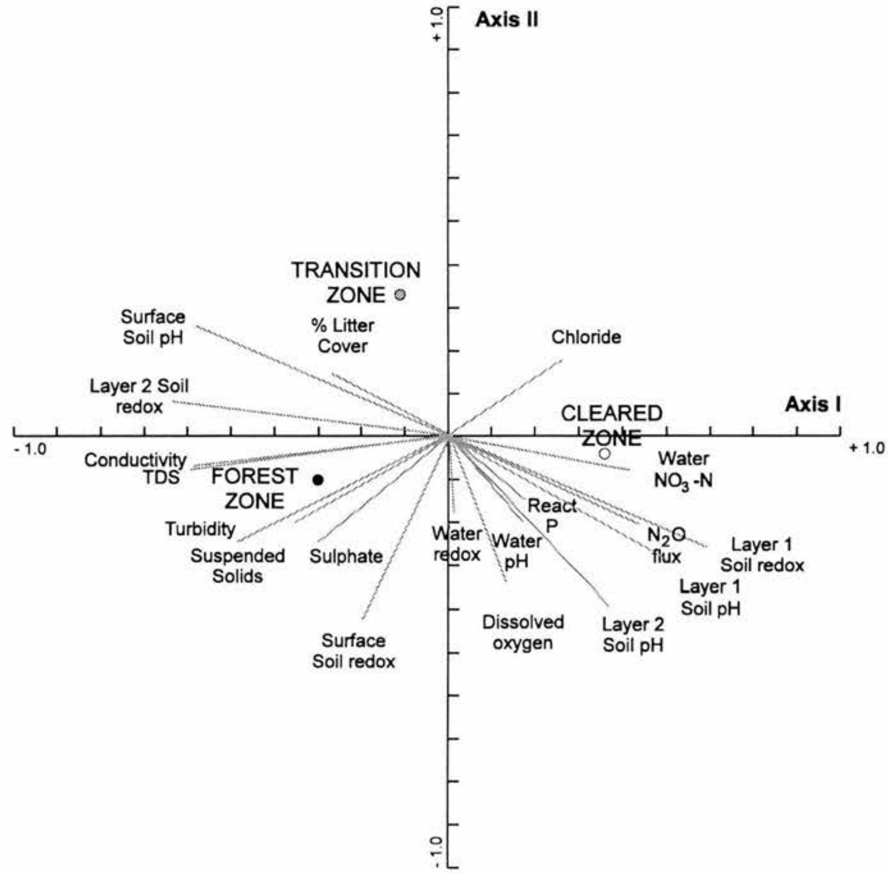
Figure 7.22 Canonical correspondence analysis: All three 1994 field sites - sample sites



This diagram shows all the 1994 field site sampling points arranged in CCA ordination space. Samples in the cleared zone are represented by open polygons, those in the transition zone by grey-shaded polygons and those in the forest by solid black polygons. The shape of these polygons separates the three field sites. It can be seen that the ordination has clustered the *samples into three groups, corresponding to the three sampling zones. Ordination Axis I - the horizontal axis - has an eigenvalue of 0.745, Axis II has an eigenvalue of 0.207. Together they account for 100.0% of the variation in the species-environment relationships and 48.1% of the variation in the site data shown. The lower eigenvalues for this CCA when compared with that of the 1992 site alone, reflects the fact that this latter diagram has had to include a greater range of gradients, such as the vegetation differences identified above in the DCA. This also accounts for the lower explanatory power of these axes reported in the cumulative percentage variance figures seen in Table 7.4.*

The arrangement of the sample sites in Figure 7.22 shows that the ordination has been relatively successful in separating then into groups corresponding to the cleared, forest and transition zones. This clustering is weaker than that seen for the single site analyses of Figure 7.13 and Figure 7.15. This is thought to be because of the added variance introduced by the inter-site vegetation differences.

Figure 7.23 Arrangement of environmental variables in CCA ordination space: All three 1994 sites



This diagram shows the position of the environmental variable vectors in ordination space. The three circles mark the calculated positions of the cleared, forest and transition zone class centroids. The axes are interpreted in the accompanying text.

Figure 7.23 shows the position of the environmental variables in this ordination space. Axis I separates the three zones in the order forest, transition, cleared. This suggests that as before this axis may be indicating levels of forest disturbance. This labelling is partially supported by the position of the environmental variables on the ordination diagram and the significant environmental variable-axis relationships given in Table 7.4. Negative positions along this axis show conditions most common in the forest: high litter cover values, high levels of turbidity, suspended solids, and conductivity. The higher surface soil redox also seen from Figure 7.23 is attributed to the greater organic covering, which tends to raise the soil surface above the water-level, resulting in localised oxidation. The higher values of layer 2 soil redox indicate the oxidising activity of live mangrove roots occurring at depth in the forest. Positive positions along Axis I show some of the environmental characteristics more typical of the cleared areas: slightly higher water pH, a higher nitrous oxide flux and water nitrate-N content (indicating that denitrification is occurring and that inorganic nitrogen concentrations are increasing because of the absence of plant uptake). The higher redox potential of the upper soil layer in the cleared area may indicate oxidation of this portion of the soil during periods of low water.

Axis II once more isolates the transition zone from the other two vegetation groups. However the variables which appeared responsible for this separation in the 1992 Burnt Site (dissolved oxygen levels and conductivity) are not behaving in the same way here. Dissolved oxygen levels appear to drop in the transition zones of the 1994 sites and conductivity appears to be far more closely aligned to Axis I. Instead, water chloride concentration appears to be responsible for the transition zone points' higher position on this axis. These findings confirm the need for further research into the significance of chloride levels in the mangrove.

Table 7.4 Summary of CCA results - All three 1994 field sites

	Axis I	Axis II	Axis III	Axis IV
Eigenvalues	0.754	0.207	0.793	0.246
Species-environment correlation	0.868	0.455	0.000	0.000
Cumulative percent variance of species data	37.7%	48.1%	87.7%	100.0%
Cumulative percent variance of species-environment relationship	78.5%	100.0%	-	-
	Environmental variable-axis relationships, significant at t=1.96			
Turbidity	-0.42	n.s.	n.s.	n.s.
Water Ammonium-N	+0.35	n.s.	n.s.	n.s.
Water pH	+0.15	n.s.	n.s.	n.s.

7.9 Conclusions from the 1994 fieldwork

The indirect gradient analysis highlighted differences in the standing vegetation at the three field sites. The Punta del Este site had the highest biomass but far lower average tree height and breadth than the Texaco and Burnt sites. The orientation of this gradient suggested that it was the result of variations in chloride concentration, with the highest chloride levels recorded at the Punta del Este site. This chloride difference has proved hard to interpret - it shows a trend which differs from that of conductivity and sulphate, suggesting that this difference is not merely reflecting variations in saltwater influence.

Direct gradient analysis was able to separate the three vegetation zones found at the field sites. The primary canonical ordination axis was identified as an axis of disturbance, arranging the forest, cleared and transition sites in this order along its length. The second axis separates the transition zone from the other too, but shows a weak correlation with the environmental variables, making further interpretation difficult.

7.10 Conclusions from all the ordination work

The ordination analysis of the field site data has highlighted several trends. Analysing the spatial changes in the environmental properties has shown that the sample sites can be classified into groups which correspond with observed differences in their vegetation cover. A case has been made for retaining a three zone classification, with a transition zone lying between areas of remaining forest and completely cleared land. The shape and width of this transition zone changes according to the variable being measured and differences between the forest and transition zone properties seem to decline with depth.

All the analyses identify a primary gradient across the field sites which indicates changes in the environmental properties attributed to selected clearance. The 1992 work suggests that there is also a second gradient in soil phosphorus levels which is believed to be due to different levels of faunal activity (notably the feeding activity of wading birds) in the cleared and forest zones.

Detrended correspondence analysis has shown that the observed differences in the standing vegetation found at the three 1994 field sites are reflected in differences in the value of the environmental properties measured there. Chloride concentration has been found to be negatively correlated with increases in forest biomass, but the exact mechanism for this relationship remains elusive, requiring further investigation.

Canonical correlation analysis of the 1994 field site data has shown that these biomass differences do not obscure relative differences between the value of the measured environmental properties in the three sampling zones. When considered together, the 1994 field site data show that deforestation of areas results in a detectable gradient in the value of the environmental properties, aligned along the axis of clearance.

The differences found between environmental properties measured in cleared and forested areas at each field site are explored in more detail in chapter nine, which interprets the result of the transect sampling work.

8 Semivariogram analysis: revealing the spatial scale of change

The need for semivariogram analysis

The data analysis techniques used so far have all focused on the search for spatial patterns. Confidence in the identified trends and patterns can be increased if they are supported by information about the scale at which the causal processes operate. One relatively simple method for identifying the scale of spatial change is semivariogram analysis, although it requires large amounts of spatial data. This chapter applies this geostatistical technique to the largest environmental dataset - that gathered at the Burnt field site in 1992.

This chapter seeks to quantify the spatial scale at which processes operate, by measuring spatial covariation amongst the datapoints. This statistical measure which has generally received little attention to date, quantifies the effect of neighbouring samples upon the value of a property measured in any one place. This provides two contributions to the current research:

1. It allows a post-fieldwork "quality" control on the sampling intervals used in the fieldwork, ensuring that the scale of investigation was sufficiently fine to reveal genuine patterns of spatial change.
2. Related to this, differences in the spatial autocovariation of environmental variables may explain why certain variables show marked differences between the cleared and forest zones and others do not. This will also provide a further level of interpretation of the gradient analysis stemming from the ordination diagrams examined in the previous chapter.

8.1 Semivariograms - a theoretical introduction

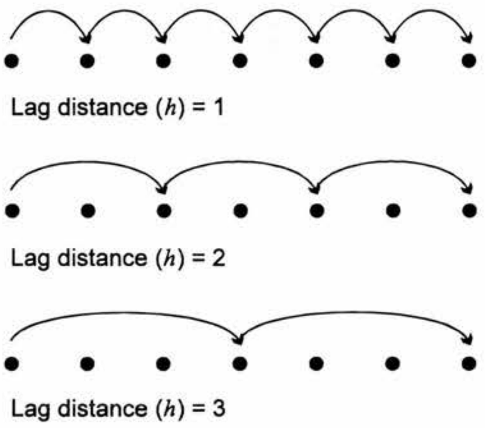
Semivariogram analysis is one of several geostatistical techniques which have been developed for data which show spatial autocovariance. This is where sample points that lie close to one another tend to have more similar values than sample points which lie further apart, but where no simple relationship exists between a sample point's value and its location in space. That is, there is no, or not just, a simple regional trend in the data. Semivariance $\gamma(h)$ is an average measure of the difference in a property Z measured at two locations x_1 and x_2 a distance (h) apart, usually referred to as the lag distance. Semivariance can be formally expressed as:

$$\gamma(h) = \tfrac{1}{2} \text{ variance } [Z(x_1) - Z(x_2)]$$

Equation 1

Figure 8.1 shows how the lag distance is calculated.

Figure 8.1 Calculating the lag distance



By varying the number of possible sampling points between each comparison, different lag distances can be generated for a set of sampling points (shown as solid black circles). The semivariance would be calculated using a data set containing all the paired comparisons (represented by arrows) for each lag distance. Thus, for regularly spaced data, the smaller the lag distance, the larger the number of possible comparisons.

By calculating the semivariance for different lag distances (h) a picture of the structure of the spatial variation of the environmental properties measured across the field site can be produced. The significance and applicability of this technique requires a brief discussion of its wider theoretical context to illustrate its relevance to the present research.

8.1.1 Regionalised variable theory

Semivariogram analysis applies what has been termed "regionalised variable theory" and stems from the work of Matheron (1965, 1969, 1971). It considers the value of a property Z measured at point x as the sum of three components:

$$Z(x) = m(x) + \varepsilon'(x) + \varepsilon''$$

Equation 2

These are:

$m(x)$ the major "deterministic" structural component, which is often constant over certain areas, (e.g. the mean carbonate content of shoreline sediments), or which can be calculated from the knowledge of some large scale trend, (e.g. the decline in salt content with increasing distance from the sea).

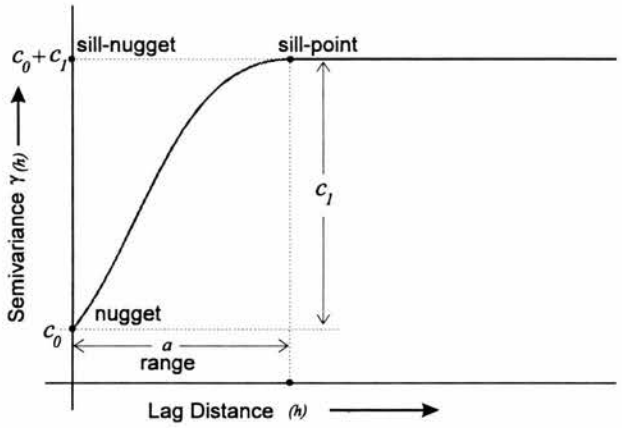
$\varepsilon'(x)$ the spatially correlated, but random variation. Essentially this can be thought of as the effect of neighbouring points.

ε'' a residual, spatially *independent* "noise" term, which is assumed to be normally distributed with a mean of zero.

The analysis of previous chapters, particularly the statistical comparisons of chapter six based on sample means, has revealed differences in the major structural component(s): $m(x)$ in Equation 2. The semivariogram analysis contained in this chapter will add to our understanding by considering the two other components: $\varepsilon'(x) + \varepsilon''$. Of particular importance is the relative balance between these two components, which can be measured by a property known as the structural variance.

Plotting the semivariance of a single measured environmental property for many different lag distances, produces a diagram called a semivariogram. An idealised semivariogram is shown below in Figure 8.2

Figure 8.2 An idealised semivariogram



Several points on this diagram are used as indicators of the spatial autocovariance of the measured environmental property. The nugget[1] variance, marked on the y-axis at the point (c_0) at the start of the figure shows the sample variance at a lag distance of zero. This shows the spatially independent component of the variation, instantly quantifying the parameter ε'' from Equation 2. The location of what is termed the sill-nugget located at the point ($c_0 + c_1$) on the y-axis represents the sum of the spatially correlated variation (c_1) and the independent component, (c_0). Using the terms given in Equation 2 this is $[\varepsilon'(x) + \varepsilon'']$. Knowing this value allows the spatially correlated component c_1 [or ε''] to be calculated by subtraction. The height of the sill along the y-axis is theoretically equal to the variance of the property if measured over the whole sampling area (Burrough, 1987). Along the x-axis, the range a, from the origin to the sill-point is the distance within which the values of sample points

[1] These terms stem from the field of ore-prospecting, in which the technique was developed.

are spatially dependent. For an inquiry into local-scale spatial patterns, the sampling interval, must, therefore be less than this range.

8.2 Assumptions underlying the technique

Regionalised Variable Theory makes several assumptions about the statistical properties of measured variables over the area of interest, which affect the composition of suitable sample populations. Two are applicable to this work, known as the "assumption of stationarity" and the "intrinsic hypothesis".

8.2.1 The assumption of stationarity

The stationarity assumption is that the statistical properties of the spatially correlated variation, $\varepsilon'(x)$ are the same over the whole structural unit. In effect, this is to say that the influence of surrounding data values upon any given sample point are *independent* of that point's exact location in space. The statistical properties considered can be divided into two - termed first order (the mean) and second order (variance, covariance and semivariance). Strictly applied, Regional Variable Theory assumes both first and second order stationarity, i.e. that both the mean and variance of a set of sample points within a given "landscape unit" are constant and thus independent of the location of these points within that unit (Webster & Oliver, 1990). Where the assumption of second order stationarity holds, a range of geostatistical techniques can be used, the two most common of which are autocovariogram analysis and semivariogram analysis.

8.2.2 The intrinsic hypothesis

The assumption of second order stationarity, i.e. a stable variance across the field site has often been found not to hold, requiring a weaker assumption to be used - the intrinsic hypothesis. This assumes that even if variance does alter across the field site, the incremental difference between the value of property Z at pair of sample points separated by a distance (lag) of h, i.e. $Z_{(x+h)}$ - $Z_{(x)}$ has a mean of zero and a finite variance, whose value does not depend upon the position of the points used in the comparison, i.e. the value of x. Where only the intrinsic hypothesis holds, autocovariance methods cannot be used as they rely upon a constant mean. However, semivariogram analysis can still be applied as they rely only upon the difference between successive pairs of points being constant, (Burrough, 1987).

8.2.3 Applying these assumptions to the Burnt 1992 field site

There is insufficient evidence to conclude that the stationarity assumption is true across the field site, because of the lack of regional scale data. It also seems doubtful whether the intrinsic hypothesis holds true over the field site considered as a single unit, given the different cleared, transition and forest zone distribution patterns of measured environmental properties seen in previous chapters. However it is far more reasonable to assume it to hold true *within* each of the two major sampling units of the field site, namely the cleared and forest zones, thus rendering the data suitable for semivariogram analysis, for two data populations:

1. The cleared zone, which for this technique comprises the 35 points from the areal sampling[2] (C1, C2, C3,.. ..C35) in this area plus the five points in the transition zone which lie on the cleared side of the cut-line (TZ2, TZ4, TZ6, TZ7, TZ8) and also the first three points from each of the linear transects (LT1, LT2, LT3, MT1, MT2, MT3, RT1, RT2 & RT3), giving a total of 49 sample points.
2. The forest zone which is redefined in this chapter as being the 35 forest points from the areal sampling (F1, F2, F3,.. ..F35) plus the points in the transition zone which lie on the forest side of the cut-line (TZ1, TZ3, TZ5) and the 12 points at the end of each linear transect which lie wholly in the forest (LT5 - LT16; MT5 - MT16; and RT5 - RT16), giving a total of 74 sample points.

Point 4 on each of the three linear transects was not allocated to either group for this work, as it lay exactly on the cut-line and thus did not fit exclusively into either category. The transition zone contained too few points for it to be analysed separately.

8.3 Selection of variables

Variables measured in the field in 1992 were selected for semivariogram analysis according to certain criteria: Samples representative of

1. Those which had shown marked differences in their value when measured in the cleared and forest zones, as revealed by the visualisation techniques in chapter six, (water pH, soil exchangeable potassium, % soil weight loss on ignition, soil pH).
2. Those which had shown a statistical difference in their values measured in the cleared and forest zones, as revealed by ANOVA and Mann Whitney-U tests (water dissolved oxygen content).
3. Those which the ordination work of chapter seven had shown to strongly influence the environmental gradients found across the three field sites (water conductivity).
4. Those which may have been expected to have been included in the above lists, but were not,, to see if this omission could be revealed by the scale of their spatial autocorrelation, (soil redox potential, soil exchangeable calcium).

Revealing the spatial scale of variation in soil redox potential was of particular interest as the work of Scholander *et al.* (1955) and McKee (1993) suggests that the oxygen export activity of mangrove pneumatophores may mean that considerable variation in soil redox potential may occur over distances of only a few centimetres. If this is the case, this very localised variation may be sufficient to mask differences between the larger forest and cleared zone "structural" component of variation.

The environmental data were not transformed before semivariogram analysis. Most had been found not to differ significantly from the normal distribution, and semivariogram analysis is anyway a

[2] The position of these points is given in Figure 11.3 in Appendix 4.

relatively robust technique (Webster & Oliver, 1990) which does not assume that the environmental data are normally distributed. Furthermore, such mathematical transformation would hinder the interpretation of the semivariogram results.

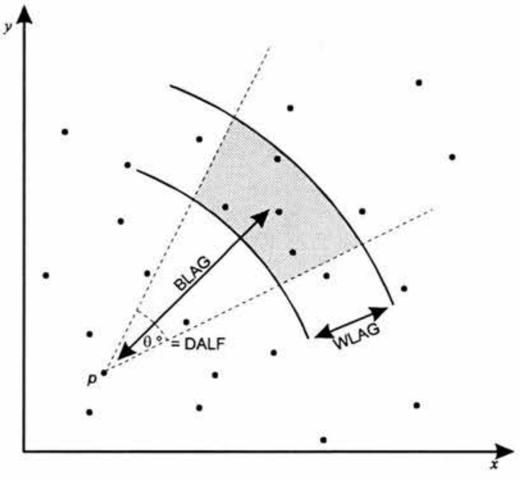
8.4 Configuring the analysis

Calculation of sample semivariograms was carried out using the program GEOPACK Version 1.0, (Yates & Yates, 1989). The number of samples available for use in these calculations is rather lower than would be ideally available. Many other such analyses such as those summarised in the review of Oliver *et al.* (1989a) use far larger datasets (150-500 or more sample points per analysis). As such the results of the analyses which follow should be treated with caution, they are only exploratory, and regrettably the modelled responses of the variables was not considered suitably robust to follow this analysis with the creation of kriged surfaces, similar to the interpolated figures of chapter six.

8.4.1 Inclusion parameters

The semivariogram program was configured to provide as many datapoints for calculation as possible. Despite in the worst case (the cleared zone) having only 49 sample points, the number of comparisons for at least the short interval lags can be increased significantly through manipulating the parameters used in lag calculation[3]. These are the distance between lagged distances (referred to as "BLAG" in GEOPACK), the width of the lagged interval ("WLAG") and the width of the angle class ("DALF"). The meaning of these measures is shown diagramatically in Figure 8.3 below:

Figure 8.3 Inclusion parameters used in GEOPACK



This diagram shows the sample datapoints (represented as black circles) arranged over the field site surface, as viewed from above. The shaded region represents the zone in which possible "partners" for the chosen sample point (p) may be found. The shape of this region is controlled by the three parameters - "BLAG", "WLAG" and "DALF". The diagram shows the simplest case, where the first lag distance is being generated, i.e. the lag (h) is equal to "BLAG" multiplied by 1.

Based on Figure 7.15 in Burrough (1987).

[3] For most diagrams, each lag point was produced from at least 30 couples, a figure which rose to 80-100 couples for lags three times BLAG or more.

The generated lags are all multiples of the distance between lagged distances, "BLAG". For example, if "BLAG" was set to 4 m, lags of 4 m, 8 m, 12 m, 16 m, etc. would be calculated. Using such an exact figure for the lag may be misleading, for the reported semivariance value for a given lag is actually an average value for a narrow range of lags, the width of which is set by the parameter "WLAG". By default, GEOPACK sets "WLAG" equal to half the value of "BLAG" and this setting was left unchanged. Thus for a sample run where "BLAG" was set to 4 m and "WLAG" set by default to 2 m, the generated sets of semivariance values for lags 4 m, 8 m, 12 m, etc., would actually be averaged lags for the ranges 2-6 m, 6-10 m, 10-14 m, etc. By increasing the tolerance of this "inclusion criterion" many more possible lag figures can be generated, particularly as in this case, if the datapoints are randomly rather than systematically distributed. The final parameter which can increase or decrease the number of pairs of sample points fitting the inclusion criterion is the width of the angle class ("DALF"). This effectively sets the width of a conical zone of potential lag points, stemming out from the first sample point in the comparison, in the direction in which the semivariogram is being calculated. (The significance of the direction of the semivariogram is considered further below). The default value of "DALF" is 90°, but this was thought to be rather too generous, giving a 45° swathe of points either side of the line. For the purposes of this analysis it was therefore reduced to 60°. This value was obtained by a process of trial and error, and is a compromise figure which minimises the value of "DALF" but maintains sufficient number of couples for each lag distance to produce relatively smooth semivariograms. The value of "BLAG", the distance between lagged distances varied between three and five metres during sample runs, the exact value was chosen to produce a variogram with the fewest number of erratic looking points at low lag distance values, those most crucial to curve fitting.

8.4.2 Directional spatial variation

Another question to consider in an analysis of spatial relationships, is whether these vary in space. Variables which show an even pattern of spatial covariation in all directions are referred to as isotropic, those which show different degrees of spatial covariance varying with the direction of measurement are termed anisotropic. Possible anisotropy in a dataset can be detected by calculating several semivariograms measured in different directions. Burrough (1987) suggests that two or three directions are usually sufficient for detection purposes.

Two approaches were adopted in an attempt to detect anisotropy: semivariograms were computed for different azimuthal directions to detect differences in the horizontal, and also for samples gathered at different depths, to detect changes in the vertical, sometimes referred to as zonal anisotropy (Webster & Oliver, 1990).

Semivariograms were calculated along the two directions thought most likely to reveal differences. The first should show any forest/cleared differences, (referred to as 0° in Table 8.1 below). It uses a semivariogram centred along a line perpendicular to the cut-line, running from the cleared zone into the forest. The second direction follows a line perpendicular to the first (referred to as 90° below) and should therefore detect any changes along the marine-terrestrial gradient.

Semivariograms were calculated for two different depths (Layer 1 and Layer 2) for soil pH, redox potential, weight loss on ignition, exchangeable calcium and exchangeable potassium content in both the forest and cleared zones.

From the surface modelling analysis of chapter six, spatial anisotropy in the horizontal can be expected in variables such as water pH and soil exchangeable potassium which show a marked gradient across the field site

Spatial anisotropy is generally considered an undesirable feature, especially in attempts to produce kriged data surfaces (i.e. estimate a data surface for the modelled parameter, generated using computational methods which, unlike that used in chapter six to develop the terrain models, *can* accommodate the revealed degree of spatial covariation). This is because spatial anisotropy undermines the validity of the semivariogram used in the kriging interpolation process.

However, the presence of spatial anisotropy is to be welcomed in a study of environmental changes along a gradient. Anistropy, i.e. a directional trend in the spatial covariation of data values corroborates the theorised gradients of change, particularly if they run along an axis perpendicular to the cut forest edge.

Zonal anisotropy is also expected, it is a common feature of other semivariogram analyses of soil data, such as that of Oliver & Webster (1987). It can be attributed to differences in the abundance, distribution and function of plant roots, varying with depth and more generally to the intrinsically variable nature of terrestrial biology.

8.4.3 Model fitting

The GEOPACK program allows the fitting of several models (curves) to the data - using the standard linear, spherical, gaussian, exponential and power models described in Burrough (1987) and Webster & Oliver (1990). There is no single universally-accepted method for model fitting, some advocate using numerical techniques, others prefer selecting which curve best fits the data by eye. In this work, the model was selected using primarily numerical methods, (the nonlinear least squares minimisation technique of Marquardt (1963), as suggested by Oliver *et al.* (1989b)) moderated by visual inspection in cases where the differences were very close.

8.4.4 Omitting extreme data points

Erratic datapoints, that is certain points which seem to lie far outwith the perceived pattern shown by the semivariance at other lag distances, were to be expected for two reasons. The first is the relatively small number of couples used to generate the semivariograms, which will mean that rare extreme values will have a greater influence on the resulting semivariance, than if the sample size was greater. Secondly the relatively "hostile" environment in which the environmental properties were measured - the semi-flooded, disturbed, partly cleared mangrove forests of the field site can be expected to show far greater heterogeneity than the regularly ploughed and carefully fertilised fields of the agricultural stations where many of the measurements used in the early semivariogram work were taken. In an attempt to produce credible semivariograms, some extreme datapoints were removed.

The first category for removal were datapoints for large lag values because the small number of available couplings may make their value erratic. On semivariograms where a sill had clearly been reached (such as Figure 8.3o) if the semivariance for the last few datapoints was markedly higher or lower than this sill value, then these points were removed before calculating the model fit. Such manipulation of the data assumes that this deviation from the sill is merely a function of the sample size and not indicative of periodic or cyclical variation which could result in such a pattern. To fully answer whether this assumption is justified requires further work in the mangroves involving a more intensive sampling strategy.

The other datapoints occasionally removed from the analysis are those which are generated for very small lags. Because the sample points are in the main randomly rather than systematically distributed over the field site, the number of couples which contribute to very small lags is relatively low. This means that these points are also subject to the influence of a single extreme value, which in certain cases required their removal.

8.5 Presentation of results

The results of the semivariogram analysis are presented in two ways below. Figure 8.4 shows the semivariograms together with the fitted models which best describe the data. Table 8.1 lists the key points from these diagrams - the value of the sill, nugget and range, plus listing the type of model fitted. It also shows the structural variance, a measure of an environmental variable's spatial dependence. It is ratio of $\varepsilon'(x)$ the spatially correlated, but random variation, divided by ε'' the residual, spatially *independent* "noise" term, expressed as a percentage. Caution should be exercised in interpreting variograms where the structural variance is very low, because this indicates that the data show little spatial covariance.

Table 8.1 Semivariogram analysis results

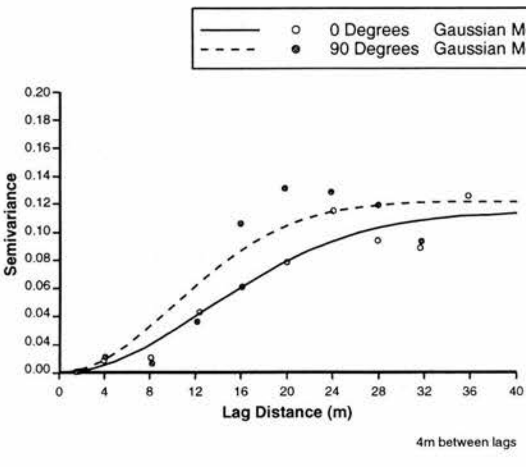
Variable Measured	Sampling Zone	Variogram Angle	Model Fitted	Nugget c_0	Sill-Nugget (c_0+c_1)	Range a	Structural Variance
Water pH	Cleared	0°	Gaussian	0.00	0.11	18.25	100%
		90°	Gaussian	0.00	0.12	14.32	100%
	Forest	0°	Spherical	0.08	0.38	48.37	79%
		90°	Gaussian	0.18	0.43	30.79*	58%
Dissolved Oxygen	Cleared	0°	Spherical	0.47	2.10	34.14	78%
		90°	Spherical	0.32	2.30	29.08	
	Forest	0°	Gaussian	3.94	2.10	30.53	86%
		90°	Exponential	3.91	5.36	14.18	27%
Conductivity	Cleared	0°	Gaussian	0.00	0.75	20.65	100%
		90°	Gaussian	0.00	0.75	17.26	100%
	Forest	0°	Gaussian	0.13	0.26	12.76	50%
		90°	Spherical	0.13	0.53	39.24	76%
Soil pH Layer 1	Cleared	0°	Exponential	0.05	0.48	50.63	90%
		90°	Spherical	0.02	0.24	27.99	92%
	Forest	0°	Gaussian	0.12	0.20	21.14	40%
		90°	Spherical	0.06	0.33	32.02	82%
Soil pH Layer 2	Cleared	0°	Gaussian	0.11	0.32	21.74	66%
		90°	Spherical	0.01	0.25	24.88	96%
	Forest	0°	Spherical	0.06	0.41	37.77	85%
		90°	Spherical	0.06	0.30	28.05	90%
Exch. K Layer 1	Cleared	0°	Exponential	0.00	0.07	18.66	100%
		90°	Spherical	0.01	0.03	18.98	67%
	Forest	0°	Spherical	0.00	0.15	15.80	100%
		90°	Gaussian	0.01	0.12	12.42	92%
Exch. K Layer 2	Cleared	0°	Gaussian	0.00	0.21	70.57	100%
		90°	Spherical	0.00	0.08	102.68	100%
	Forest	0°	Spherical	0.01	0.13	19.63	92%
		90°	Gaussian	0.01	0.10	11.06	90%
Soil Redox Layer 1	Cleared	0°	Exponential	0.00	9139.4	3.48	100%
		90°	Exponential	0.00	8498.5	20.72	100%
	Forest	0°	Exponential	0.00	24991	6.45	100%
		90°	Exponential	1165.9	21247	2.96	99%
Soil redox Layer 2	Cleared	0°	Gaussian	1291.1	7589.7	13.57	83%
		90°	Exponential	0.00	7159.1	12.88	100%
	Forest	0°	Exponential	83.05	14298	12.16	99%
		90°	Exponential	0.00	11199	3.70	100%
Wt LoI Layer 1	Cleared	0°	Spherical	0.00	9.69	5.12	100%
		90°	Exponential	4.32	8.38	14.83	48%
	Forest	0°	Spherical	5.88	40.76	5.88	86%
		90°	Spherical	18.66	44.36	13.54	58%
Wt LoI Layer 2	Cleared	0°	Gaussian	4.65	5.19	4.52	10%
		90°	Spherical	0.00	9.33	4.71	100%
	Forest	0°	Gaussian	0.00	43.57	5.63	100%
		90°	Gaussian	11.18	56.28	11.51	80%
Exch. Ca Layer 1	Cleared	0°	Spherical	0.00	0.63	6.92	91%
		90°	Gaussian	Poor Fit			
	Forest	0°	No pattern				
		90°	No pattern				

The varying significant digits shown in the value of the sill, nugget and range are a function of the 5 figure plus exponent output format used in the GEOPACK program. Structural variance has been rounded to the nearest percent.

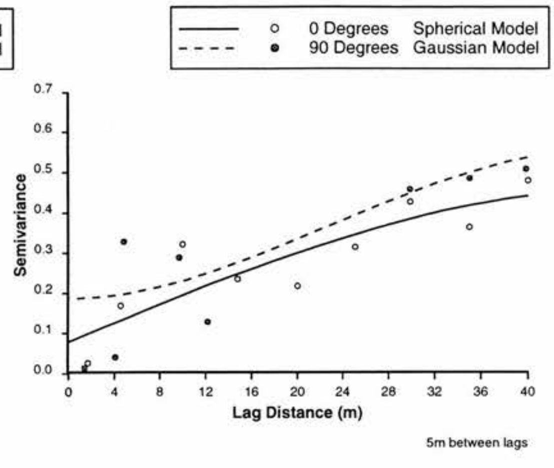
Figure 8.4 Soil and water property semivariograms

The figures below are semivariograms calculated using data from the 1992 Burnt Fieldsite. Each semivariogram shows variations in two directions across each zone (at angles of zero and ninety degrees to the long axis of the fieldsite) to highlight any large scale drift. The data points shown are those which were used to calculate the models, represented below by the fitted curves. Some data points showing extreme deviation from the curves have been omitted - see the accompanying text for a full discussion of this. The semivariograms were calculated using the lag distance indicated below each figure, the width of each lag interval is half this figure, and an angle class of 60° width was used. These terms are explained more fully in the text. Semivariance units are the same as those use throughout this work to measure the environmental property.

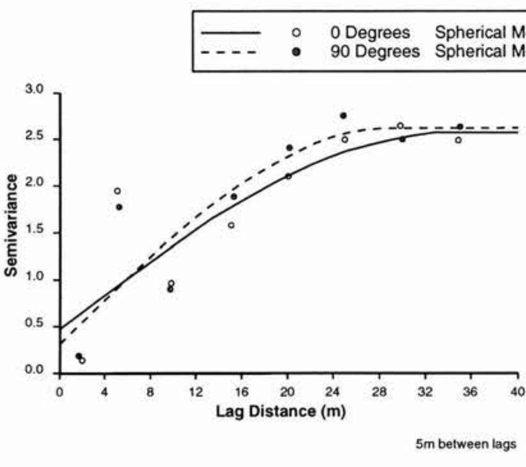
a. Cleared Water pH



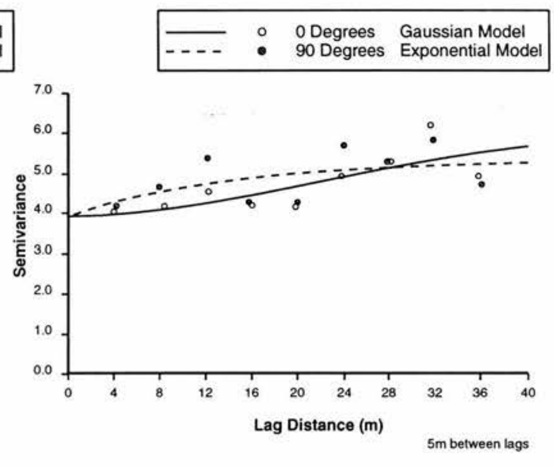
b. Forest Water pH



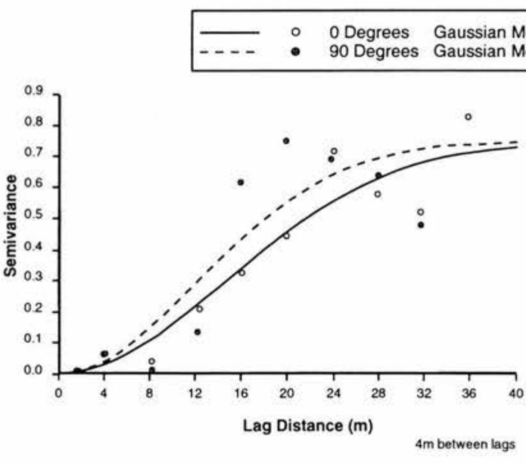
c. Cleared Dissolved Oxygen



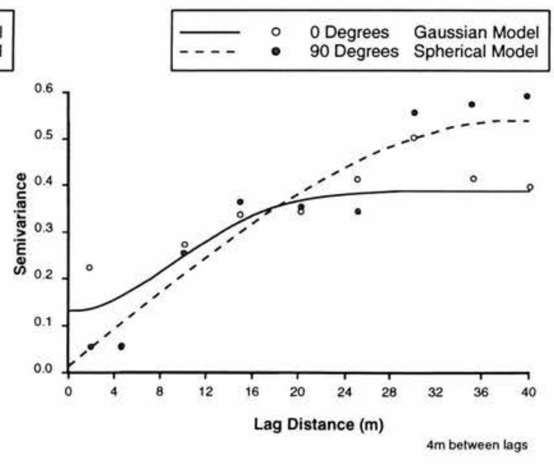
d. Forest Dissolved Oxygen



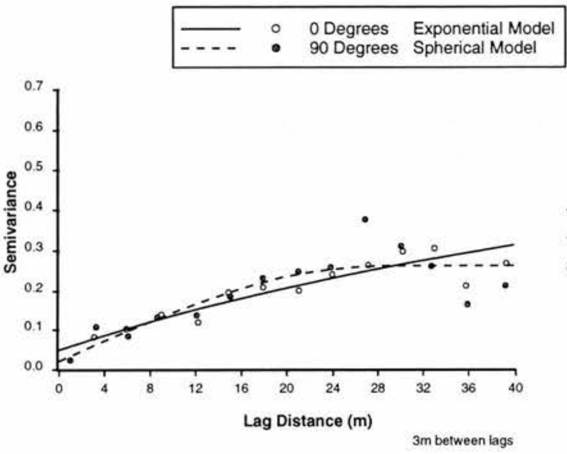
e. Cleared Conductivity



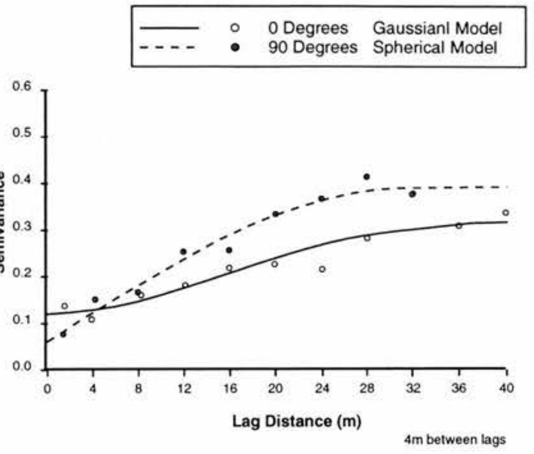
f. Forest Conductivity



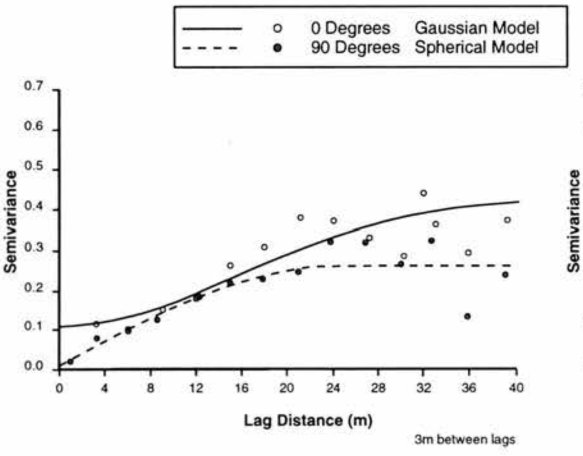
g. Cleared Layer 1 Soil pH



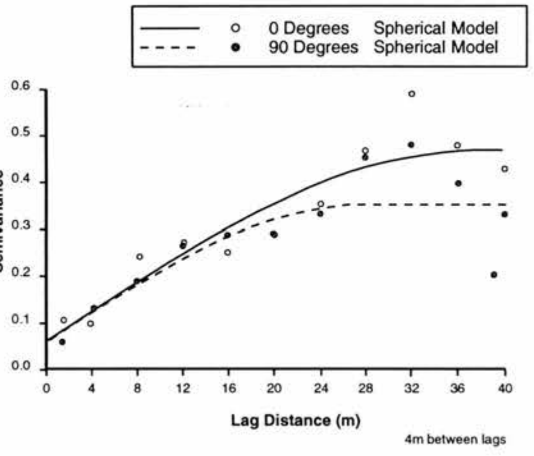
h. Forest Layer 1 Soil pH



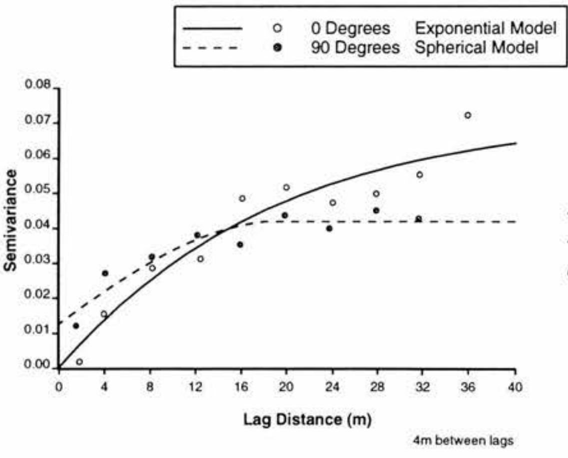
i. Cleared Layer 2 Soil pH



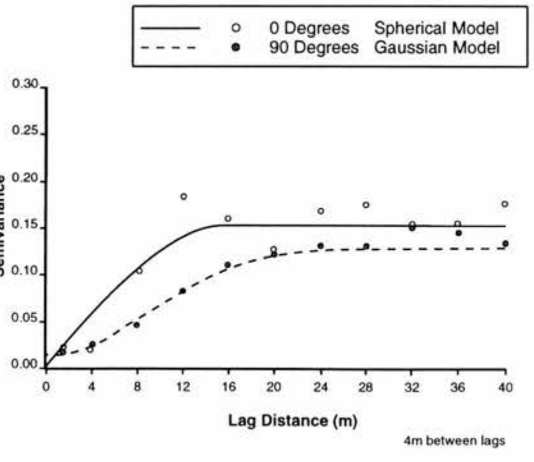
j. Forest Layer 2 Soil pH



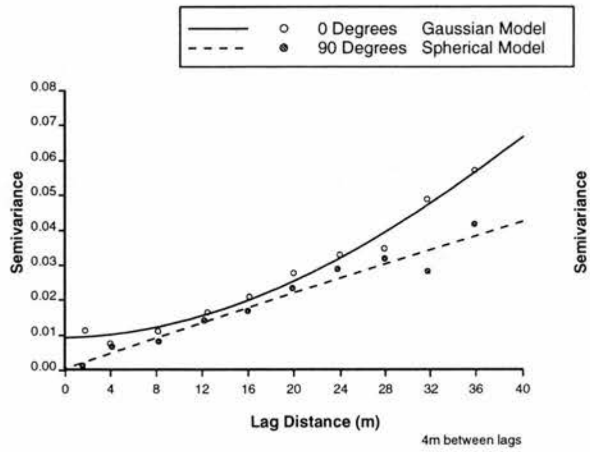
k. Cleared Layer 1 Soil Exch. Potassium



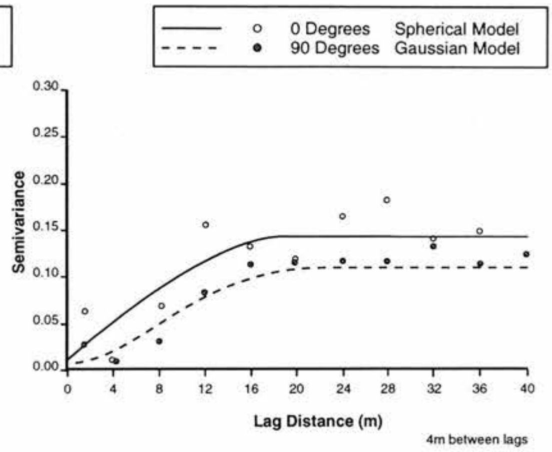
l. Forest Layer 1 Soil Exch. Potassium



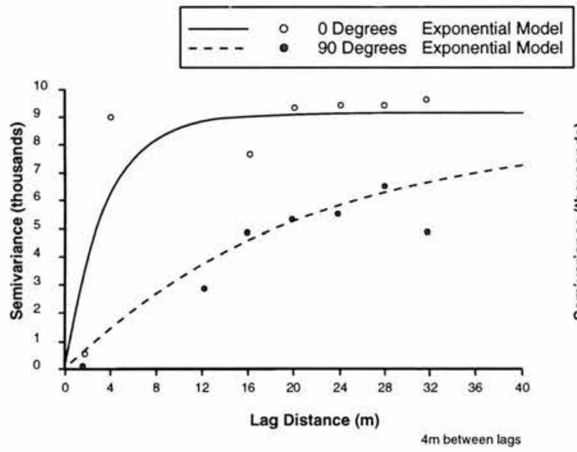
m. Cleared Layer 2 Soil Exch. Potassium



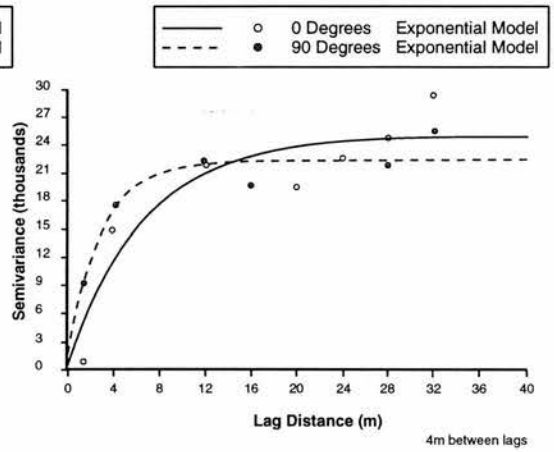
n. Forest Layer 2 Soil Exch. Potassium



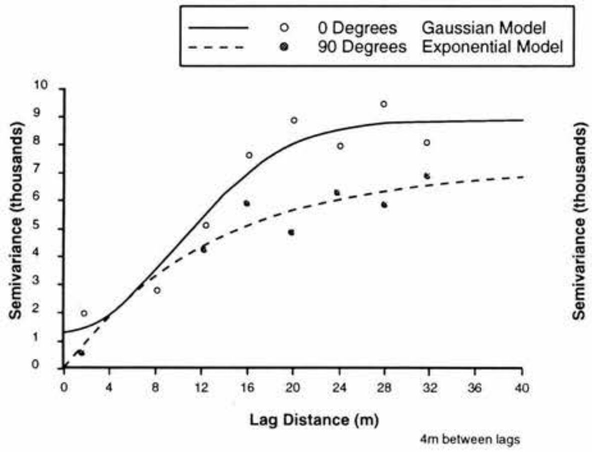
o. Cleared Layer 1 Soil redox



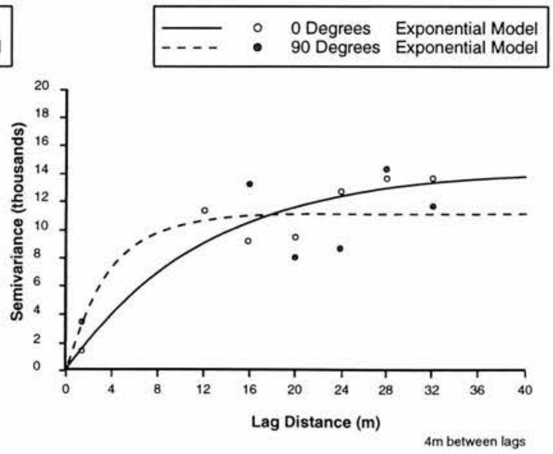
p. Forest Layer 1 Soil redox



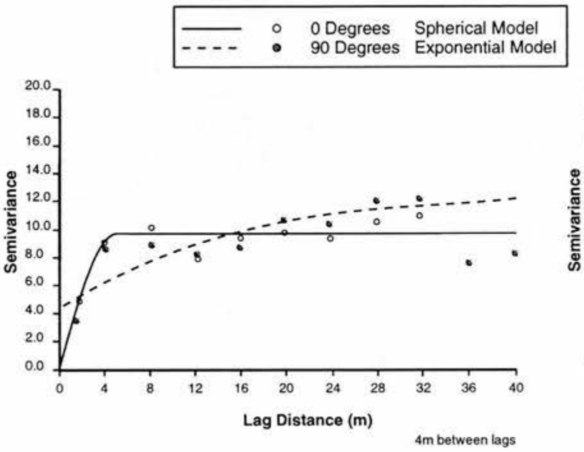
q. Cleared Layer 2 Soil redox



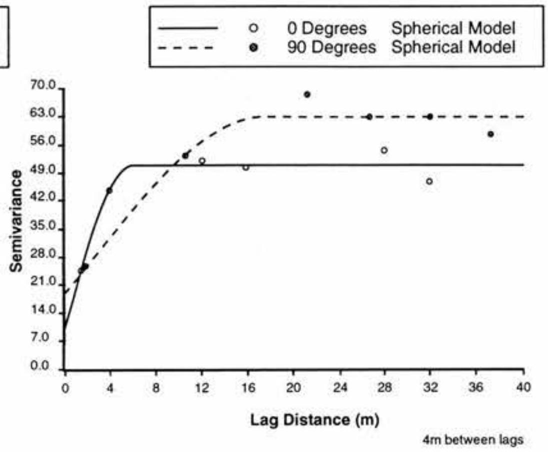
r. Forest Layer 2 Soil redox



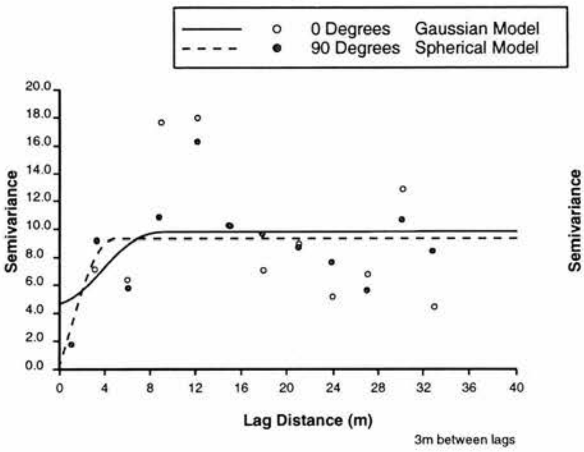
s. Cleared Layer 1 Soil Wt. Loss on Ignition



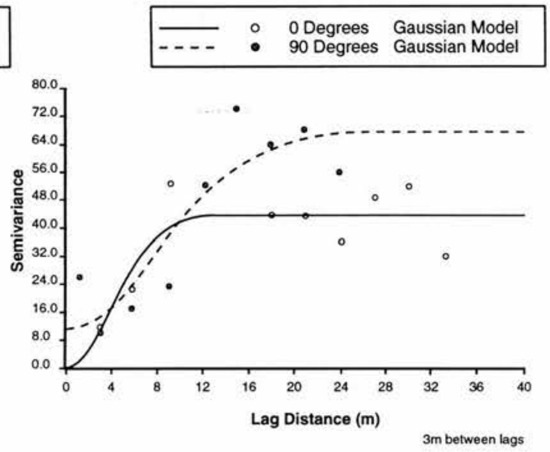
t. Forest Layer 1 Soil Wt. Loss on Ignition



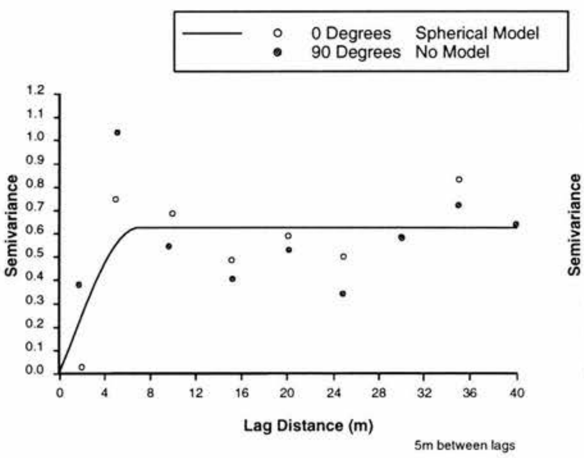
u. Cleared Layer 2 Soil Wt. Loss on Ignition



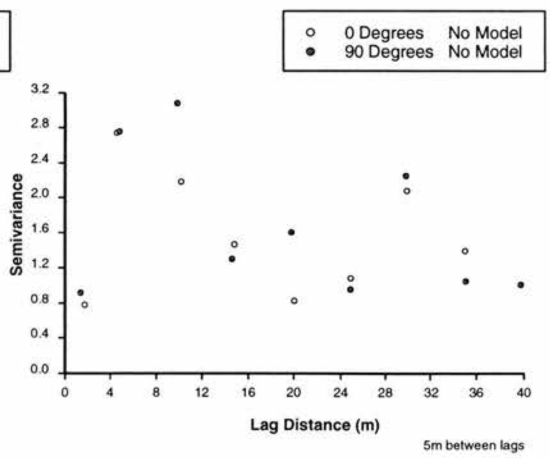
v. Forest Layer 2 Soil Wt. Loss on Ignition



w. Cleared Layer 1 Soil Exch. Calcium



x. Forest Layer 1 Soil Exch. Calcium



8.6 Comparing the semivariogram pairs

Figure 8.4 and Table 8.1 allow each environmental property's scale of spatial variation to be compared for the forest and cleared zones. Below, a description of the key differences are given for each measured property. Further interpretation of general patterns observed in the data follows in Section 8.7. This later interpretation focuses separately on first the choice of model, then whether anisotropy is present in the data and finally upon the significance of the scale of spatial variation revealed by the semivariogram analysis. When comparing the graphs shown in Figure 8.4 attention is drawn to possible differences in the *y*-axis scale between the semivariograms. Although wherever possible differences in scale have been avoided, in some cases they have had to remain to show the shape of the distributions clearly.

8.6.1 Water pH

The forest and cleared area water pH semivariograms seen in Figure 8.4 are quite different. The forest diagram has a large nugget value, showing that water pH values vary considerably, even over short distances in the forest. In contrast to this, the cleared semivariogram plots as a horizontal line at low values. This means that water pH values in the cleared zone are very similar over short distances.

Table 8.1 shows larger semivariogram sill-nugget values for the samples in the forest, revealing a greater degree of pH variation in this zone.

8.6.2 Water dissolved oxygen content

The cleared and forest dissolved oxygen semivariograms show even more differences. The forest variograms are nearly linear and the curves are almost horizontal. This means that dissolved oxygen values in the forest have a small spatially correlated component to their variation. Dissolved oxygen levels in the cleared zone show a spherical model, with a far lower nugget value. This reveals that the dissolved oxygen content of points in the cleared zone are far more homogeneous over short distances than points in the forest.

8.6.3 Water conductivity

The conductivity semivariograms are more similar for the two zones, than the other properties measured in water. Three of the models show a very low nugget value, meaning that the random component of variation for this variable is very small. Only one fitted model, the 0° forest gaussian model, differs, and shows definite signs of directional anisotropy (discussed in more detail in Section 8.7.2). This suggests that the movement of saltwaters through the forest may be more easy in one direction (perpendicular to the cut line) than the other (from the road to the sea).

8.6.4 Soil pH

Four semivariograms have been produced for soil pH, because measurements were taken at different depths in both the forest and cleared zones. The low nugget value of all these diagrams shows the random component of variation in pH values to be small. The semivariograms for sites in the cleared zone have a lower sill value (and thus a lower spatial component) and also a shorter range. This means that the spatial effects of pH values at one site upon values at another operate over a shorter distance in the cleared zone than they do in the forest. This increased spatial component of variation in forest pH values may be the result of the actions of live mangrove roots. These can alter pH conditions around themselves (Scholander *et al.,* 1955; McKee, 1993), which may act to create locally uniform areas of pH in the forest soil.

Comparing the semivariograms for pH measurements obtained at different depths, samples from the second layer, particularly those obtained in the forest, have a higher sill-nugget value. This means that in the forest, the pH values of samples at depths are more affected by the pH of neighbouring sites than similar samples in the cleared zone, and also in the upper soil layer.

8.6.5 Soil exchangeable potassium

The exchangeable potassium semivariograms calculated for different directions in the forest are more similar than those in the cleared zone, although all the models have very low nugget values. The semivariance of forest sites is also far greater than cleared sites (approximately three times a high, as seen in the differences in the *y*-axis scales). This is a result of the higher exchangeable potassium levels found in forest sites, compared with those in the cleared zone. The semivariograms also differ for samples obtained at different depths, with the layer two cleared site semivariogram showing a particularly large spatial component to its variation (no obvious sill). Semivariogram analysis has therefore detected both spatial and zonal anisotropy in this variable's distribution.

8.6.6 Soil redox

The most striking feature of the four soil redox potential semivariograms is the very short range. The semivariograms reach their sill value at a relatively short lag distance compared with the other variables measured. This can be attributed to the oxygen exporting activity of the mangrove roots, and confirms the expectations of McKee (1993)[4]. Sites in the forest reach their sill at a higher semivariance value. This is a function of the greater range of redox potential values measured in the forest. Comparing samples at different depths, sites from both zones in the upper soil layer reach their sill before those from layer two. This greater range for samples at depth means that the spatial component of variation continues to affect soil redox values over a greater distance at depth. Two possible reasons exist for this difference. It may be because of greater numbers of mangrove cable roots in the lower

[4] McKee's work involved very fine-scale sampling (points a few centimetres apart) along linear transects. It did not, however, include any semivariogram analysis.

soil samples, resulting in greater spatial uniformity in layer two. Alternatively in the upper, layer one soil samples, perhaps very localised changes in the surface soil redox potential, e.g. very small-scale oxidation, are great enough to outweigh the larger scale effects occurring at depth.

Whilst the semivariograms shown in Figure 8.4 agree with the findings of previous work, they should still be interpreted cautiously. During analysis, soil redox values showed the greatest degree of variation at low lag distances, making fitting a smooth curve difficult. The final models required removing some extremely high and extremely low semivariance values obtained at short lag distances. This irregularity is thought to be merely a function of the few generated lag couples (less then 30 for the points removed) and would disappear if the analysis was repeated for datasets containing a greater number of sample points. However this assumption awaits experimental confirmation.

8.6.7 Soil weight loss on ignition

The semivariograms for weight loss on ignition, measured at two depths, show a clear difference between samples in the forest and samples in the cleared zone. These differences reflect the greater organic matter content of forest soils - this accounts for the higher nugget and sill-nugget values in the forest zone. The greater range found for samples in the forest is a function of the greater organic matter variation in the soils of this zone.

Layer 1 samples from both sites show a much better model fit than those from layer 2. This is thought to be because of greater sample heterogeneity in layer two. Whilst the upper soil layer is predominantly organic-rich peat, the second layer is far more varied and could be thought of as two separate sample populations, one almost pure clay, the other a mix of clay and organic material. The wide deviation of layer two points from the fitted models may reflect the balance of pure-clay and mixed organic-clay samples used for each lag distance calculation.

8.6.8 Soil exchangeable calcium

Soil exchangeable calcium was chosen as a variable for semivariogram analysis because although it is taken up by plants, it did not show marked differences in value when measured in the cleared and forest zones. Perhaps, studying the spatial scale of calcium variation would reveal why this was the case.

The exchangeable calcium semivariograms differ markedly from the others seen so far, because they show no obvious trend in the data. Model fitting was attempted for samples measured from both layer one and layer two samples, with little success. Only one model fitted - a spherical model applied in a 0° direction to layer one soil samples from the cleared zone. The results of the semivariograms for layer two samples are not given in Figure 8.4, but they show a similar lack of trend to that seen in the layer one forest values. This inability to fit models suggests that the spatial variation of calcium values occurs at a very large scale and the sampling interval has not been great enough to detect it. Had there been no real spatial component to soil calcium content, the resulting semivariograms would have been horizontal. In effect, all the values shown on the semivariograms reveal only the variable's nugget variance.

The major source of calcium in mangrove soils is thought to be from sediments deposited by river systems. The local distribution of such sediment deposits is likely to be highly variable because of seasonal variations in river flow and the low elevation of the coast, which will not constrain water movement into well defined channels. If calcium levels do vary considerably over long distances as this preliminary semivariogram interpretation suggests, then this would explain why no significant differences in soil calcium content were found following clearance.

8.7 Interpretation

Having compared the semivariograms individually, three aspects of the data are looked at in more detail, to try and establish trends for all the variables measured. The three aspects considered are:

1. The significance of the shape of the fitted model.
2. Whether signs of spatial and zonal anisotropy can be detected over the field site (which may indicate a gradient).
3. The spatial scale of variation - using the range values obtained to evaluate the sampling interval used in the fieldwork.

8.7.1 The choice of model

The "Model Fitted" column of Table 8.1 shows a general difference in the model used between environmental variables measured in the soil and those measured in the water. Variables measured in water seem to favour a gaussian model, whilst those measured in soils tend to favour an exponential or spherical model. This predominance of exponential and spherical models of semivariance for soil data is consistent with similar conclusions by Webster & Burgess (1984).

Burrough (1987) notes that the spherical model is most applicable to a variable which shows abrupt changes in value, where there is no single clearly defined distance between these abrupt changes. Such a model is consistent with the uniformity of the dense vegetation cover in the forest zone, and equally with its near total absence in the cleared zone. An example of a site which could be expected to have clearly defined distances of abrupt change (and thus where the fitting of a spherical model should be questioned) is one where the vegetation cover consists of isolated individuals and thus changes in soil properties occur at regular intervals corresponding to environmental limits such as shade effects and the maximum extent of root growth from the trunk.

Burrough (1987) describes the exponential model as being applicable to data showing abrupt changes in value at all distances, where the spacing between changes varies according to the Poisson distribution, i.e. changes at small distances are far more common those at large. This is consistent with the scale of many soil processes, particularly those dependent upon uptake or export of substances around plant roots, such as those which would result in a change in soil redox potential. Table 8.1 shows that in seven of the eight cases, it is an exponential model which best describes the soil redox semivariograms.

Gaussian models are common for variables which vary smoothly over space (Burrough, 1987). The flooded nature of the field site will act to produce such a smoothing effect on variables measured in the water. The inflection at the beginning of the variogram, where the model is often very nearly horizontal, implies that for a certain range of short lag distances, there is no appreciable increase in sample variance. This may be because although differences in water properties exist at a large scale (such as a salinity gradient dependent on distance from the sea), over small distances potential differences in the concentration of materials in the still waters of the field site are likely to be negated by localised diffusion processes. Of the three water-based measurements, dissolved oxygen seems to fit least well with this interpretation. This suggests that diffusion of oxygen from areas of high concentration to those of low is severely inhibited in the field site, and/or that water dissolved oxygen levels may be strongly affected by a soil-based process, the most obvious candidate for which is the oxygen exporting action of mangrove roots.

8.7.2 Anisotropy

An environmental variable which exhibits spatial anisotropy will show different models, sill and nugget values for the two directions. Variables with obviously contrasting models, indicative of spatial anisotropy are soil redox potential and soil weight loss on ignition (particularly in the forest zone). Redox potential shows greater variance along the zero degrees axis, suggesting a forest-cleared zone redox gradient, which can probably be related to differences in the density of live roots. Conversely, and somewhat surprisingly, weight loss on ignition shows a greater variance across the ninety degrees axis. This suggests that the greatest variation in organic matter *within* each zone occurs along a gradient not aligned along a forest - clearance gradient, but one perpendicular to this, running from the shore inland. This may indicate movement of surface organic material across the field site by severe storms, forcing material inland and washing away material nearest the shore, or wind transport of material, the prevailing direction is generally offshore in this area.

Weaker signs of spatial anisotropy can be detected in the semivariograms for soil pH and exchangeable potassium. These are also thought to be due mainly to differences in root distribution. The semivariograms for soil exchangeable calcium are not clearly defined enough to allow any useful interpretation.

Significantly, the environmental variables which show the greatest spatial isotropy are those measured in water - particularly those in the cleared zone, where the greatest opportunities for wind-driven water mixing occurs. Such actions would act to reduce directional differences in the measured properties. The apparent anisotropy in forest conductivity values may be a result of the standing vegetation reducing the mixing effect of the wind, maintaining a slight salinity gradient.

Zonal anisotropy, differences in the variance of values with depth shows a different pattern. There is little evidence of zonal anisotropy for soil pH in the cleared zone, but there is a stronger case in the forest, particularly along the 90 degree axis. This may indicate a subsoil buffering of pH by seawater intrusion, which has a greater effect for the generally more acidic soils in the forest. Cleared soil exchangeable potassium semivariograms are very different, showing a far greater variance at the soil surface. This could be the result of a very localised pattern of potassium leaching or uptake by invading plants and algae. It could also be the result of the uneven distribution of animal faecal matter, particularly from birds, attracted to the crabs, grazing without the protection of the forest cover. Depth differences in the variance of soil exchangeable potassium in the forest are far less marked. This is probably due to a more stable hydrological regime and the dense network of roots seeking to take up soil potassium in the forest. The soil redox semivariograms reach their sill value earlier at the surface, indicating that spatial dependence is restricted to a narrower range of distances. This may be because very localised differences in surface soil redox are occurring as a result of the combination of root oxidising effects and the periodic oxidation and reduction of exposed areas of soil linked to fluctuations in the water level over the field site. There is little difference in the semivariograms for weight loss on ignition for samples measured in the cleared zone, but there is a marked difference with depth in the forest (note the difference in the *y*-axis scales). This is a result of the greater variation in soil organic content in the forest zone, due to variations in the pattern of litter deposition and subsequent decomposition in this area. Removal of the tree cover in the cleared zone has resulted in a greater uniformity of soil organic carbon values.

8.8 The scale of spatial variation - evaluating the sampling intervals

The "Range" column of Table 8.1 provides the necessary criterion for assessing the sampling intervals used in the fieldwork. Full details of the transect sampling intervals has been provided in Figure 5.13. The smallest sampling interval used in transect work is 1.25 m, between points four and eight on each of the three linear transects from the 1992 Burnt site fieldwork. However, smaller distances between individual pairs of samples occur in the randomly sampled data used in the areal comparison work at this site. The largest interval is 10 m, used on the 1994 Texaco transect.

Most of the variables examined, approach their semivariance sill value at a range greater than 10 m, meaning that the sampling intervals used in all stages of the fieldwork are suitably fine to yield a set of spatially dependent values suitable for the construction of interpolated surfaces and transects. However, there are two exceptions to this: soil redox potential and to a lesser extent the organic carbon content of soil, expressed as the percentage weight loss on ignition. These two variables have ranges some of which are less than 10 m. This suggests that in the case of the 1994 Texaco transect (which used a 10 m sampling interval), great care should be taken before inferring any trend in the value of soil redox potential from the datapoints[5] (weight loss on ignition was not measured at this site). The very low range value for some of the soil redox semivariograms, notably the figure of 2.96 m for the 90° aligned semivariogram for layer 1 data measured in the forest zone, initially suggests that the other 1994 transect work which used a sampling interval of 5 m may also be suspect for an analysis of the spatial distribution of redox values. However, these other transects (at the Burnt and Punta del Este field sites) were carried out in a direction which corresponds with the 0° axis direction of the semivariogram, which yields a higher range, greater than 5 m for all but one case, implying that the sampling interval at these sites is likely to be fine enough to detect any spatial trends in redox values.

8.9 Conclusion

Semivariograms have been calculated for selected environmental variables using two sets of data from the 1992 fieldwork. These have been termed the cleared and forest datasets, as they are separated by the cut edge of the forest. Despite the number of datapoints being rather low, particularly for short lag distances, it has proved possible to generate relatively smooth looking semivariograms. Model fitting separates the environmental properties into those which are measured in water (favouring a gaussian model) and those measured in the soil (exponential and spherical models). This difference can be attributed to the localised mixing and diffusion processes which occur in the water of the mangroves, which acts to greatly reduce environmental gradients over short distances.

Semivariogram analysis of the data has also revealed signs of spatial and zonal anisotropy. Spatial anisotropy is interpreted as evidence of the presence of environmental gradients across the field site. These have been found acting both perpendicular to the forest cut line, indicative of an edge effect and also parallel to the cut edge, interpreted as a marine influence. Zonal anisotropy is attributed to differences in the distribution and changing function of plant roots with depth.

Examination of the position of the semivariogram sill has allowed the evaluation of the sampling interval used. Most variables appear to show spatial covariation over distances greater than 10 m (the largest transect sampling interval used) meaning that the interpolation of continuous data value surfaces of chapter six can be justified. Two variables showing a low range are soil weight loss on ignition and in particular, soil redox potential. The small range of soil redox potential is attributed to gas exchange occurring around the roots of mangroves.

[5] Although more confidence in this conclusion would require a more intensive sampling of soil redox values.

Variables with a relatively high range on the semivariogram and in particular those showing a smooth distribution (such as water pH, dissolved oxygen content, conductivity and soil exchangeable potassium), possess strong spatial dependence. This explains why these variables show the strongly differentiated elevation models and the statistically significant differences seen earlier in chapter six. These are also the variables which exert a strong influence on the environmental gradients detected in chapter seven. Variables which show a low semivariogram range value, (such as soil redox potential and exchangeable calcium levels) are those which show little influence in the ordination diagrams and no statistical difference between the forest and cleared zones. In the case of variables such as exchangeable calcium, this is thought to be because of a very high deterministic component to the variation.

Many of the calculated range figures are less than 22 m, the width of the mangrove buffer which Belizean legislation requires to be left alongside any water body if the remainder of the site is developed. This means that the value of at least some of the soil and water properties throughout the remaining buffer zone will be affected by changes in the properties of variables due to clearance, development and drainage. This point will be considered further in the chapters which follow, beginning with a look at the transect data measured at the field sites around Belize City.

9

Edge effects: looking at the transect data

Introduction

This final investigative chapter focuses upon the second research hypothesis, attempting to identify and then quantify any edge effects resulting from forest clearance and drainage. It uses data gathered both in 1992 and 1994 along the transect lines, across all the field sites. Graphs of the key transect datasets which typify or contradict the expected trends are included in the text below. The complete transect dataset is given in Appendix 4.

This chapter draws upon the discussion of edge effects introduced in chapter one. It seeks to establish how far into the remaining forest (or cleared zone) changes in the environmental properties can be found. Studies in both tropical and lowland forests have found measurable differences 20-30 m into the forest following disturbance. If such a pattern is mirrored in the mangrove, then this must undermine the sustainability of the narrow 22 yard (c.20 m) buffer zone required by the current legislation.

Four sets of transect data from the present research are considered in this chapter. These have been shown diagramatically in Figure 5.13 and are summarised below in Table 9.1:

Table 9.1 Summary of the fieldwork transects

Field site	Transect length	No. of points	Point spacing	No. of transects	Angle with edge
Burnt Site 1992	40 m	16	Variable	3	90°
Burnt Site 1994	60 m	13	5 m	1*	90°
Texaco Site 1994	120 m	13	10 m	3	45°
Punta del Este 1994	60 m	13	5 m	1*	90°

* *Some measurements were repeated along these transects on different days.*

9.1 Variables measured along the transects

The transect data differs from the areal sampling data in the range of properties measured. There are four reasons for these differences:

1. The techniques were changed over the fieldwork programme. Most of the transect work was carried out in 1994. Before this second field season, the decision was made to focus upon variables measurable in the mangrove waters, to speed up the process of laboratory sample analysis.

2. Variables which change rapidly in the field (such as ground level insolation and soil nitrous oxide flux) could only be measured along the transects. The longer sample collection time arising from the greater sample population of the areal work would have rendered such measurements incomparable.
3. Other variables whose measurement is very labour-intensive (such as estimating crude root biomass) were restricted to sampling along the transects.
4. Upon return to the UK, the option to increase the number of variables measured (to include measurements such as soil sulphate-S and total iron) occurred because of the unexpected availability of a small quantity of further laboratory reagents. These measurements were made using the smaller sample set: the transect data.

9.1.1 Changes in the soil units along the transects

A transect sampling strategy is well suited for displaying soil profile data. Figure 9.1 shows the soil profiles sampled along all eight transects used in this work. The profiles show that the soils of the mangrove comprise a series of clays, overlain by a layer of peat. The thickness of the peat layer is highly variable and is often underlain by a second soil unit which is predominantly clay but has a high (30-40%) organic material content. In recently cleared sites there is no obvious difference in the thickness of the organic rich mangrove peat layer. However, as Figure 9.1 shows, the return visit to the Burnt site in 1994 found that much of the organic material in the cleared zone has been lost through erosion. This indicates that the soil profiles do change following mangrove clearance.

As Figure 9.2 shows, the bulk of the soil profiles are comprised of clay. This varies from the almost uniform massive grey unit shown, to a series of different layers, incorporating shells and shell fragments, quartz clasts and varying proportions of silt and sand. These units, particularly those containing complete shells, indicate that the clay was laid down offshore, in a low-energy marine environment.

Mangrove roots are most common in the upper 30 cm of the soil, with any found below this depth generally being confined to coarser *Rhizophora* anchoring roots. In soils from forest sites, the upper 10cm of the soil are bound firmly together by *Avicennia* pneumatophores, as seen below.

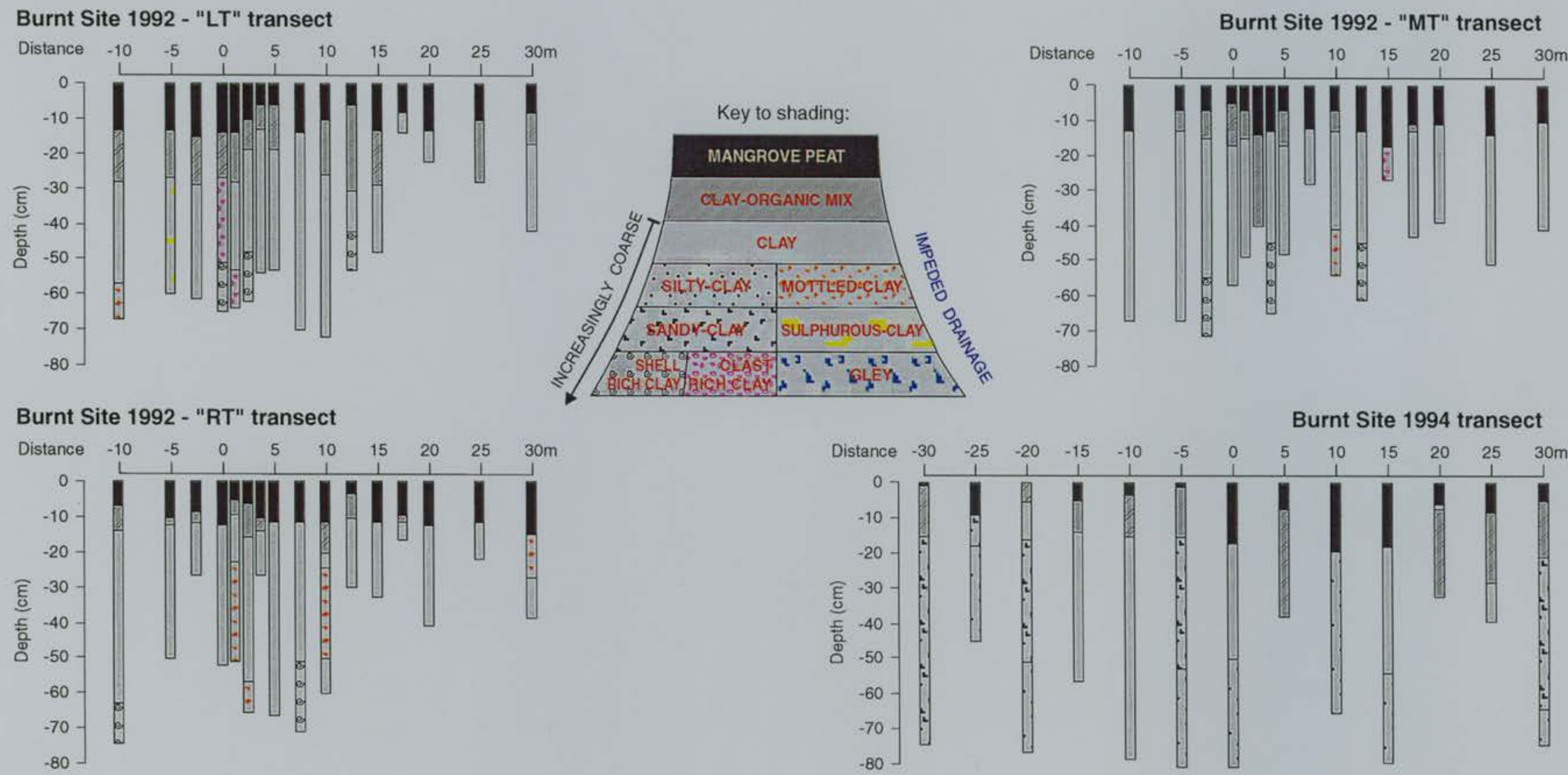
Figure 9.1 Soil profiles along the transects

This figure shows the soil profiles taken along the transect lines during the fieldwork. Each soil core is shown pictorially below, split into soil units defined in the field.

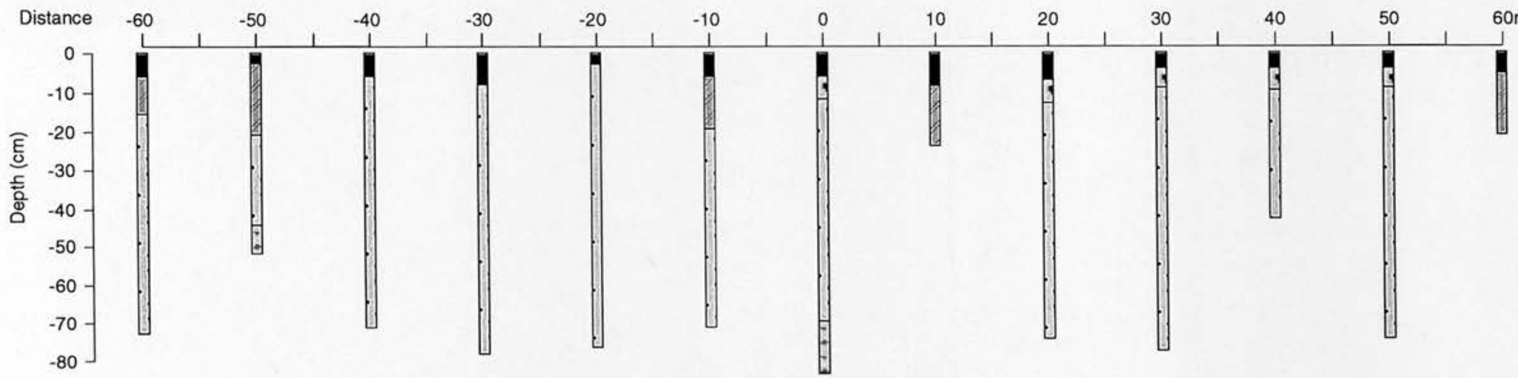
Soil profiles from four groups of transect lines are shown. On this page,transects from the Burnt fieldsite are shown, three from the 1992 work and one from a return visit in 1994.

Overleaf are shown two more sets of transects, one from the 1994 Texaco fieldsite and three transects from the Punta del Este fieldsite (PLT, PMT, PRT).

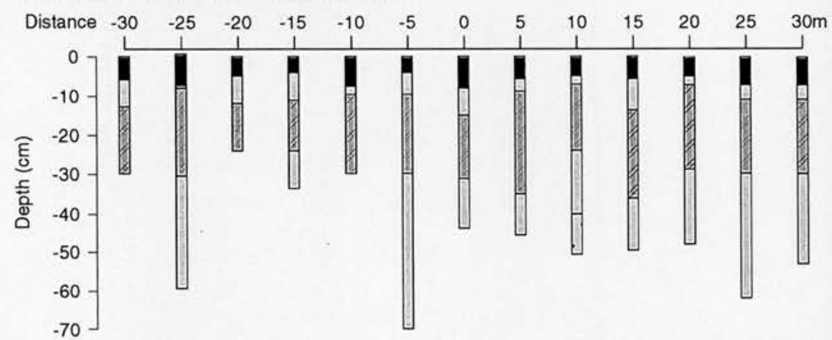
The same horizontal and vertical scales are used in each transect diagram. The distance scale has been arranged so that the cut edge lies at zero metres, points in the cleared zone lie to the left of this, and those in the forest to the right.



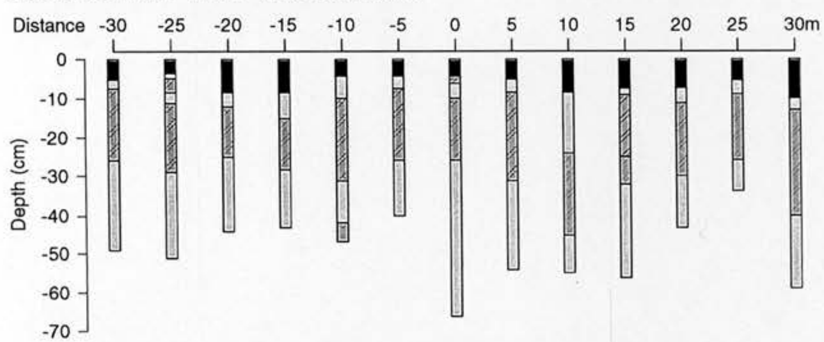
Texaco transect 1994



Punta del Este "PLT" transect 1994



Punta del Este "PMT" transect 1994



Punta del Este "PRT" transect 1994

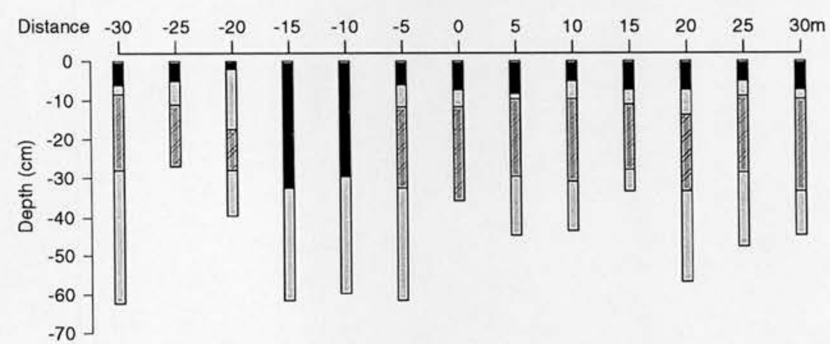


Figure 9.2 A typical mangrove soil core

This figure shows a soil profile obtained from a forested portion of the Texaco site in 1994. The right hand side of the picture shows the soil surface, with a mangrove pneumatophore still in place. Below this is a unit of mangrove peat, which gradually changes down-profile into a mixture of clay and organic material. This forms a further irregular boundary with the massive grey-brown clay unit. This clay unit contains very few roots. The disturbance seen at the left hand of the soil core is the result of removing the core catcher. The scale bar in the top right hand corner is marked in centimetres.

Some of the clay from samples taken at depth show soil mottles and gley features indicating that metal species such as ferric-iron are being reduced. An example of a mottled core is shown in Figure 9.3 below.

Figure 9.3 Soil mottles at the base of a core

This core was taken from a cleared area at the Texaco field site. It has been cut in half to reveal clean surfaces. The top of the core lies beyond the left hand side of the picture, its proximity is indicated by the white cut-faces of Avicennia cable roots. Three soil units can be identified, the brown, root-rich organic zone, a dark grey-brown clay unit in the centre of the picture, and a pale grey clay. The pale nature of the lowest clay unit suggests the absence of the coloured, oxidised forms of metal ions (such as ferric iron) and indicate reducing conditions in this zone. The right hand end of the core shows signs of mottling, which suggests that in this region the soil alternates from reducing to oxidising conditions. The yellow colour implies that the coloured mottles are due to the presence of oxidised (ferric) iron. The scale bar in the bottom left corner is marked in centimetres.

Many samples, particularly those in the Punta del Este transect show a "repetition" of soil units, with marked regions of greater organic content both at the surface, and at depth. These could be result of the accumulation of dead roots at this depth, but it is thought more likely[1] that these are in fact previous soil surfaces buried by hurricane and storm deposition.

In summary, the soil profiles taken at sites recently cleared show little difference in either the thickness or ordering of the major soil units, a series of marine clays overlain by mangrove peat. Differences emerge over time, as the peat is lost through erosive processes, and following root death and drainage, when the soil's oxygen availability alters, affecting the metal species present in the soil.

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[1] Given the frequency of hurricane impact in this region.

9.2 Trends in the transect data

The environmental properties measured along each transect can be divided into three groups, matching the interpretation strategy employed in chapter six. The three processes used for this classification, litterfall and decomposition, drainage and physical compaction, are considered in turn.

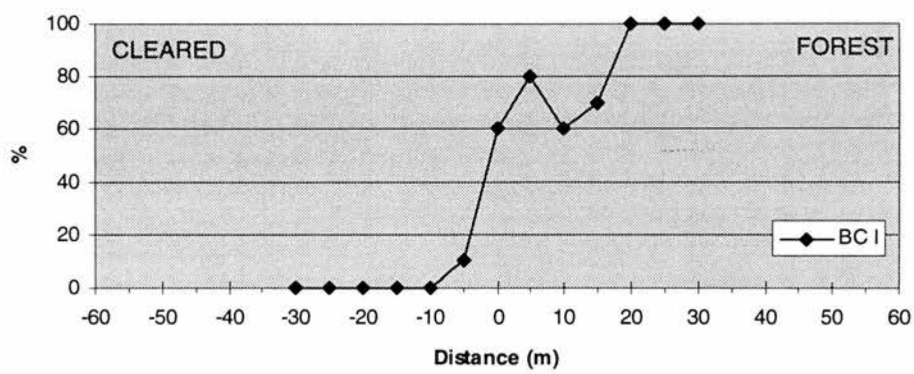
9.2.1 Litterfall and decomposition processes

The smaller sample size along the transects allows a wider range of measurements. Estimates of litter cover and depth are considered below, and exchangeable potassium levels are discussed as an example of trends in the levels of the soluble cations in the soil. The effects of the vegetation loss are also quantified, using measurements of ground level insolation and root biomass.

Litter cover

The distribution of litter at the field sites falls into two patterns. The first, typical of both the Texaco and Burnt sites, is show in Figure 9.4. At these sites, the soil with the greatest surface litter cover is found in the forest.

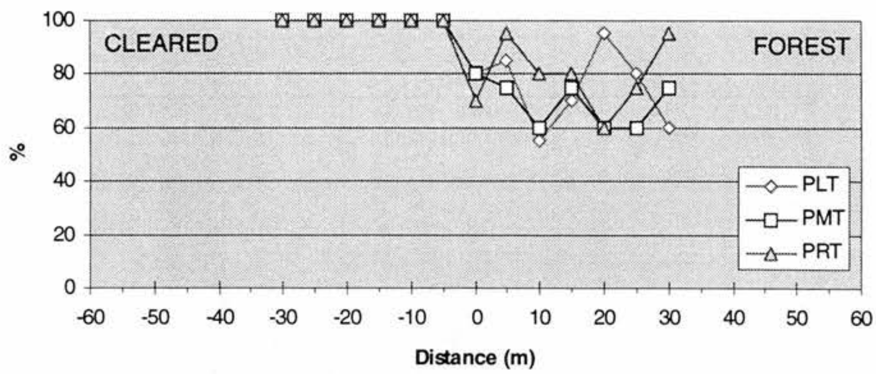
Figure 9.4 Percentage of surface covered by litter, Burnt site, 1994



This figure shows the percentage of the soil surface covered in litter. The transect is 60m long, centred on the cut edge (0 m on the graph). The distance scale measures distance into the forest, which means that samples in the cleared zone have negative values, and those in the forest, positive values. All the transect diagrams are plotted along a 120 m x-axis, to allow comparison with data from other sites.

Figure 9.5 shows the pattern at the Punta del Este site, where samples with the greatest proportion of soil covered by litter are found in the cleared zone. This is attributed to the fact that this site is the most recently cleared. Temporal differences between the sites, such as the differences in litter cover discussed above, are considered further in Section 9.4.

Figure 9.5 Percentage of surface covered by litter, Punta del Este, 1994

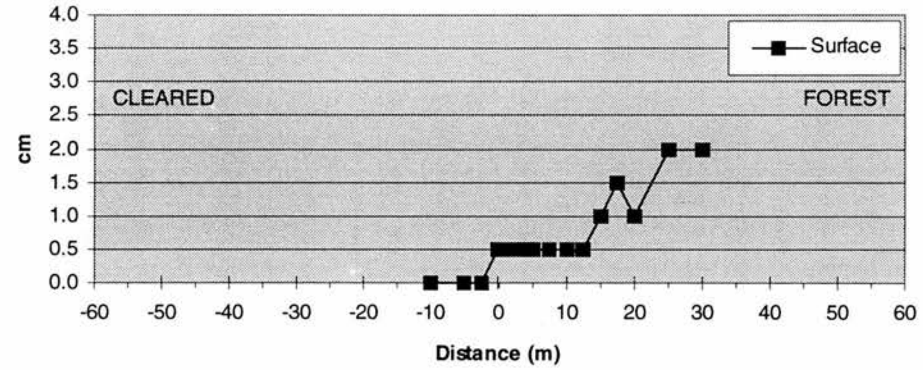


This graph shows litter measurements for three transects at the Punta del Este site each 60 m long, centred on the forest edge.

Litter depth

In 1992, estimations of the litter cover were accompanied by measurements of the litter depth. Figure 9.6 shows a graph for the left hand transect of the 1992 Burnt site.

Figure 9.6 Soil litter thickness, Burnt site "LT" transect, 1992



The 1992 Burnt site transects were 40 m long, designed so that most of the samples lie in the forest. The cut edge lies at 0 m.

This graph clearly shows the absence of litter in the cleared zone, which would have been consumed during the post-clearance burning of material. Values rise slightly upon crossing the cut-line, but still are noticeably lower at the forest edge than at locations further into the forest. This edge effect is thought to be a combination of three factors:

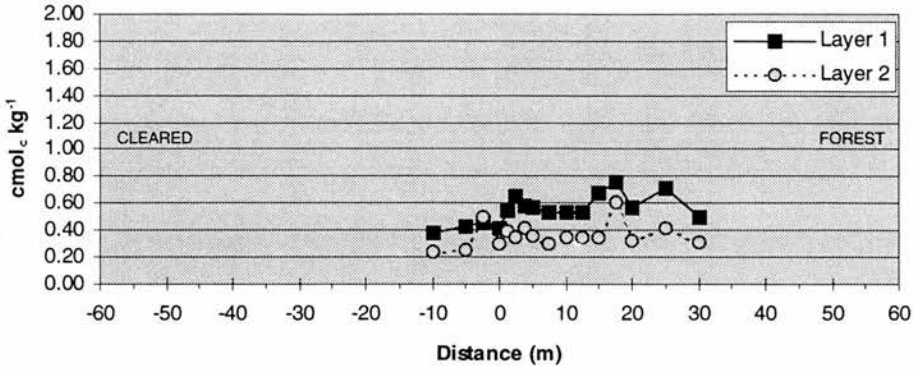
1. The absence of trees, the litter source, at the edge of the forest.
2. Removing trees makes the edge site more exposed, and so litter may be removed by wind-blow effects.
3. There may be greater crab-predation upon litter at the exposed forest edge.

This pattern of litter thickness is mirrored in the pattern of properties such as the soil organic content[2], which show higher values in the forest. Measurements of soil nutrients such as calcium, magnesium,

[2] Not shown here, but organic carbon data are given in Appendix 4.

potassium and sodium along the transects also show a pattern of higher values in the forest, as seen in Figure 9.7 below.

Figure 9.7 Soil exchangeable potassium, Burnt site "RT" transect, 1992

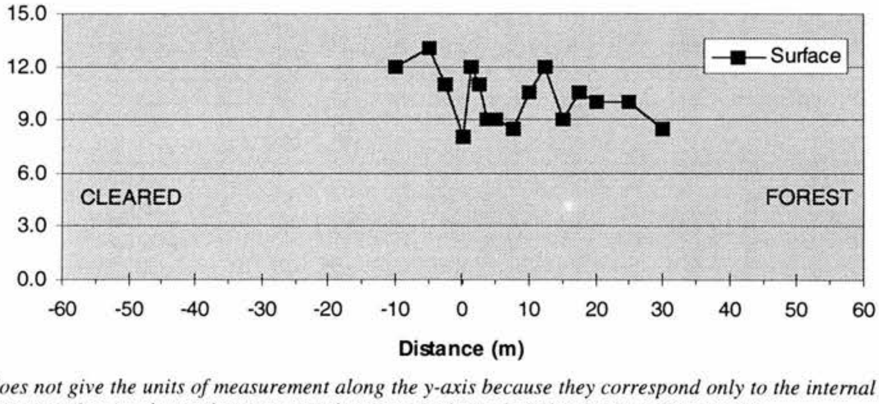


These values confirm the picture found in the areal sampling work. The level of soil nutrient values along the transect are similar to those in the earlier work. Several graphs, such as that shown above, also imply a drop in nutrient levels in the cleared zone. However, because of the small number of transect samples in the cleared zone, for some of these graphs the drop in value in the cleared zone is harder to detect. The semivariogram work of the previous chapter has also shown that many of these variables exhibit considerable spatial covariance. This will act to minimise differences in value near to the cut edge.

Insolation

Measurements of the ground level insolation were made along the Burnt site transects in 1992, using an uncalibrated hand-held light meter. The results of these measurements are shown below in Figure 9.8. The measurements were taken on a slightly overcast day.

Figure 9.8 Surface insolation level, Burnt site "RT" transect, 1992



This figure does not give the units of measurement along the y-axis because they correspond only to the internal properties of the meter. However, they can be used to give an indication of relative light levels along the transect.

The results shown are rather surprising, in that the sites in the forest do not show a significant drop in light levels, as was experienced in the field. This may be a function of the relatively low light conditions at the time of measurement, which may be acting to lessen any potential differences. Despite this, upon more detailed examination, a weak trend can be inferred. Samples in the cleared zone show the highest vales and sites far into the forest (at distances of at least 20 m from the cut edge) show a pattern of more consistently low values. The highly variable measurements in between may be a result of the fragmented canopy in this area, some of which is attributable to tree removal and/or damage during clearance.

Root biomass

Upon returning to the Burnt site in 1994, measurements were taken of the crude root biomass, using 10 cm cores of soil obtained from the soil surface. The soil was washed out of the samples and the remaining root fraction dried and weighed. No attempt was made to sort live from dead roots.

Figure 9.9 Crude root biomass, Burnt site, 1994

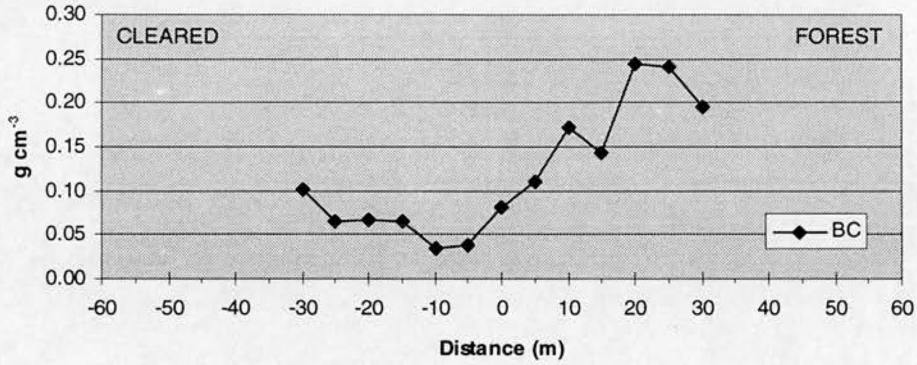


Figure 9.9 shows that sites in the cleared zone contain very few roots, compared with sites in the forest, where the soil still supports a living vegetation cover. The fact that the root biomass level is seen to rise almost continuously in the first 20 m of the forest suggests that tree density and vigour may be lower near the cut edge.

The variables whose values are affected by litter-influenced processes show broadly similar patterns at the Burnt site and Texaco transects. The Punta del Este site shows higher litter levels in the cleared zone, as a result of the more recent deforestation of this site. Returning to the Burnt field site two years later, the root biomass of samples from the cleared area is seen to be significantly less than that of the forest. This shows the effect of deforestation and the failure of plants to recolonise the cleared area.

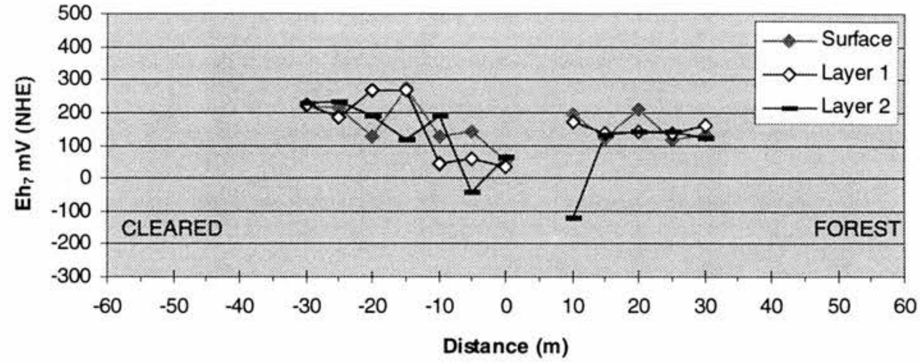
9.2.2 Drainage-processes

Measurements of soil redox potential, pH and the level of compounds likely to be reduced, such as sulphate-S were taken along the transects to determine drainage effects. Measurements were also made of variables indicating possible changes in the marine input (water conductivity) and the rate of denitrification (such as nitrous oxide flux), which is dependent upon the level of soil moisture.

Redox potential

The areal sampling work has shown that draining the site results in increased redox values in the upper regions of the soil. Figure 9.10 shows redox potential measurements along a transect at the Punta del Este site, the most severely drained of the field sites.

Figure 9.10 Field soil redox potential, Punta del Este "PLT" transect, 1994



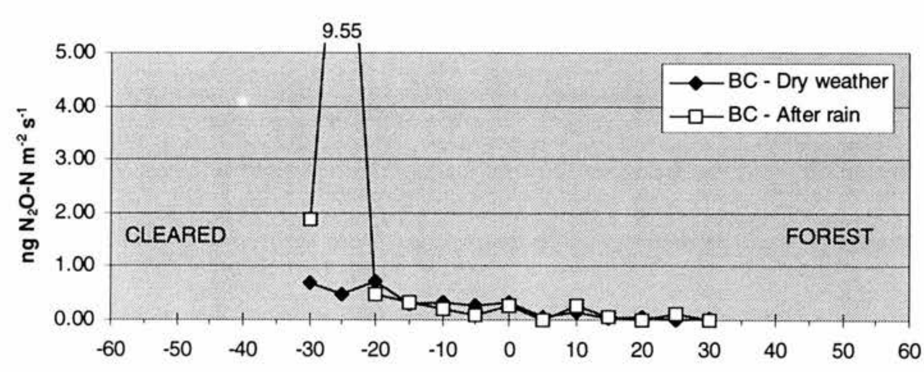
The gap in the middle of this dataset is due to electrode failure.

This figure shows a pattern that varies with depth. Measurements taken at the soil surface all show relatively high values, around 100 mV. This is consistent with the lack of soil water at the surface. Looking at the values for soil layers one and two, there is a far greater consistency of values in the forest zone. As before, this is attributed to oxygen translocation by mangrove roots maintaining oxidising conditions. In the cleared zone, values are far more irregular, with some of the lowest values nearest the cut edge.

Denitrification

The redox potential will affect denitrification processes. Figure 9.11 shows the results of two sets of nitrous oxide flux measurements along a transect at the Burnt field site.

Figure 9.11 Soil surface nitrous oxide flux, Burnt site, 1994

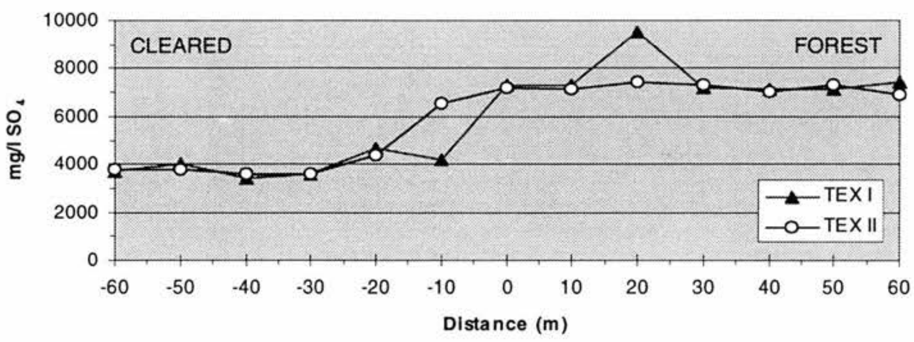


The samples taken after a sustained period of dry weather (at least three days without rain) show very low nitrous oxide flux, indicating little denitrification activity. The second samples collected immediately after a period of heavy rain show that in some of the exposed sites, denitrification rates have increased significantly. The low levels of denitrification more typical of the majority of the measurements suggests that the oxidising conditions at the soil surface are favouring nitrification and so inorganic nitrogen is present as nitrate-N. Only when rainfall occurs, creating temporary anaerobic surface conditions can this nitrate-N be reduced to nitrite-N and then gaseous forms, to be released at the soil surface. Except immediately after rainfall, these denitrification rates are far lower than for other soils in Belize (Rees, 1993). These results should, however, be interpreted cautiously, as denitrification is a dynamic process, making soil nitrogen values highly spatially and temporally variable (Ross, 1989).

Sulphate-S

Measurements of the level of sulphate-S in mangrove waters all show higher values in the forest. The pattern is most clearly seen at the Texaco site, shown below in Figure 9.12.

Figure 9.12 Water sulphate-S levels, Texaco field site, 1994

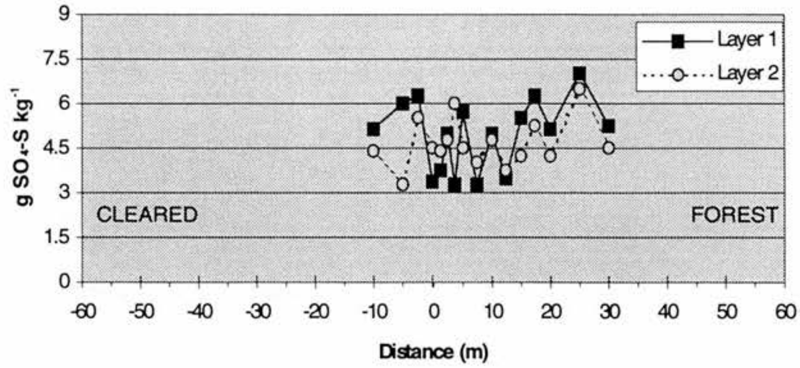


Water sulphate-S measurements at this site were repeated on two separate days.

Figure 9.12 presents a clear edge effect, suggesting that the decrease in the levels of sulphate-S in the cleared zone because of litter input loss, is being locally offset by a flow of sulphate-S from the forest. The direction of this trend coincides with topographic variation, as the forest sites are on higher land. It is possible that this sulphate-S flow into the cleared zone may be enhanced by gravitationally driven water movement, but this canot be confirmed from this data, gathered along a single transect.

Figure 9.13 shows the level of sulphate-S in the soil at the Burnt site. Interpreting this figure is difficult, because of the absence of a clear trend. Surface samples from the cleared zone show high sulphate-S values, which drop rapidly at the cut edge. From this point the level of soil sulphate-S gradually rises again, reaching values equivalent to those at the cleared zone, around 20 m inside the forest. Levels of sulphate-S in forest samples from the second, clay-rich layer follow a similar trend. The three samples in the cleared zone show a lower sulphate-S value.

Figure 9.13 Soil sulphate-S levels, Burnt site "RT" transect, 1992

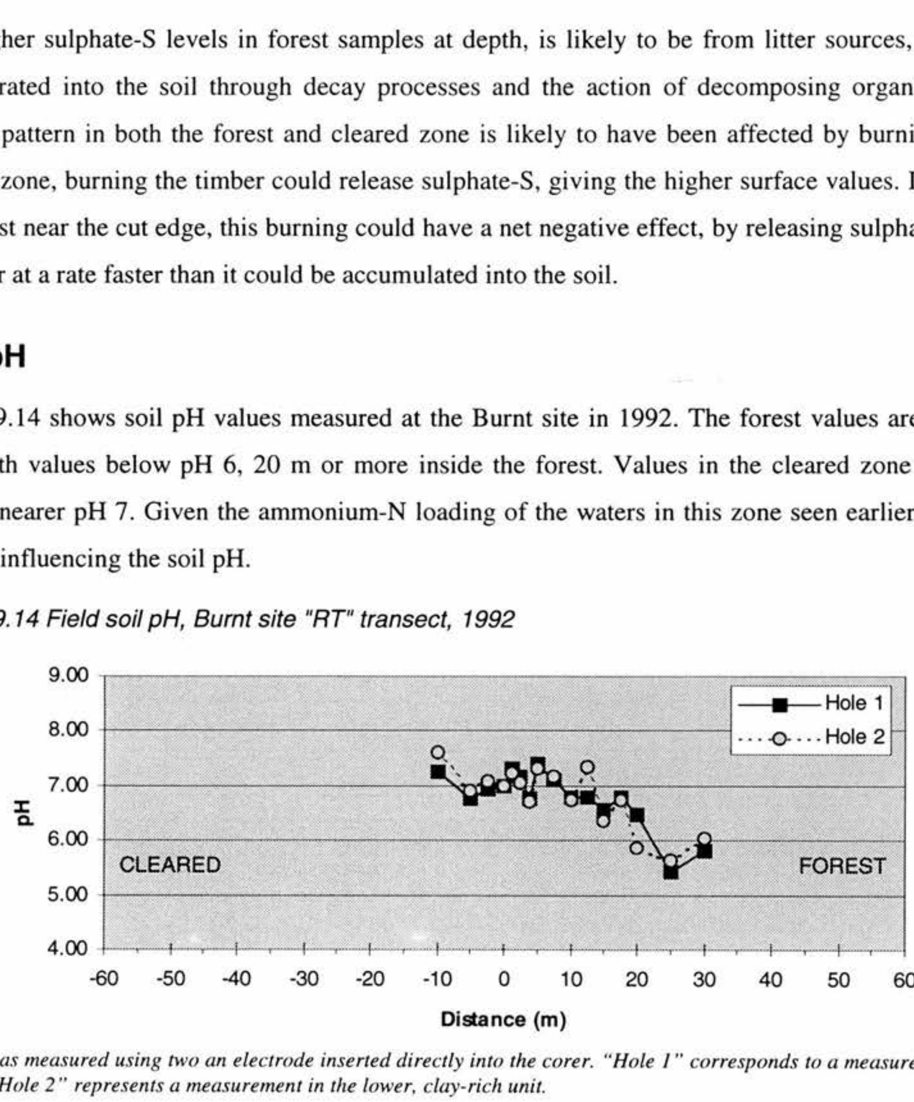


The higher sulphate-S levels in forest samples at depth, is likely to be from litter sources, gradually incorporated into the soil through decay processes and the action of decomposing organisms. The surface pattern in both the forest and cleared zone is likely to have been affected by burning. In the cleared zone, burning the timber could release sulphate-S, giving the higher surface values. In areas of the forest near the cut edge, this burning could have a net negative effect, by releasing sulphate-S from the litter at a rate faster than it could be accumulated into the soil.

Soil pH

Figure 9.14 shows soil pH values measured at the Burnt site in 1992. The forest values are typically low, with values below pH 6, 20 m or more inside the forest. Values in the cleared zone are much higher, nearer pH 7. Given the ammonium-N loading of the waters in this zone seen earlier, this may well be influencing the soil pH.

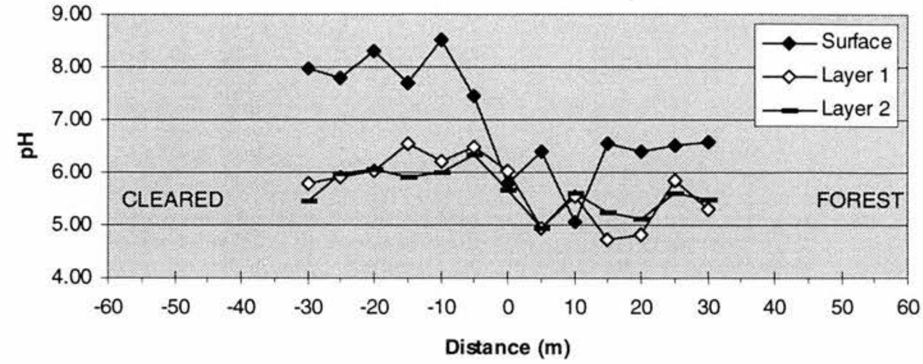
Figure 9.14 Field soil pH, Burnt site "RT" transect, 1992



Soil pH was measured using two an electrode inserted directly into the corer. "Hole 1" corresponds to a measurement in soil layer 1, "Hole 2" represents a measurement in the lower, clay-rich unit.

Returning to the site in 1994, pH samples were re-measured. Measurements at the soil surface showed a similar pattern to the trends identified in 1992, but below the surface the soils have become considerably more acidic, possibly because of the release of organic acids during decomposition.

Figure 9.15 Field soil pH, Burnt site, 1994

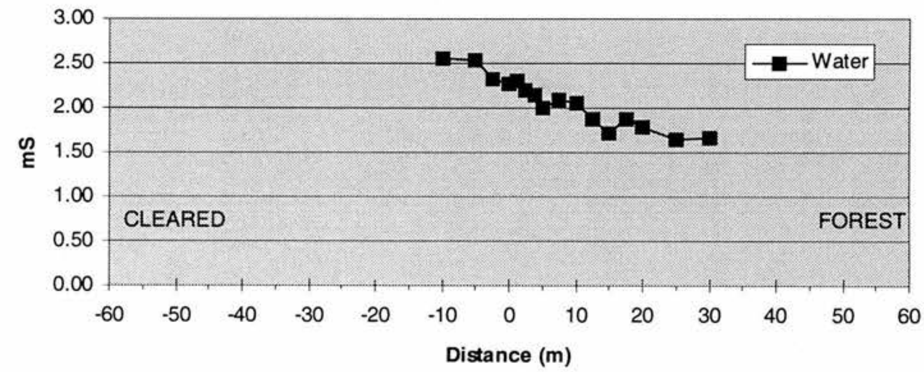


Measurements of soil pH were taken from the soil surface and also corer openings representing layers 1 and 2.

Conductivity

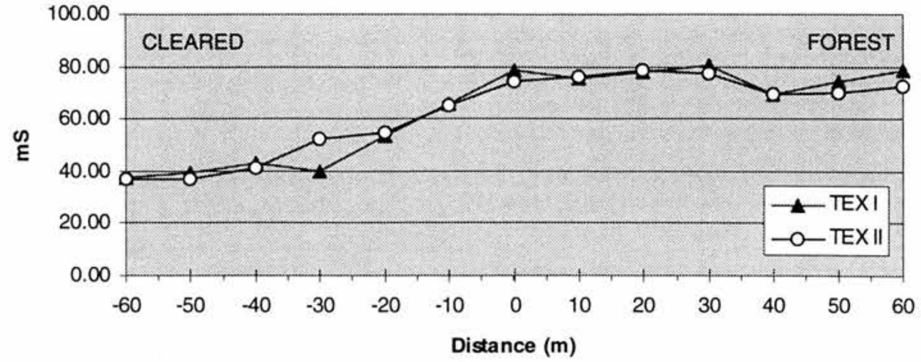
Conductivity values along the 1992 transects in the Burnt site displayed in Figure 9.16 show a decrease in water conductivity into the forest. This may represent an evaporation-driven concentration of salts in the unshaded cleared zone, combined with greater plant uptake of ions in the forest. However, caution should be exercised because of the possible contamination effects seen in the earlier, areal sampling work. The transects were located in such a way that the start, at the edge of the cleared zone, coincides with the peak in conductivity values.

Figure 9.16 Water conductivity, Burnt site "MT" transect, 1992



Measurements of conductivity in 1994 show the opposite trend, water conductivity increases in the forest. This trend is most clearly seen at the Texaco site, shown below in Figure 9.17, but can also be seen in data from the Burnt site, and to a lesser extent at Punta del Este.

Figure 9.17 Water conductivity, Texaco site, 1994



Conductivity measurements were repeated on different days at this site.

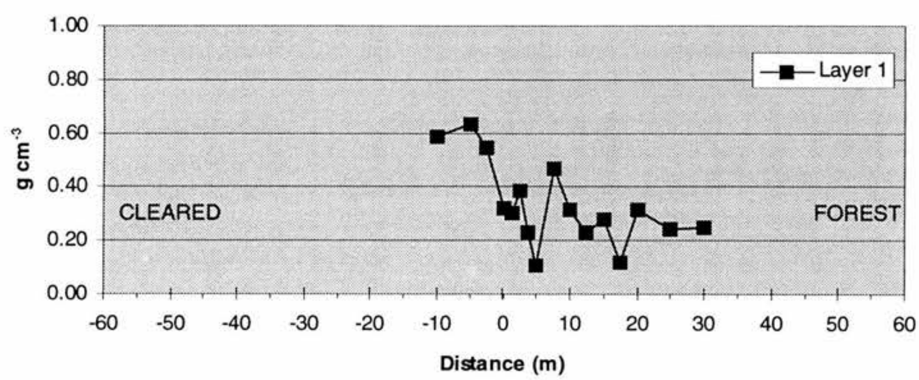
The higher conductivity at these sites, coincides with a greater concentration of ions such as potassium and sulphate in the forest. The higher forest conductivity values are therefore thought to be the result of sustained litterfall (and stemflow) in the forest and canopy trapping of atmospheric species in the salt-spray, rather than leaching or solution effects in the soil. Given the greater elevation of forest samples, if water-transportation of ions was significant, the resulting pattern would have shown greater values in the cleared zone.

The pattern of variables affected by drainage processes at each transect are less consistent than the litter-influenced processes. This is a result of the different drainage conditions found at each field site, particularly the fluctuating water table conditions common at sites where the water table is still above, or very close to the soil surface.

9.2.3 Compaction effects

Bulk density samples were taken along the 1992 transects. An example is given below in Figure 9.18.

Figure 9.18 Soil bulk density, Burnt site "MT" transect, 1992



This figure shows highest bulk density figures (indicating compaction) in the cleared zone (at the left hand side of the graph) and lower values in the forest (to the right).

It shows a typical pattern of high values in the cleared zone, particularly near to the forest edge, and declining values in the forest. This confirms the findings from the areal sampling work.

9.3 Edge effects

The examination of the transect data shows that for many of the measured properties, a distinct edge effect can be seen. The gradient of change occurs both in the forest, and cleared sides, of the cut edge. For properties such as surface soil pH (Figure 9.15) which show high values in the cleared zone and lower values in the forest, the period of transition (the edge effect) occurs in the cleared zone. Sub-surface soil pH measurements (Figure 9.14) and ground level insolation (Figure 9.8), both also show higher values in the cleared zone, but for these properties, the transition occurs inside the forest. The transition can also be found on both sides of the cut-edge for properties which are lower in the cleared area. Both conductivity at the Texaco site (Figure 9.17) and water sulphate-S levels (Figure 9.12) show that the higher forest values extend into the cleared zone before dropping. Conversely, lower cleared zone values of other variables such as root biomass (Figure 9.9) only begin to rise within the forest.

Edge effects thus occur both in the forest and the cleared zone, depending on the variable being measured. Which zone the edge effect occurs in, is dependent upon the process involved, whether properties are affected by water transport of materials, or dependent on surface changes such as litterfall differences, sunlight or wind sorting of materials.

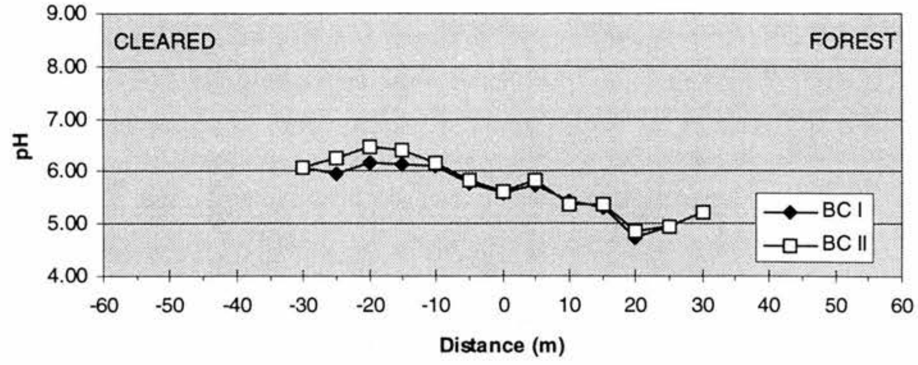
9.4 Temporal trends in the transect data

Some of the patterns of the measured variables show different ranges of values at each of the field sites. This is interpreted as indicating that these field sites are at different (temporal) stages in the clearance and drainage process. A range of variables showing such changes are discussed below, drawing examples which show differences as a result of the two key processes, drainage of the site and secondly, litterfall and decomposition.

9.4.1 Water pH

The pattern of water pH values at the Burnt site (shown in Figure 9.19) is very similar to the pattern seen in the 1992 areal sampling data, with acidic pH values in the forest and near neutral values in the cleared zone.

Figure 9.19 Water pH, measured at the Burnt site, 1994



The graph shows the value of water pH samples collected on two different days.

This pattern of difference, attributed to a greater ammonium-N concentration in the cleared zone, is not repeated at the other two sites. Water pH values across the Texaco site are all near neutral (c. pH 6.5), values at the Punta del Este site are all far more acidic (c. pH 5.0). The lower pH across the Punta del Este site may be a result of the more efficient drainage creating conditions favouring acidic species such as sulphate-S. Examination of the soil redox values at the Punta del Este site (shown in Figure 9.10) shows a more constant oxidising pattern with depth, compared with the other two locations. The consistently high water pH values at the Texaco site are harder to explain: there is no reason to expect greater ammonium-N levels at this site. This stable, near neutral pattern of pH values may be because of the unimpeded water movement across the site, which acts to prevent the build-up of acidic compounds. Alternatively, given the fact that this site is the furthest inland, the higher pH may be a result of lower amounts of acidic compounds in the sediments, derived from marine deposits of sulphate-S and sulphide-S.

The Texaco water pH values are thought to be typical of sites which are regularly flushed by fresh water. The pattern at the Burnt site shows water pH values more typical of a site a long time after clearance, but which remains covered by water. The pattern at the drained Punta del Este site is more typical of other studies of mangrove development (e.g. Hesse, 1961a), showing how pH decreases upon drainage.

9.4.2 Water chloride

The field sites also show marked differences in the amount of chloride in the waters of the mangrove. The highest chloride values are found in samples from the Burnt site, the lowest from Punta del Este. These data give rise to the chloride gradient in the ordination of the three sites, discussed at length in chapter seven. No real difference can be seen in the value of samples from the cleared and forest zones at the sites[3]. This suggests that there is an underlying large scale gradient in chloride concentration which determines sample values, rather than changes occurring as a result of deforestation or drainage.

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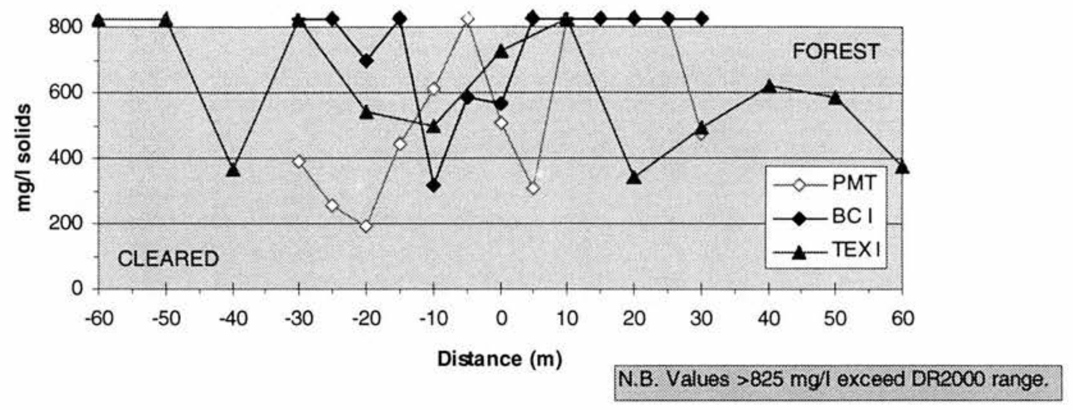
[3] The two very high chloride values seen in the transect TEX I are possibly the result of dilution errors.

9.4.3 Water turbidity and suspended solid content

Examination of the water turbidity and suspended solids content (the latter is shown below in Figure 9.20) reveals no real difference between the forest and cleared vales.

Figure 9.20 Suspended solids measurements, 1994 field sites



However there is a weak inter-site pattern. Values are highest at the 1994 Burnt site, intermediate at the Texaco site and lowest at the Punta del Este site. This is thought to indicate water movement and drainage. Water movement across the ponded Burnt site was minimal, and drainage severely impeded. Water movement through the Texaco site was facilitated by overland flow from the topographic high inland of the field site and the drains built during road construction at the seaward edge. The soil surface at this site was also notably better drained than the nearby Burnt site. The close proximity of the canal and the large land drains present in the Punta del Este site makes it the best drained of the three field sites. This lack of surface water means that leaching processes are more effective, resulting in a lower suspended and dissolved loading of water present in the soil at this site.

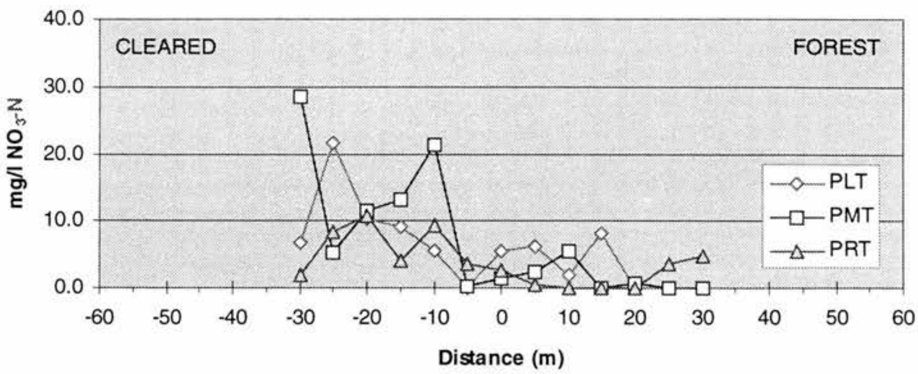
9.4.4 Litter cover

Section 9.2.1 has shown that graphs of percent litter cover show higher values in the cleared zone of the Punta del Este site, but the opposite pattern, namely higher values in the forest zone, at the Burnt and Texaco sites. This reflects the more recent clearance of the Punta del Este site, the massive litter input from felling the forest and the disturbance to the soil surface results in a continuous litter cover. In the forest zone, because of the high tree density at this site, the thick carpet of pneumatophores acts to direct the movement of falling litter, maintaining exposed areas of soil. The higher litter cover values in the forest zones of the two older sites, represent a post-clearance stage where the continuous litter input from the forest has overtaken the single clearance litter input, much of which will have been lost through erosional and decompositional processes.

9.4.5 Nitrate-N

The amount of nitrate-N present in the waters of the three sites was only high enough to be measurable at the Punta del Este field site. This can be attributed to the better drainage at this site, allowing nitrification of soil ammonium-N to occur. Figure 9.21 shows the value of nitrate-N to be higher in the cleared zone. This supports the importance of drainage in determining nitrate-N levels as the higher values in this zone can be explained by a greater evaporation rate, resulting in better drained soils.

Figure 9.21 Water nitrate-N variations along the three Punta del Este transects



This graph shows measurements along three parallel transects aligned perpendicular to the forest cut edge.

In summary, samples measured along the Punta del Este transect, the most recently cleared show litter patterns and subsequent nutrient-release dominated by the recent felling of the mangrove timber. In both the older sites, Texaco and the Burnt site, litter cover and soil nutrient levels are higher in the forest. The Burnt site, cleared in early 1992 has seen the importance of the felled material decline, but the sustained high water levels and poor water movement across the site has acted to impede further change. It is the younger Punta del Este site, which seems to be furthest along the hypothetical timeseries of clearance-induced change developed in chapter five. This is because of the effective drainage measures implemented at this field site.

9.5 Conclusion

Examining the transect data has shown that the processes of drainage, compaction, litterfall and decomposition, identified in chapter six, affect the variables measured here. By considering properties such as insolation, root biomass and soil nitrous oxide flux, a more complete picture of the effects of forest clearance and drainage has emerged. The pattern of the environmental properties measured along the transect has shown many of them to possess distinct edge effects, with changes in the cleared zone affecting values in the forest, or being moderated by the buffering effect of the remaining forest.

This evidence of change presented in the analytical chapters can be combined with the earlier discussion of mangroves' known environmental tolerances to provide sufficient information to inform a discussion evaluating the effects of mangrove disturbance and the present legislation in Belize. This discussion provides the focus for the concluding chapter.

10

Conclusion: whether the changes are significant

Predicting the fate of the remaining mangrove forest

This chapter brings together the earlier hypothesis testing and studies of mangroves' tolerance to stress. It considers the ecological stability of mangroves: whether forest abutting the cleared areas, and thus by analogy the 66' buffers of mangrove required by law, will be affected by the nearby disturbance. The opportunity is also taken to reflect upon the success of this work, its implications for future research methods in the mangrove, and the further questions it has uncovered.

10.1 Unfolding the argument

Figure 1.1 showed how the arguments contained in this thesis have been developed. The first chapter introduced the research topic and the aims of this work:

1. To examine how mangrove clearance and drainage affects a range of soil, water and other environmental properties. This has been achieved by measuring these properties in both selectively cleared sites and in the remaining mangrove forest, allowing the following three issues to be addressed:

- Ascertaining whether these two areas - the forest and the cleared zone - are statistically different.
- Investigating the nature of this difference: identifying which variables are important indicators of change.
- Revealing how this pattern of change is manifested over both time and three dimensional space.

2. To measure the degree of penetration of any changes in the remaining forest - an investigation of edge effects.

Before a fieldwork testing strategy could be devised to answer these questions, three aspects of mangrove disturbance had to be considered. These are:

1. The causes of mangrove clearance.

2. The effects of such clearance upon environmental processes (the impact upon the mangrove ecosystem).
3. The effect of such changes upon the mangrove vegetation (by focusing on mangroves' tolerance to a range of stress factors).

These three aspects have been considered in turn in chapters two, three and four[1].

Chapter two shows that mangrove clearance in Belize differs from that occurring in many other parts of the world, because it is driven by a demand for housing, rather than agriculture. This means that clearance is concentrated around existing settlements, with both coastal and inland areas of mangrove threatened by "development". In Belize, sites are developed by first felling the mangrove forest cover (often by hand) and then a combination of drainage and landfill measures used to reduce the flooded state of the soil.

The effect of such disturbance upon the mangrove ecosystem is considered in chapter three. Felling of the standing vegetation is seen to upset the established nutrient cycling processes. It results in a short-lived peak followed by a long term decline in the levels of many nutrients in the soil and waters of the mangrove. Cleared areas lose the continuous nutrient inputs from stemflow and litterfall, seen in the forest. Nutrients are released from the fallen material in the cleared zone through the processes of decomposition and mineralisation. The rates of these reactions, however, are severely retarded if reducing, anaerobic conditions remain. Furthermore, the high clay content typical of mangrove soils results in the immobilisation of some important nutrients such as phosphorus. Drainage of the site results in even greater changes, as soil conditions move from a generally anaerobic to aerobic environment. This accelerates decompositional processes and nitrification, favouring oxidised soil species. This tends to reduce plant stress, rendering the new land vulnerable to revegetation by non-mangrove species.

Chapter four shows that mangroves have developed a wide range of stress tolerance and avoidance strategies. Of the four main stress factors considered, flooding and salinity are expected to be most relevant to this work, with the changes in insolation and extremes of temperature along the edges of cleared sites not significantly large enough to stop the mangroves from growing. None of the five environmental factors also found to influence mangrove distribution: tidal action, sedimentation, precipitation, aridity and wind, are expected to reach levels extreme enough to retard mangrove growth. Rather, it is changes in the chemical factors: pH, redox potential and nutrient levels, which are

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[1] This means that there are effectively three introductory chapters in this thesis, before most of the new data are presented. Such a detailed introduction was felt necessary because of the multi-disciplinary nature of this work, where aspects such as the causes of clearance, its effects upon the ecosystem and the mangroves' response all interact to shape the final outcome. Without a knowledge of all three factors, the resulting interpretation would be far poorer.

expected to affect the future vegetation in both the cleared areas and in the mangrove forest along the cut edge.

Combining knowledge of the ecological processes active in the mangrove, data regarding the scale of current clearance schemes (examined in chapter two) and a review of existing legislation (in chapter three), provides a suitable scale for the fieldwork in this study. Chapter five sets up a series of areal and transect sampling strategies designed to detect change over distances of a few centimetres to tens of metres. It is the interpretation of these measurements which allows the questions raised at the start of this work to be answered.

10.2 Interpreting the results

The four chapters which followed combined data in different ways, providing an understanding of the questions raised in the aims. These can be separated into questions concerning the spatial pattern of values, measurements of the penetration of change and edge effects, and the implications of these patterns, both to the remaining vegetation and in an evaluation of the existing protective legislation in Belize.

10.2.1 Spatial patterns

The search for spatial patterns addresses three of the aims of this work, stemming from the principal research hypothesis:

> *Mangrove forest clearance (and drainage) results in sufficient physical and chemical changes in the soil, water and surrounding environment, that such altered areas differ significantly from those where the forest cover remains.*

Three aspects of this question are explored separately:

1. Ascertaining whether the two areas - the forest and the cleared zone - are statistically different (from the results of chapter six).
2. Investigating the nature of this difference: identifying which variables are important indicators of change (using the results of chapters six and seven).
3. Revealing how this pattern of change is manifested over both time and three dimensional space (using the results from chapters six, seven, eight and nine).

Comparing the forest and cleared zones

Univariate statistical comparisons of environmental properties measured at the field sites revealed that the majority of them show a significant difference between values in the cleared and forest zones. These differences arise from changes in nutrient availability and the physical structure of the soil following forest clearance, and the alteration of soil water and oxygen availability following site drainage. Examining the frequency distribution of sample values and the results of multivariate ordination analysis both show that the disturbance has served to reduce sample heterogeneity in the cleared zone. This "homogenising of values" begins soon after forest clearance. Theoretically it should be most clearly seen in sites which have been both cleared and then drained, resulting in the development of uniform, oxidising soil conditions. However, given the high clay content of the soil, drainage measures are unlikely to be completely suuccessful. The resulting mosaic of oxidised and reduced patches of soil may instead act to increase soil heterogeneity once more.

Indicators of change

The gradient analyses contained in chapter seven repeatedly detect the existence of gradients in certain environmental properties at the field sites. These have been interpreted as gradients of forest disturbance, marine/freshwater influence and faunal activity. The variables found to be influential in these gradients correspond to those showing a significant cleared-forest difference in the earlier univariate comparisons of chapter six. Furthermore, the significant variables identified in this work are also those which other ordination studies of undisturbed mangrove have found to be strongly correlated with mangrove zonation (e.g. Ukpong, 1995). This provides further evidence of soil-imposed constraints upon plant types in the mangrove.

The forest disturbance gradient is typified by high values of dissolved oxygen, soil ammonium-N, organic carbon and exchangeable cations such as sodium and potassium and low values of bulk density, soil and water pH and redox potential in the undisturbed forest, with the reverse pattern in the cleared zone. The marine/freshwater influence is typified by high conductivity values towards the sea and greater levels of exchangeable cations particularly potassium at inland sites. The importance of the freshwater/saltwater balance in determining the vegetation pattern reinforces the significance of drainage measures at the field sites. The faunal activity gradient is largely a result of differences in one variable, the amount of reactive phosphorus in water samples. High values are more common in the cleared areas and lower values in the undisturbed forest. This reflects the difference in the grazing activity of grapsid crabs, and the resultant distribution of their larger predators, such as egrets, which alter phosphorus levels through defecation.

The pattern of change

Three aspects of the detected pattern of change between forest and cleared sites are considered here. These are the surface pattern of values across the fieldsites, differences in the pattern of these values at depth, and finally changes in these properties over time. This allows the predictions of change developed in chapter three to be re-evaluated.

The spatial pattern of the measurements made in the field has been found to be variable specific. The patterns can be divided into three groups:

1. Variables which appear to be unaffected by the disturbance. These show a uniform pattern across the field site, some of near constant value (e.g. layer 2 exchangeable manganese and calcium values), others a pattern of continual fluctuation (e.g. the thickness of the layer 2 soil unit).
2. Others show a sharp forest-cleared site divide (e.g. layer 2 soil pH and redox potential). These variables are those which show a distinct change in value following disturbance. Over time such a pattern may be maintained (particularly if the spatial scale of variation is very small, as is the case with soil redox) or this gradient may gradually decay through diffusion processes.
3. A third group of variables exists which show a three-zone pattern. As well as distinct cleared and forest properties, a third, transition zone can be seen, which contains values different to both the cleared and forest zones. A good example of such a property is layer 1 soil organic carbon content. The third zone often arises as a result of the local deposition of material around the forest edge, transferred from the cleared zone. This creates values higher along the edge than in the remaining forest. Other properties such as dissolved oxygen content also show high values in this transition area because of depositional or turbulence effects stemming from the marked decrease in wind and water velocity between the open cleared zone and the physical barrier posed by the forest.

The nature of the boundary between these units has been found to be highly irregular and again, variable specific. Whilst it is acknowledged that the exact shape of any one edge is a function of the cut-off value used, a process-based explanation has been employed to justify the generalisation of irregular edges. The radial distribution of active sub-surface roots, differences in the thickness of clearance deposits, topographic variations affecting local drainage conditions and variations in the mangrove species and their shading, litter and stemflow inputs at a particular location all combine to override any tendency for a linear boundary stemming from the regular shape of the land-parcel subdivision.

Changes with depth have been found to be confined to the upper regions of the soil, particularly those containing mangrove roots. The underlying clays soil units are relatively unaffected by forest clearance and because of their great capacity to retain water, they are altered only by the strongest drainage measures. Changes with depth in the organic, upper regions of the soil can be separated into two: those occurring as a direct result of disturbance at the soil surface and those which are a result of sub-surface change.

Surface soil samples from the cleared zone show lower values of many nutrients because of three processes:

1. The loss of sustained litter and stemflow inputs.
2. Increased leaching loss. The removal of the forest canopy means that precipitation is no longer intercepted by the mangroves and falls directly on the ground. Local drainage measures facilitate vertical water movement, also encouraging leaching.

3. The greater ground level insolation accelerates the rate of surface evaporation.

Subsurface samples in the cleared zone tend to differ from those taken in the forest because of three processes:

1. Destroying the vegetation overlying the cleared zone stops the oxygen translocation activity of live mangrove roots. This means that the soil surrounding mangrove roots is no longer oxidised, and the soil found in cleared sites becomes far more uniform and reducing than in the forest.
2. The cessation of nutrient uptake in the cleared zone. The loss of live vegetation in the cleared zone means that plant nutrients such as ammonium-N, normally removed from the soil and water by plants, increase in concentration. This is seen most clearly in the buffering effect of ammonium-N upon water pH in the cleared zone.
3. If the surface soil drainage improves, then there may be a concentration of nutrients at depth, leached from the surface.

The mangrove is a highly dynamic ecosystem, and it is not surprising that its response to the disturbance has been found to alter with time. The changes following clearance of the mangrove forest cover at each site have been found to be broadly similar to studies in other tropical forest types. The level of most of the available nutrients in the soils of the cleared area rises initially, as nutrients are released through decomposition and mineralisation of the litter. In common with other tropical soils, phosphorus levels show little change, because of rapid immobilisation. Over time the level of these nutrients declines, due to leaching losses, erosion of material and the absence of further inputs. These processes differ from tropical forest analogues however, in the rate of decomposition, mineralisation and leaching. The flooded soils and reducing conditions retard the rate of many of these processes, meaning that the time elapsed since forest clearance is, by itself, a poor indicator of site conditions. Whether forced drainage of the site has occurred (and when) is more important in determining the form and level of available nutrients at a site. Comparing the values of properties from the still-flooded Burnt site and the younger, but better drained Punta del Este site, has shown that drainage significantly alters the soil and water properties.

Evaluating the predictions of change

Predictions of the expected pattern of change following clearance and drainage were developed in chapter three. Lacking published data for mangroves, many of these predictions were based upon parallel work in tropical rain forests. It therefore seems timely to return to these predictions and use the results of this work to evaluate their validity.

For many of the variables considered, such as the compaction effects and cation levels, the observed differences between cleared and forest sites match those predicted. The temporal accuracy of these models remains uncertain, however, because the field sites used had been cleared too long to show the initial peak in values which many graphs predict should immediately follow clearance. The issue of temporal accuracy is particularly true for the inorganic-N models, which show the weakest correspondence with field measurements. This is thought to be because of errors in anticipating the time of changes in the balance between ammonification, ammonia volatilisation, nitrification and denitrification. Certainly from the limited measurements presented in this work, it seems that in comparison with other tropical forest types, mangroves show a remarkably low denitrification rate. This is particularly surprising given the high soil temperatures and the mixture of reducing and oxidising soil conditions which would seem ideally suited to denitrification. The low rate achieved is probably due to the same stress factors which limit the range of vegetation which can grow in the mangrove: high salinity and the presence of toxins (notably tannins, and reduced forms of sulphide) acting to limit bacterial activity.

This work shows that the pattern of change in environmental properties following clearance in the mangrove is generally similar to that already developed for sites located in areas of tropical rain forest, but, there are a few differences. These are primarily due to the high salinity and the poor drainage at the time of clearance which makes mangrove soil conditions far more reducing than in true terrestrial forests, retarding aerobic bacterial activity and requiring alternative decomposition pathways.

10.2.2 Penetration and edge effects

The secondary aim of this work is restated below:

> *To reveal how such a process of change is manifested on the ground, allowing the quantification of any gradient of change running into the forest, indicating how far such changes penetrate and thus affect the remaining forest.*

The results from measurements of environmental properties along two-dimensional transects have been presented in chapter nine. These show that edge effects have been found at each of the fieldsites, on both sides of the cut edges. For properties measured in water, the edge effect is usually found in the cleared zone, typically with higher values in the forest spilling out into the cleared zone. These patterns are most pronounced at the Texaco site. This could be because of the higher elevation inland of this site, resulting in a greater down-slope water transportation of material from the forest into the cleared zone. For properties which show relatively consistent values within each of the two zones, edge effects can be seen 20-25 m into the cleared zone for sulphate-S, and up to 50 m into the cleared zone for conductivity.

Properties dependent upon the presence of trees, their litter and stemflow inputs, such as root biomass and the level of exchangeable cations, show edge effects inside the forest. It is effects such as these which may threaten the long term sustainability of strips of exposed forest. Probably because of a greater inherent variability in the processes determining the value of these properties, these variables tend to show a greater range of values within each of the two zones. An exception is surface soil pH, which shows relatively stable values away from the cut edge. Analysis of transect data from the Punta del Este site shows a notable disturbance in pH values 10-15 m either side of the cut edge.

For many of the transects, however, the considerable variation in sample values even within the two sampling zones makes identification of a characteristic "cleared" and "forest" value difficult. This hinders attempts to fully quantify the penetration of such changes. The semivariogram analysis in chapter eight offers an alternative route. By calculating the range (the maximum distance over which the value of a property measured in one position will affect that of neighbouring points), and combining this with a measure of the structural variance, (the relative importance of the spatially correlated component) an estimate can be made of likely edge effects.

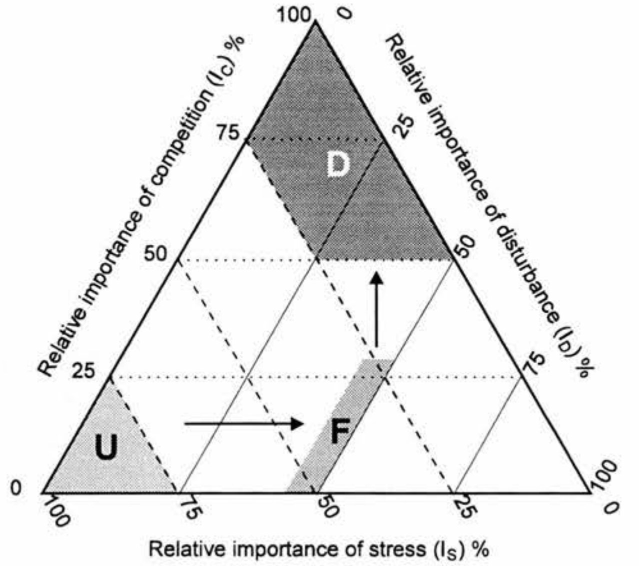
Water properties tend to have ranges of about 15-40 m, with a high structural variance. This figure is of a similar range to the edge effects detected above. Soil properties show a far greater variation. Some, such as redox potential have very small range values (3-6 m) suggesting any edge effects will be very limited, whilst others such as soil exchangeable potassium (range of 12-20 m) and soil pH (range of 20-30 m) imply the possibility of changes much further into the forest. The significance of such changes for the long term sustainability of the remaining mangrove forest depends on the likely stress such factors will impose on the plants, and the effect these changes will have upon plant competition.

10.2.3 Implications of these changes for the mangrove

Chapter four outlined mangroves' known tolerance limits to a range of stress factors. The results of measurements presented in chapters six to nine show that in general most of these are not exceeded in either the cleared zone (suggesting that if undisturbed, it could be recolonised by mangroves) or the forest (implying that the mangrove in these buffer zones will remain healthy).

That is not to say, however, that the environmental properties of a site remain unchanged following clearance and drainage. The results of the fieldwork have shown that after clearance and drainage, soil pH rises, redox potential increases (conditions become more oxidising) and the level of nutrients in the soil and water declines. Whilst the measured changes in the environmental properties may not be sufficient in themselves to stop the mangroves from growing in these areas, the reduction in the level of many of the stress factors present in undisturbed mangrove soils (particularly marked if the site is drained), may allow non-mangrove species to compete in these areas. To show the significance of this it is useful to return to the ordination diagram introduced in chapter one which shows the three factors Grime (1979) felt important in determining plant distribution:

Figure 10.1 Plotting the three stages of disturbance on Grime's ordination diagram



The shaded areas on this diagram reflect the three stages of disturbance: undisturbed forest, (U), sites after felling (clearance) of the forest, (F), and finally once the cleared land is drained, (D). Their position indicates the relative importance of the three factors identified by Grime (1979) as important in determining plant distribution. It should be noted that the positions marked on this diagram are based on estimates of the relative importance of these factors.

In chapter one, areas of mangrove forest (marked as zone U in Figure 10.1) were plotted on this diagram in the bottom left of the diagram, their position indicating that disturbance is relatively unimportant in determining the plant distribution. Competition from other plants at this time is also low, because of the harsh flooded, saline, anaerobic environment. This creates considerable stress upon the vegetation, making this the most important factor in determining plant distribution. Work in Queensland by Hutchings & Saenger (1987) identifies mangroves as generally adopting "stress-tolerating" strategies, corresponding to the zone labelled as U in the current work. They used measurements of mangrove density and dominance to estimate disturbance, and measurements of leafing rate to indicate stress. Their findings must be interpreted cautiously, however, because the lack of measurements indicating the importance of competition means that the ordination diagrams they created do not strictly indicate the relative importance of all the three of Grime's factors.

As a result of the findings presented in this work, estimates[2] of two further positions on the ordination diagram can be made, corresponding to the situation after first felling the mangrove, and then draining the site.

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[2] The regions plotted on the ordination diagram are not derived from quantitative data, rather they reflect estimates of the likely importance of the three factors identified by Grime. Whilst there is, therefore, an argument for plotting these figures without the numerical scale as it gives a false-impression of accuracy, it was retained because it was felt to aid the interpretation of these trivariate plots.

Felling the standing forest results in an increase in the importance of disturbance, as new niches are created by the loss of canopy and disturbance to litter inputs. The relative importance of the stress factors identified above declines, to compensate for the increased importance of disturbance. Because of the maintenance of anaerobic soil conditions, competition from other plants is still restricted, resulting in the low plotted position of zone F in the above figure.

Drainage results in the largest change in the balance between Grime's three factors. As aerobic soil conditions develop and salts are washed out of the soil by leaching, the importance of stress declines. This makes the soil far more amenable to colonisation by non-mangrove plant species, seen in the very high relative importance in plant competition shown by the position of zone D. The significance of disturbance is, perhaps surprisingly, seen to be only similar to that attributed to felling the forest. The low relative contribution of this factor is a result of the greater importance given to competition from other plants.

This diagram confirms one of the major conclusions of this thesis, that in Belize, it is site drainage rather than deforestation which provides the greatest threat to maintaining a vegetation cover of mangrove.

Ecological stability

The possibility of non-mangrove plants competing for space in the cleared zone and along the forest edge raises questions about the ecological stability of these buffer zones. Ecological stability is a term borrowed from theories of thermodynamics in physics, which are concerned with the ability of a system to return to an equilibrium point following disturbance (Hill, 1987). Connell & Sousa (1983) have shown that ecological equilibrium is rarely achieved, making it a poor tool for measuring disturbance against. Sutherland (1981) has suggested the initial state of the system as a suitable alternative, and this will be used in this work.

Two aspects of ecosystem stability are important to this study, termed *resistance* and *resilience* by Hill (1987). Resistance is the ability of a system to resist displacement from its initial state when subjected to disturbance. This concept is particularly applicable to the forest zone. Resilience is the ability of a system to return to its initial state after disturbance. In the current research, this term can be usefully applied to the cleared zone.

Several criteria have been suggested for assessing disturbance. In ecological studies the focus has traditionally rested with measures of species abundance (Hill, 1987). Westman (1978) advocates a 50% change in the abundance of plant species to indicate a change from the initial conditions. Such an approach has not been used in this work for two reasons:

1. With only two or three different species in the mangrove forest of the fieldsites, the loss of only one of these would indicate significant ecological change.
2. There is a lack of baseline data to provide a long term view of trends in mangrove species abundance at the field sites.

Instead, this work has considered changes in the underlying soil and water conditions following disturbance. If clearance and drainage result in increased plant stress, or alternatively the creation of conditions more favourable to non-mangroves, then the ability of the original mangrove vegetation to restore the system to its initial conditions is assumed to be compromised.

The timescale used in such evaluations is also important. Dayton *et al.* (1984) suggest that the length of studies considering a system's response to change must exceed the lifetime of the individuals contained in the study area. Sutherland (1981) advocates time periods corresponding to one or two generations following the disturbance. Such a view makes studies of change in long-lived organisms such as trees difficult, and this approach has not proved suitable for the present work. Cairns & Dickson (1977) promote a more anthropocentric view, suggesting that for studies of human disturbance, the period should be the human lifespan. This is still too great a time period for the purposes of the present study and so the discussion that follows is based on the *expected* response of the mangrove ecosystem to disturbance.

Three aspects of the disturbance are considered below, felling the forest (clearance), draining the site, and the viability of the remaining area of vegetation.

Forest clearance

Mangroves have evolved to cope with disturbance - hurricanes, lightning strikes and storms are all common features of mangrove habitats. The clearance of the mangrove seen at the field sites can be likened to windthrow damage. Edges are also common features in mangrove habitats, found at the marine limit of fringing mangrove communities, along the banks of rivers and lagoons, and at the terrestrial boundary formed with saltmarshes. The pioneering activities of mangroves requires them to be tolerant to high levels of insolation, wind and wave-induced stresses. Therefore it is not surprising that the conditions in the cleared zone and along the forest edge remain conducive to mangrove growth following clearance. Indeed there is evidence that such disturbance may even accelerate the growth and survivorship of mangrove seedlings in exposed positions (Ellison & Farnsworth, 1993). The long term health of such exposed specimens has, however, been recently questioned by work in Florida (Rey, 1994). Whilst he too found exposed seedlings to have a lower initial mortality rate and a higher growth rate, such plants failed to acheive the great final height of equivalent plants in the forest. This suggests that their growth in such exposed sites may incur a greater carbon cost and thus in the long term such plants may be more vulnerable to out-competition by non-mangrove plants than those within the forest canopy.

A study of *Rhizophora mangle* logging in Ecuador has shown that areas up to 20 m wide will regenerate naturally by seed dispersal (Blanchard & Prado, 1995). This implies that simply felling the trees and the associated edge creation do not pose a great long term threat. The mangrove forest at the field sites is therefore expected to show a high resistance to change from nearby felling activities and even the cleared zone should be resilient. Evidence of this resilience can be seen in the mangrove regrowth around the Haulover Creek (potential) field site and in the attempted recolonisation of the Burnt site by seedlings during the fieldwork of 1992, which became so established that the vegetation at the site had to be reburnt in early 1994.

Drainage

Mangroves dominate flooded areas in the tropics, but anaerobic soil conditions are not a prerequisite for their establishment or continued growth. In areas of northern Belize near Shipstern Lagoon, mangroves can be found growing at the edge of a seasonally dry saltmarsh, with roots growing in dry soil. Thus drainage itself does not pose an immediate threat to mangroves, but it means they lose their competitive advantage. Adaptations to conditions of high salinity and their ability to locally oxidise the rhizosphere in otherwise reducing soils become redundant. This leaves them vulnerable to competition. In the absence of competing species, mangroves are expected to show considerable resilience to such disturbance and recolonise these areas, aided by the head-start provided by seed stocks already present in the soil. During the process of field site selection in 1994, *Rhizophora mangle* seedlings were observed growing in the newly cleared, mechanically scoured and drained soils next to the Punta del Este site. The closed canopy of the remaining mangrove is likely to aid the forest's resistance to colonisation by invading species.

Buffer width

Perhaps most crucial to the long term success of mangrove buffer zones is whether the narrow width (66') dictated by the legislation is sufficient to support the full range of floral, faunal and fungal species necessary to sustain a healthy mangrove ecosystem. Nearby mangrove clearance and drainage may not directly change soil and water conditions to such an extent that the mangroves cannot grow, but if conditions within the remaining forest are not amenable to important fauna such as the bees which pollinate *Avicennia germinans*, then the ecological stability of these areas of mangrove must be questioned. As yet, answering this awaits further research.

10.2.4 Implications for legislators

Chapter three shows that current Belize legislation (specifically the *1939 66' Reserve Act* and the *1992 National Lands Act*) require a 22 yard buffer of mangrove forest to be left alongside water bodies and along the coastal edge next to developed areas. This is designed to prevent erosion of the land. A consideration of similar legislation in other countries shows no consensus of opinion regarding a suitable width for this zone.

The preliminary semivariogram analysis of chapter eight shows that changes in the value of many soil and water properties in cleared areas may alter the value of these properties right across the mangrove buffer. Whilst individually, such changes are insufficient to affect the viability of the remaining mangrove, over time the cumulative effects of such changes may result in the mangrove being outcompeted by terrestrial species. Likely candidates are buttonwood (*Conocarpus erectus*) and palmetto (*Thrinax radiata*), both of which are common components of the back-mangal and scrub forest which currently grow inland and on raised areas of the larger offshore cayes. The confirmation of edge effects in mangrove forests presented in this work suggests that this legislation requires a detailed re-evaluation. As well as evidence from soil and water sampling, ecological studies (particularly those of mangrove insects) are required to establish the minimum width of forest which will maintain the necessary mix of fauna, flora and fungi to be truly sustainable.

10.2.5 Implications for developers

This work reinforces the view of the mangrove as a highly dynamic ecosystem. Changes occur in the soil and water properties long after clearance and drainage. Before construction occurs, efforts should be made to confirm that the fallen material has adequately decomposed, a process that will be accelerated by aerobic conditions, emphasising the importance of efficient drainage. Merely covering the fallen timber in a layer of clay fill will just trap the decompositional products beneath the soil surface. Combined with a gradual degradation of the soil's physical structure through imperfect drainage, this may lead to subsidence problems in the future, such as the tilted warehouse seen along the Northern Highway.

10.3 The wider applicability of this work

This work has used three fieldsites around Belize City. The properties measured all lie within the range found in the 1991 mangrove surveys along the coast of Belize (Furley & Ratter, 1992; Furley & Munro, 1993). For example soil pH values at the Belize City fieldsites have been found to be between pH 5 and pH 6 in the forest, and near-neutral following clearance. Both these sets of values are well within the range of pH values measured nationally. Sites in the north of the country, such as Sarteneja and Shipstern Lagoon have carbonate-rich soils, yielding pH values between 7 and 8.5. Sites in the south, with a greater organic input such as Sittee River, show lower pH values than any measured at the Belize City sites, with some samples as acidic as pH 2.5. This implies that sites in the south with a low pH and high original organic carbon content will be most vulnerable to pH changes following clearance and drainage, the least affected will be those in the north with a high carbonate content.

Comparing these results with those from other studies of soils in Belize is hampered by the fact that most other workers have tended to ignore mangrove-covered areas. Typical is the national survey of King *et al.* (1992) where only one sample (profile OZ32, San Pedro, Ambergris Cay) is from a mangrove area. The results of the present study, therefore, plug a gap in our "base-line" knowledge of local soil properties.

Comparisons across Central America as a whole must be made more cautiously, as the local environmental conditions, faunal interactions and the normal level of stress factors (detailed in chapter three) alters. Comparisons with soils from further afield, particularly where the mangroves present may be more varied and/or of different species to that found in Belize demands further caution and a detailed understanding of how the local situation may differ from that found around Belize City. Bearing these reservations in mind, a cautious comparison can be drawn from the data in Table 10.1 overleaf.

Table 10.1 Comparison of mangrove soil analyses

Field site Location	Belize[1] *Cleared*	Belize *Forest*	Belize *All*	Bahamas[2]	Tabasco, Mexico[3]	Ganges, India[4]	South East Nigeria[5]	Sierra Leone[6]	Western Australia[7]	Ranong, Thailand[8]
Sampling Depth	0-c.30 cm	0-c.30 cm	0-c.30 cm	10 cm	0-30 cm	1-15 cm	0-40 cm	3-10 cm	0-5 cm	0- c.20 cm
No. of Samples	82	124	252	37	12	5	160	n/s	3	5
pH (method)	6.5 ± 0.5 (Field)	6.2 ± 0.6 (Field)	6.4 ± 0.6 (Field)		7.3 (KCl sol.)	7.8 (n/s)	4.9 ± 0.1 (H_2O)	6.6 (Field)	8.3 ± 0.2 ($CaCl_2$ sol.)	7.5 ± 0.4 (Field)
Bulk ρ ($g\ cm^{-3}$)	0.45 ± 0.13	0.30 ± 0.11	0.36 ± 0.14				0.79 ± 0.1			
Moisture (%)	48.4 ± 10.9	53.9 ± 11.6	50.9 ± 11.9				77.4 ± 13.0	60.0	20-52%	
Organic C (%)	3.4 ± 1.8	5.5 ± 3.4	4.4 ± 2.9		3.69 (OM)	1.427	5.8 ± 1.3	11.9	8.2 ± 0.1	16.6±3.8%
Total P ($mg\ kg^{-1}$ soil)						278.3		1510		
Extr P ($mg\ kg^{-1}$ soil)	380 ± 139	416 ± 249	391 ± 211							
Exch Ca ($cmol_c kg$)	2.22 ± 0.88	2.47 ± 1.22	2.37 ± 1.17	1.35 ± 0.20	1.26		11.9 ± 3.6			4.10±0.44
Exch Mg ($cmol_c kg$)	3.98± 0.34	4.16 ± 0.16	4.11 ± 0.25	0.03 ± 0.01	0.17		19.2 ± 4.8			8.67±0.72
Exch Na ($cmol_c kg$)	24.96 ± 6.70	36.68 ± 10.29	32.12 ± 10.48		3.71		10.1 ± 1.3			19.67±2.63
Exch K ($cmol_c kg$)	0.75 ± 0.23	0.87 ± 0.43	0.75 ± 0.37	0.02 ± 0.01	0.001	0.001	0.2 ± 0.004			0.87±0.16
Exch Mn ($cmol_c kg$)	0.007 ± 0.003	0.006 ± 0.003	0.006 ± 0.003	0.001 ± 0.003			0.006 ± 0.011			0.008±0.002
Extr Fe ($g\ kg^{-1}$ soil)	2.63 ± 1.21	1.84 ± 1.59	2.08 ± 1.57				0.03 ± 0.001			0.17±0.08
SO_4-S ($mg\ kg^{-1}$ soil)	4.69 ± 1.17	4.91 ± 1.03	4.81 ± 1.02					1667		491.7±124.2

Values shown are sample means, ± 1 standard deviation, if known. Samples where the analytical method or sample size was not specified in the source article are shown by the abbreviation n/s. The Organic C figure for Tabasco is followed by the letters OM to indicate that this figure is actually for total organic matter and is thus likely to be an overestimate of organic carbon content.

[1] Burnt field site, this study.
[2] Wilcox *et al.* (1975).
[3] López-Portillo & Ezcurra (1989). Data used are from sites along the "mudflat" - predominantly *Avicennia.*
[4] Sengupta & Chaudhuri (1991). Data used are for their "Developed" [as in mature] mangrove swamp" class, which is nearest to those in the present study.
[5] Ukpong & Areola (1995).
[6] Hesse (1961a, 1961b) - *Rhizophora* zone.
[7] Akornkoae *et al.* (1991).
[8] Gordon (1988) Data used are those from the "Cossack" site withj restricted inundation.

Table 10.1 shows the results of the laboratory analysis of mangrove soils from around the world. The reader's attention is drawn to the different sample sizes and sampling support used by the various authors. Where possible, the results from other workers presented in the table have been converted into units which allow a direct comparison with the results from this study. Because of the greater range of soil properties measured during the 1992 field season, data from this period rather than the 1994 field season are presented in the table.

Examination of the pH results shows they fall into three broad categories. This distinction is two-fold, depending upon both the characteristics of the substrate and the analytical method used. Measurements of soil pH made in the field tend to accord with those presented in this work (in the range pH 6.0 to 6.5). Measurements made using dried soil samples show different values. As expected, pH measurements made from a mixture of soil and salt solution show higher values, those measured in water tend to yield a lower pH. The lower pH from dried samples measured in water may also be a function of sample acidification following drying.

Bulk density figures show a similar range, though interestingly the figures from the disturbed Belizean field site are lower than the Nigerian site (Ukpong & Areola, 1995). This may be due to sampling method differences (possibly greater compaction in the Nigerian work) or differences in the rate and nature of sediments deposited (the sites sampled in Nigeria were from estuarine locations).

Figures for soil moisture content and organic carbon levels show little difference between the various sites. Examination of phosphorus and iron measurements are hampered by the absence of adequate values for comparison.

Variations in the reported level of exchangeable magnesium and calcium are thought to reflect differences in the local sediment source. The results from sites in Belize tend to be slightly higher than those from other areas, reflecting the impact of the nearby barrier reef. Exceptions to this are the results from Nigeria (Ukpong & Areola, 1995) which show calcium and magnesium levels an order of magnitude greater than the other mangrove sites. This may be due to an inland carbonate-rich sediment source.

Exchangeable manganese values are uniformly low across all the sites. Values of exchangeable sodium show greater diversity, with the values reported from the site in Belize being notably higher than the other mangrove areas. This is interpreted as revealing differences in the land use. The other sites are areas of relatively undisturbed mangrove, whilst the fieldsite in Belize had been cleared and subjected to infrequent attempts at drainage. Salt levels in the upper layers of the soil at the Burnt field site have been locally increased due to a combination of restricted tidal flushing and evaporation.

The level of sulphate-sulphur in the Belizean soils is far lower than that of the acid-sulphate prone soils of West Africa reported by Hesse (1961a, 1961b) and sites in Asia (e.g. Kryger & Lee, 1995). This can be attributed to the absence of sulphide-rich compounds from the sediments around Belize City.

Thus, the analytical results presented in this work show a range of values broadly similar to those obtained from other mangrove covered areas of the world. Differences which do exist, stem from two sources: local land management practices and differences in the sedimentation rate and sources. It has to be remembered that the majority of published results are from relatively undisturbed areas of mangrove forest, whilst the study sites in this work have all been subjected to partial clearance and attempts made to drain the soil. The most signifcant "physical" difference is the absence of high sulphate levels in mangrove soils from Belize, which have proved such an obstacle to attempts to develop mangrove soils in Africa and Asia.

10.4 Suggested modifications to mangrove research in the light of this work

This work shows that new geostatistical techniques such as semivariogram analysis, which have been developed at relatively homogeneous inland locations, are also suitable for use in more dynamic, varied environments such as those found along mangrove-covered coasts. The analyses presented in this work should, however, only be considered as preliminary measures. The semivariograms suffer from low confidence in the figures obtained at short lag distances, which is a function of the stratified random sampling strategy used in the field. Future studies measuring properties in the mangrove, should use a regularly-spaced (systematic) sampling strategy to overcome this. Studies investigating processes operating over very small spatial scales (such as redox potential), would be well advised to use a very fine scale sampling strategy. This reinforces the findings of McKee (1993), that a sampling interval of a few centimetres may be necessary in order to detect changes arising from differences in root distribution.

This work confirms the view that studies of changes following disturbance should not just concentrate on the time period since forest clearance. The nature of the disturbance is important, notably whether the site has been significantly drained or not, following forest clearance.

10.5 Future research avenues

This research reveals three areas worthy of further investigation. These relate to the need to expand the scale of this work, to broaden the ecological perspective of the problem, and to question the assumptions used in this research.

10.5.1 Expanding the scale of this work

The work presented in this study stems primarily from two three-month field seasons in Belize, separated by a period of two years. As such, little consideration could be given to processes operating at timescales which are greater than those encountered in the fieldwork (supra-annual processes such as comparing the vulnerability and response of undisturbed and cleared areas to hurricane impact). Secondly, because of the decision to focus upon short to medium term spatial changes, the very fine-scale changes in processes which operate at immediate, hourly, diurnal, and even to an extent, seasonal timescales have not been given the consideration workers in other disciplines might have wished.

As in all aspects of terrestrial ecology, therefore, this work would benefit from the establishment of long term continuous (mangrove) monitoring programmes. This would allow a more informed assessment of the claims of this work, relating to the impact and subsequent response of areas of mangrove to disturbances, from both natural and anthropogenic sources.

During the field period, it did not prove possible to locate a fieldsite which had been cleared and drained more than three years earlier, and yet not then built upon. If such a site could be found, then this would allow an extension of this study, reducing its temporal limitations.

10.5.2 Broadening the ecological perspective

This research has employed strong physico-chemical and spatial approaches to the study of mangroves' response to disturbance. It would benefit from associated ecological studies examining the wider effect of disturbance. The edge effects present in the level of soil and water properties, identified in this work, may be accompanied by parallel effects in the floral, fungal and faunal components. For example, the creation of forest edges may affect the pattern of processes such as insect herbivory and pollination, fungal infestation and bird activity, all of which could result in long term changes in the mangrove forest. The large input of decaying material from clearance may attract more pests, resulting in greater predation of trees along the cut edge. With increased light along the forest edge, there may also be interesting plant-plant interactions between mangroves and epiphytic or parasitic plants.

Studies comparing plant biomass partitioning and litterfall at the edge of the forest with that in the centre could detect the signs of plant stress which can be inferred from this work. These could also be accompanied by remote-sensing techniques using aerial photographs, satellite and spectroradiometer data to indicate the precise location and distribution of such stressed regions. Such investigations could then be used to evaluate the validity of this study's use of the undisturbed forest as a statistical control.

10.5.3 Questioning the assumptions of this work

This research uses measurements of environmental properties in the remaining forest as a statistical control, to provide an estimate of properties in undisturbed mangrove. Whilst this assumption may well hold for short term studies such as this one, its validity in the long term must be questioned. Further work, comparing environmental properties in isolated, undisturbed regions of mangrove and those in sites abutting development would allow this assumption to be put to the test.

This research has, however, identified the presence of edge effects in mangrove forests and managed to quantify the significance of the physico-chemical changes resulting from mangrove clearance and drainage. Through a range of visualisation techniques, it reveals how such changes are manifested in space. Moreover, it has shown that there are still plenty of interesting research questions to be answered, both in undisturbed areas of mangrove and along the recently created forest edges.

10.6 Summary of findings

The conclusions of this work can be grouped under six headings relating to issues of development, the effect of clearance upon the soil, the effect upon mangrove fauna, the impact of drainage, vegetation responses identified and the detection of edge effects.

Development

- Mangrove clearance and drainage is accelerating in Belize, concentrated around the existing urban centres. It is being driven not by demands from the agricultural or industrial sector, but rather, by the creation of large housing schemes.
- Development proceeds in two distinct stages, forest clearance and site drainage. The time between clearance and drainage varies from periods of a few weeks, to several years.

Effect of clearance upon the soil

- Felling of the forest disturbs the normal pattern of nutrient cycling. The level of many key plant nutrients has been found to rise shortly after clearance and then fall away. Some nutrients released from the fallen material such as phosphorus are rendered unavailable to plants, because they are rapidly immobilised and/or fixed in the soil.
- Burning the fallen material results in the loss of carbon and nitrogen through volatilisation.
- The release of nutrients from the fallen material via decomposition and mineralisation is severely retarded if the site remains flooded.
- Tree death terminates the localised downward translocation of oxygen by mangrove roots. This results in increasingly reducing soil conditions.
- Loss of the vegetation cover results in the accumulation of ammonium-N in the cleared area. This acts to neutralise the normally acidic mangrove waters.

- Compaction effects are generally very small and extremely localised. This is attributed to the manual clearance methods employed in many parts of Belize.
- Many of the changes in the soil properties as a result of forest clearance are confined to the shallow organic layer near the surface. The effect of these changes is to reduce sample heterogeneity.

The effect upon mangrove fauna

- Removing the forest cover affects faunal activity. Crabs seem to favour recently cleared areas, presumably exploiting the increased availability of fallen vegetation. This resulted in an associated increase in the number of wading birds in such areas, feeding upon the exposed crabs.

The impact of drainage

- Draining the land results in a further change in soil conditions. The previously anaerobic, reducing environment is transformed. The soil becomes aerated, favouring oxidising, aerobic conditions. Oxidised species predominate under these conditions, which can result in increased soil acidity.
- Drainage accelerates leaching loss and the aerobic conditions stimulates decomposition. Over time, leaching should act to reduce salinity levels. This results in changes at greater depth than seen after forest clearance.
- Dry, drained land is more prone to physical erosion. If the surface rootmat which acts to bind the soil together is lost, then nutrient losses will accelerate.

Vegetation responses

- Neither clearance nor drainage are enough in themselves to prevent mangrove regrowth. Whilst the level of some stress factors such as insolation and temperature increase, others such as salinity decline.
- Mangroves have evolved to exploit niches in a harsh, dynamic environment where disturbances such as storms and hurricanes are common. Increased light levels in cleared areas act to stimulate the growth of mangrove seedlings. Natural regeneration of the disturbed sites can therefore be expected, particularly if the sites are not drained.
- However, after drainage, the low salinity and oxidised soil conditions rob mangroves of their competitive advantage. This leaves them vulnerable to out-competition by true terrestrial species.

Edge effects

- Development of a site results in the creation of environmental gradients between the cleared land and remaining areas of forest. Edge effects similar to those first revealed from studies in tropical rain forests have been detected in the mangrove-covered fieldsites examined in this study.

- These edge effects differ from those in tropical rain forests however, in that the most significant factor in their creation and maintenance appears not to be a loss of forest cover, rather the change from anaerobic to aerobic soil conditions which follows soil drainage.
- Edge-effects running into the forest tend to be a result of nutrient-loss, those extending out into the cleared area are usually water-transported variables. Transect analysis reveals quantifiable differences in forest properties up to 50 m into the forest.
- The spatial pattern of these edge effects is highly variable specific. This reflects differences in the diffusion and transportation processes, nutrient inputs and exports and the spatial scale of variation.
- Many variables show a large spatially dependent component of variation, with changes in the value of a property in one location found to affect the value of points up to 40 m away.
- The present protective legislation which requires only a 66' mangrove buffer adjoining developed sites should be reconsidered. The identification of edge effects presented in this study suggests that this figure may have to be revised upwards if the remaining forest is to withstand changes along its edges.

Through the spatial mapping of environmental properties across a range of selectively-cleared areas of mangrove forest, this work has been able to show that edge effects exist in mangroves which are broadly similar in nature to those already known to occur in tropical rain forests. In a similar manner to tropical rain forests, deforestation of mangrove sites results in an increase in the homogeneity of soil properties, but this trend may be reversed if later drainage measures are only partially successsful, leaving a mosaic of reducing and oxidising regions in the soil.

The spatial pattern of the edge effects revealed in this work, however, shows that edge effects in mangroves differ subtly from their tropical forest analogues. Although requiring further investigation, it seems that mangrove edge effects may be greater in extent, because of the effect of water-transportation and differences in the diffusion of variables in the flooded soils of the mangrove. Thus management guidelines based on studies of tropical rain forests cannot just be applied to mangroves as if such areas are simply another form of terrestrial forest, because of the greater availability and importance of underground water movements within the soils of the mangrove.

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Personal communications

Because of the nature of this research, a great deal of information and insight into the problems relating to mangrove clearance in Belize were obtained through interviews and informal discussions with local Belizeans and visiting foreign researchers. Those cited in the text are named below:

Furley, P.A. Reader, *Department of Geography, The University of Edinburgh*, Drummond Street, Edinburgh EH8 9XP, Scotland.

Green, E. Chief Forest Officer, *Forest Department, Ministry of Natural Resources,* Belmopan, Belize.

Griffiths, F. Manager, *Belize Center for Environmental Studies* 55 Eve Street, Belize City, Belize.

Hanson, G. Mangrove Manager *Forest Department, Ministry of Natural Resources,* Belmopan, Belize.

McShane, F. Lecturer *Department of Geography, The University of the South Pacific*, P.O. Box 1168, Suva, Fiji.

Minty, C.D. Physical Laboratory Manager *Department of Geography, The University of Edinburgh*, Drummond Street, Edinburgh EH8 9XP, Scotland.

Munro, D. Research Fellow, *Department of Geography, The University of Edinburgh*, Drummond Street, Edinburgh EH8 9XP, Scotland.

Nicolait, L. Director, *Belize Center for Environmental Studies* 55 Eve Street, Belize City, Belize.

Ross, S.M. Senior Environmental Consultant, *SGS Environment*, Chapel Street, Liverpool, L3 9AG, England. Formerly with the *Department of Geography, The University of Bristol*, University Road, Bristol BS8 1SS, England.

Waight, L. Secretary, *Belize Audubon Society*, P.O. Box 1001, Belize City, Belize.

Wilson, R. Technical and Scientific Advisor, *Programme for Belize* PO Box 749, Belize City, Belize.

Zisman, S.A. Mangrove Specialist 1992-3 *Ministry of Natural Resources/NRI* Forest Planning and Management Project, Belmopan, Belize. Now with the *Department of Geography, The University of Edinburgh*, Drummond Street, Edinburgh EH8 9XP, Scotland.

Appendix 1: Vegetation data

A global mangroves species list

Controversy exists in any attempt to produce a definitive list of mangrove species. This stems from two sources: different classification of plants producing a different range of mangrove species (e.g. whether *Rhizophora samoensis* is merely a local variant or a different species to *Rhizophora mangle*); and different definitions of what constitutes a mangrove species and thus which plants should be included. This debate has already been explored in Section 2.1. The list below follows the work of Tomlinson (1986) and his definition of "true mangrove" species, combining data from his Tables 2.1, 3.1, 3.2 and 3.3.

Table 12.1 Mangroves species found around the globe

Family	Genus	Species	Aerial roots	Vivipary
Avicenniaceae	*Avicennia*	*alba*	++	+
		bicolor		
		eucalyptifolia		
		germinans		
		lanata		
		marina		
		officinalis		
		schaueriana		
Combretaceae	*Laguncularia*	*racemosa*	+	-
	Lumnitzera	*littorea*	+	-
		racemosa		
Palmae	*Nypa*	*fruticans*	-	+
Rhizophoraceae	*Bruguiera*	*cylindrica*	++	++
		exaristaa		
		gymnorrhiza		
		hainesii		
		parviflora		
		sexangula		
	Ceriops	*decandra*	++	++
		tagal		
	Kandelia	*candel*	-	++
	Rhizophora	*apiculata*	++	++
		x *harrisonii*		
		x *lamarckii*		
		mangle[1]		
		mucronata		
		racemosa		
		x *selala*		
		stylosa		
Sonneratiaceae	*Sonneratia*	*alba*	++	-
		apetula		
		caseolaris		
		griffithii		
		ovata		
Total				
5	9	34		

Key to Aerial roots and Vivipary annotations:

+ present
++ present or well-developed
- absent

Notes

[1] A further possible Rhizophora species, *R. samoensis*, which is morphologically scarcely distinguishable from *R. mangle*, is found in New Caledonia, Fiji, Samoa and Tonga. Although geographically isolated from *R. mangle*, opinion is divided as to whether it is truly a different species (Tomlinson, 1986).

The mangroves of Belize

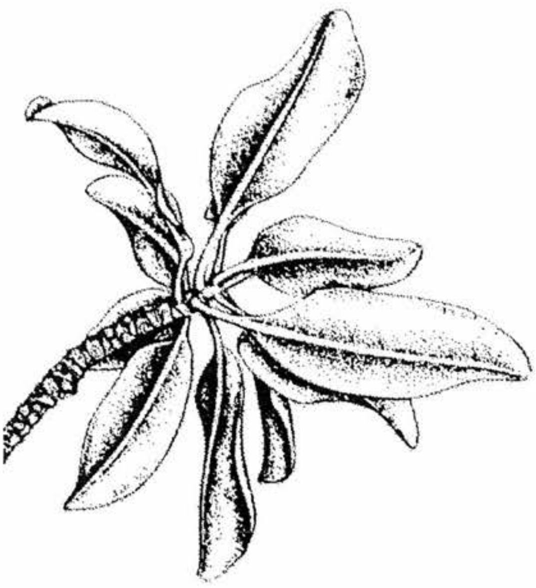
The descriptions which follow are based on those given in Tomlinson (1986), supplemented by field observations. Local names for the mangrove species are taken from Standley & Record (1936). The individual species descriptions are followed by photographs of the mangroves, all taken in Belize.

Rhizophora mangle L. 1753

The most abundant mangrove species found in Belize, this member of the Rhizophoracea family is known locally as the "red mangrove" or "mangle colorado" and by the Mayan Indian name of "Tapche". It is very wide ranging and has been found along the west coast of Africa and both the Atlantic and Pacific coasts of the Americas.

It is easily identified in the field by its extensively developed network of aerial "prop" roots. In older trees, secondary "drop" or stilt roots may be seen growing out of the trunk and older branches. Leaves are about 10-12 cm in length, waxy and arranged in pairs, angled slightly less than 90° from each other, to reduce mutual shading. They have a characteristic stem scar pattern, which is shown in Figure 12.1 and can be used to age individuals. *R. mangle* are wind pollinated. The fruit are olive green, with a rough textured surface. The seedlings are 15-20 cm long, and are water transported, able to survive for up to a year before finally taking root.

Figure 12.1 Leaves and stems of Rhizophora mangle

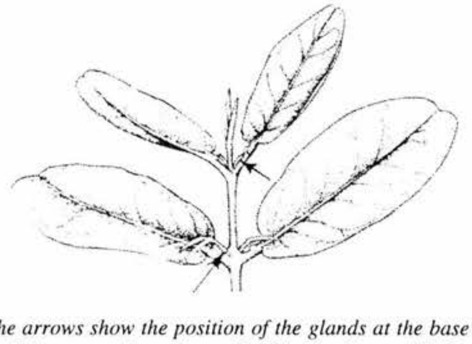


This figure shows a typical leaf arrangement. and the scarring on the stem. An exert from Figure B.67 in Tomlinson, (1986).

Laguncularia racemosa (L.) Gaertn.f. 1805

Known locally as the "white mangrove", "mangle blanco" and "Zacolcom" this mangrove from the Combretacae family is restricted to America and West Africa. *L. racemosa* are usually found only at the landward fringe of the mangrove community, but they can readily exploit disturbed areas, forming pure stands. They are rare members of the mangrove forest at the more inland sites (Texaco and the Burnt site).

Figure 12.2 Leaves of Laguncularia racemosa



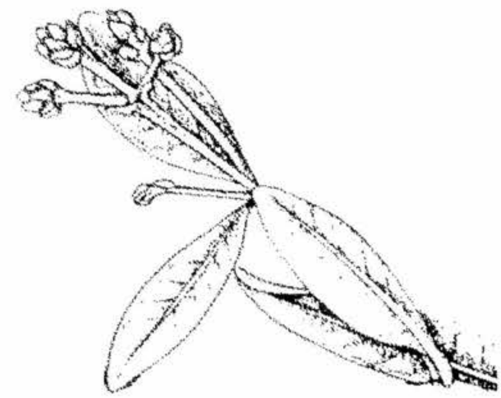
The arrows show the position of the glands at the base of the leaf. An extract from Figure B.19 in Tomlinson,(1986).

Pneumatophores in *L. racemosa* are only facultatively developed; for any given individual, the number of pneumatophores varies between none and several hundred, the exact stimulus for their development has not been identified. They are most easily identified in the field by their leaves - opposite, bluntly ovate, and slightly fleshy, with an obvious pair of glands at the base of the leaf. They has a distinct flowering season, corresponding with the warmest months, though not all trees produce seeds. Fruiting occurs in large numbers, but seedling mortality in the first year is very high.

Avicennia germinans (L.) Stearn 1958

This species, referred to locally as the "black mangrove" or "mangle negro" was the subject of a disputed classification until 1958. In old texts it is sometimes referred to as *A. nitida* Jacq. A member of the Acanthaceae family, it is widespread in its distribution, along both the Atlantic and Pacific coasts of the Americas. *A. germinans* can be found throughout the tidal range, and shows the highest salinity tolerance of the four mangroves species in Belize. At the fieldsites it is most common in basin areas, inland of a coastal fringe dominated by *Rhizophora*.

Figure 12.3 Leaves of Avicennia germinans



The characteristic narrow leaves distinguish this from the white mangrove. An exert from Figure B.8 in Tomlinson (1986).

They have an extensive network of underground roots, which terminate in characteristic "pencil-like" growths known as pneumatophores, which grow to a length of 20-30 cm. These vertical pneumatophores are attached in rows to horizontal cable roots which radiate out from the trunk. Short anchor roots descend laterally from the cable roots to provide stability. Flowers are often pollinated by insects, especially bees and lead to the development of many small viviparous fruit. The fruit is shed as a unit, but with a split pericarp and able to take root as soon as it becomes stationary. These trees can be easily identified in the field by the presence of pneumatophores, its black, fissured bark and its ovate leaves, which have a dark green upper surface and a matt white lower leaf surface. Salt crystals can sometimes be found on the leaves, excreted by the plant.

Conocarpus erectus L. 1753

Tomlinson classifies this species as a "mangrove associate" because it lacks any of the morphological and biological features which characterise true mangroves. Known locally as "buttonwood", "buttonbush", "Bontoncillo" and "Kanche", it is another member of the Combretacae family. Two species are identified within this genus, this one is the more widely distributed species, found both in tropical America and West Africa. The silvery leaved variety (var. *sericeus* Grisebach - *C. pubescens* Schumach.) is common, at least around the Belize City area.

Figure 12.4 Leaves of Conocarpus erectus

This figure shows the leaves and characteristic fruiting heads which give rise to its local name. An extract from Figure B.25 in Tomlinson (1986).

It is a back-mangal constituent, growing within the limit of the highest tides. It is able to tolerate high salinities and rather dry soils, but can also grow in and near fresh water. Buttonwood is a common component of the scrub-forest which occupies the higher land on the interior of the larger offshore islands, such as Turneffe Atoll. Seeds are believed to be water dispersed, as they float. Despite setting many seeds, the number that survive to become seedlings is small compared with *L. racemosa*, suggesting that germination may be difficult or else many are aborted.

Mangroves of Belize

The photographs below have been selected to illustrate the diversity of mangrove form found in Belize. They all show mangroves at the end of the dry season.

Figure 12.8 Young black mangrove

The pneumatophores can be clearly seen in this picture, radiating out from the trunk.
Gales Point, Southern Lagoon, August 1991.

Figure 12.9 Young dwarf red mangrove

The characteristic red mangrove prop root pattern can be seen in this young specimen.
Shipstern Lagoon. July 1991.

Figure 12.5 Mature red mangrove, Texaco field site

This picture shows the prop roots of a large (c.15 m) red mangrove covered with epiphytic plants.
Texaco fieldsite, Belize City August 1994.

Figure 12.6 Buttonwood

The small button-like fruits can be seen against the sky.
Maskall River, August 1991

Figure 12.7 A young white mangrove

The lone white mangrove in this picture faces a severe threat from wave erosion.
Burnt Field Site, August 1992.

Field site vegetation sampling

The mangrove vegetation was surveyed using the PCQM (Point-Centred Quarter Method) of Cottam & Curtis (1956), which Cintrón & Novelli (1984) have found to be suitable for mangrove work. In this study surveys of 20 points were carried out, with the properties of four trees being recorded at each quarter. Tree species, height, diameter at breast height (dbh) and distance from the sampling point were recorded. Measurements of *Rhizophora* tree dbh was hampered by the presence of branching roots at breast height and so Ratter & Bridgewater's (1992) proposed modification, measuring the dbh of the trunk above the main branching point, was adopted. Dead trees were not recorded.

The raw data is listed in the tables below, followed by summary tables and an explanation of the terms used.

Table 12.2 PCQM data, Burnt site 1992 (1994)

Sampling Point	Quarter	Distance (m)	Species	dbh (cm)	Height (m)
1	a	6.50	*R. mangle*	3.20	4.00
	b	0.77	*R. mangle*	1.70	2.50
	c	2.47	*R. mangle*	1.70	4.00
	d	3.87	*R. mangle*	1.40	2.00
2	a	2.61	*A. germinans*	11.20	8.00
	b	3.62	*A. germinans*	8.00	6.00
	c	3.80	*A. germinans*	4.90	7.00
	d	3.25	*A. germinans*	3.00	4.00
3	a	4.27	*A. germinans*	3.60	7.00
	b	1.13	*R. mangle*	4.50	1.50
	c	0.73	*R. mangle*	1.60	3.50
	d	2.26	*A. germinans*	5.40	6.50
4	a	2.82	*R. mangle*	3.20	4.00
	b	5.06	*A. germinans*	17.60	11.00
	c	2.55	*A. germinans*	15.60	10.00
	d	3.25	*A. germinans*	7.20	6.00
5	a	3.49	*A. germinans*	13.40	10.00
	b	2.56	*A. germinans*	11.50	10.00
	c	2.49	*R. mangle*	3.50	5.00
	d	2.75	*R. mangle*	1.30	2.50
6	a	1.05	*A. germinans*	11.30	9.00
	b	7.01	*R. mangle*	2.70	3.50
	c	1.97	*R. mangle*	3.30	5.00
	d	2.43	*R. mangle*	8.70	10.00
7	a	1.90	*R. mangle*	7.60	9.00
	b	5.34	*A. germinans*	5.60	10.00
	c	4.56	*A. germinans*	7.90	8.50
	d	0.93	*A. germinans*	6.40	9.00
8	a	2.60	*R. mangle*	1.10	2.00
	b	4.62	*R. mangle*	2.50	6.50
	c	3.59	*R. mangle*	3.40	4.00
	d	3.07	*R. mangle*	4.80	6.50
9	a	2.79	*R. mangle*	6.70	9.00
	b	2.86	*R. mangle*	5.20	6.00
	c	3.91	*A. germinans*	8.40	9.00
	d	4.41	*R. mangle*	1.30	2.00
10	a	4.88	*R. mangle*	4.90	80.00
	b	7.53	*R. mangle*	10.50	10.00
	c	3.32	*R. mangle*	11.30	9.50
	d	1.07	*A. germinans*	7.60	6.50
11	a	2.47	*A. germinans*	5.80	8.00
	b	2.92	*A. germinans*	13.20	7.00
	c	1.17	*R. mangle*	0.50	1.50
	d	2.72	*A. germinans*	2.90	3.50

continued overleaf

Sampling Point	Quarter	Distance (m)	Species	dbh (cm)	Height (m)
12	a	8.67	*R. mangle*	7.10	8.00
	b	1.54	*R. mangle*	1.70	2.50
	c	2.97	*A. germinans*	4.10	5.00
	d	1.98	*A. germinans*	7.60	9.00
13	a	3.35	*R. mangle*	5.70	6.00
	b	4.32	*R. mangle*	4.20	6.50
	c	4.21	*R. mangle*	1.20	2.00
	d	5.98	*A. germinans*	2.40	6.50
14	a	4.64	*A. germinans*	14.50	9.00
	b	1.47	*R. mangle*	2.30	3.00
	c	6.51	*A. germinans*	7.30	7.50
	d	8.26	*A. germinans*	17.30	7.50
15	a	3.71	*R. mangle*	4.80	6.00
	b	2.87	*A. germinans*	5.70	8.50
	c	1.86	*R. mangle*	5.70	6.00
	d	2.03	*R. mangle*	3.50	5.50
16	a	2.84	*A. germinans*	12.40	7.00
	b	2.05	*A. germinans*	8.00	5.00
	c	6.93	*R. mangle*	6.40	8.50
	d	1.70	*R. mangle*	15.80	7.00
17	a	3.37	*A. germinans*	9.40	8.00
	b	0.93	*A. germinans*	4.70	5.00
	c	3.15	*L. racemosa*	10.20	7.50
	d	2.38	*R. mangle*	3.30	5.50
18	a	4.88	*R. mangle*	7.60	9.00
	b	6.54	*R. mangle*	2.00	4.50
	c	0.90	*R. mangle*	2.00	4.00
	d	2.08	*R. mangle*	1.10	2.00
19	a	1.02	*R. mangle*	1.90	2.50
	b	2.82	*A. germinans*	6.90	5.00
	c	4.35	*R. mangle*	0.80	2.00
	d	4.09	*R. mangle*	5.30	10.00
20	a	2.55	*R. mangle*	7.70	11.50
	b	4.54	*A. germinans*	10.50	10.50
	c	1.56	*A. germinans*	10.90	8.50
	d	2.20	*A. germinans*	13.20	9.00

Table 12.3 PCQM data, Texaco 1994

Sampling Point	Quarter	Distance (m)	Species	dbh (cm)	Height (m)
1	a	9.00	A. germinans	20.1	15.00
	b	1.12	L. racemosa	0.9	2.00
	c	1.48	L. racemosa	0.6	1.50
	d	2.20	A. germinans	18.1	16.00
2	a	4.68	A. germinans	17.2	14.00
	b	6.07	R. mangle	8.3	7.00
	c	2.60	A. germinans	22.6	16.00
	d	3.44	L. racemosa	1.0	2.00
3	a	3.04	A. germinans	22.6	18.00
	b	3.81	A. germinans	22.9	18.00
	c	2.16	R. mangle	20.4	17.00
	d	5.96	R. mangle	1.0	2.00
4	a	3.82	R. mangle	21.6	15.00
	b	10.11	R. mangle	11.1	12.00
	c	3.24	A. germinans	12.4	12.00
	d	2.37	R. mangle	4.5	4.00
5	a	2.35	A. germinans	8.3	9.00
	b	3.65	R. mangle	4.1	3.50
	c	3.87	R. mangle	19.4	18.00
	d	1.37	R. mangle	12.1	14.00
6	a	3.52	A. germinans	16.2	15.00
	b	3.68	L. racemosa	15.9	18.00
	c	1.08	A. germinans	17.5	17.00
	d	2.30	A. germinans	21.0	17.00

continued overleaf

Sampling Point	Quarter	Distance (m)	Species	dbh (cm)	Height (m)
7	a	4.99	L. racemosa	22.9	17.00
	b	2.32	A. germinans	16.2	17.00
	c	1.19	A. germinans	23.9	19.00
	d	3.27	L. racemosa	12.4	18.00
8	a	3.09	R. mangle	5.7	9.00
	b	1.17	R. mangle	17.2	15.00
	c	3.95	R. mangle	3.0	3.50
	d	2.10	A. germinans	15.3	16.00
9	a	3.45	R. mangle	10.2	14.00
	b	1.23	R. mangle	4.8	7.00
	c	0.83	L. racemosa	22.6	20.00
	d	3.46	L. racemosa	12.4	19.00
10	a	2.40	R. mangle	4.0	4.00
	b	2.83	R. mangle	7.3	9.50
	c	1.46	L. racemosa	11.6	17.00
	d	3.21	R. mangle	15.3	17.00
11	a	2.31	R. mangle	3.8	6.00
	b	3.42	L. racemosa	16.2	18.00
	c	8.12	R. mangle	21.6	17.00
	d	2.37	R. mangle	17.8	19.00
12	a	1.78	R. mangle	5.7	8.00
	b	1.90	L. racemosa	14.6	16.00
	c	3.40	A. germinans	15.4	15.00
	d	1.86	L. racemosa	19.4	17.00
13	a	2.10	A. germinans	17.8	18.00
	b	3.73	L. racemosa	17.0	19.00
	c	2.11	A. germinans	19.7	19.00
	d	2.80	A. germinans	13.4	18.00
14	a	1.44	A. germinans	17.2	20.00
	b	4.41	R. mangle	4.5	3.00
	c	3.00	R. mangle	17.3	17.00
	d	3.48	R. mangle	12.4	12.00
15	a	3.62	L. racemosa	19.4	17.00
	b	2.08	L. racemosa	13.7	16.00
	c	6.21	A. germinans	16.2	15.00
	d	6.13	R. mangle	6.0	7.00
16	a	5.19	R. mangle	16.6	15.00
	b	6.79	L. racemosa	12.4	15.00
	c	1.94	R. mangle	9.5	12.00
	d	1.53	L. racemosa	19.4	17.00
17	a	2.51	R. mangle	14.5	16.00
	b	5.00	A. germinans	20.5	19.00
	c	1.15	A. germinans	19.3	20.00
	d	1.00	A. germinans	2.1	3.50
18	a	3.06	R. mangle	4.3	4.50
	b	4.36	R. mangle	12.4	12.00
	c	3.02	R. mangle	17.0	15.00
	d	3.74	R. mangle	12.6	14.00
19	a	2.81	A. germinans	17.5	18.00
	b	1.58	R. mangle	8.6	13.00
	c	3.37	A. germinans	23.2	19.00
	d	2.14	R. mangle	11.6	14.00
20	a	4.96	A. germinans	20.7	18.00
	b	1.27	R. mangle	7.6	9.00
	c	6.29	A. germinans	23.6	17.00
	d	6.06	R. mangle	19.7	17.00

Table 12.4 PCQM data, Punta del Este 1994

Sampling Point	Quarter	Distance (m)	Species	dbh (cm)	Height (m)
1	a	1.60	A. germinans	3.98	3.00
	b	1.00	A. germinans	3.50	3.50
	c	1.50	R. mangle	3.50	3.00
	d	0.66	A. germinans	4.46	5.00
2	a	1.93	R. mangle	2.07	2.00
	b	0.49	A. germinans	2.39	2.50
	c	0.65	R. mangle	1.27	2.00
	d	0.67	R. mangle	1.59	2.00
3	a	0.86	A. germinans	3.50	5.00
	b	0.55	R. mangle	2.71	3.00
	c	0.88	R. mangle	3.50	4.00
	d	0.69	R. mangle	2.86	3.50
4	a	1.40	R. mangle	2.86	2.50
	b	2.20	R. mangle	4.77	4.50
	c	1.63	R. mangle	1.59	2.00
	d	0.87	A. germinans	3.82	5.00
5	a	1.40	R. mangle	1.11	1.50
	b	1.98	R. mangle	3.50	4.00
	c	0.46	R. mangle	2.55	3.00
	d	0.44	R. mangle	1.59	2.50
6	a	0.93	R. mangle	3.50	4.00
	b	0.34	A. germinans	5.09	5.00
	c	0.75	R. mangle	1.59	2.50
	d	0.89	A. germinans	2.39	4.00
7	a	1.46	A. germinans	3.18	3.00
	b	0.21	R. mangle	2.23	2.00
	c	0.54	R. mangle	2.55	3.00
	d	0.30	R. mangle	2.07	3.00
8	a	0.72	A. germinans	8.59	9.00
	b	1.91	L. racemosa	7.00	10.00
	c	0.99	R. mangle	2.86	3.00
	d	0.59	R. mangle	1.91	2.50
9	a	0.75	R. mangle	2.86	4.00
	b	0.76	R. mangle	3.18	4.50
	c	1.13	R. mangle	1.91	3.00
	d	0.81	R. mangle	2.23	2.50
10	a	1.08	A. germinans	8.28	10.00
	b	0.25	R. mangle	3.82	5.00
	c	0.48	R. mangle	1.75	2.00
	d	1.04	R. mangle	3.18	3.00
11	a	1.30	R. mangle	2.23	3.00
	b	0.40	R. mangle	1.27	1.50
	c	1.32	R. mangle	2.23	2.00
	d	0.95	R. mangle	1.91	2.50
12	a	0.86	A. germinans	5.41	7.00
	b	0.77	R. mangle	2.55	3.00
	c	1.17	R. mangle	2.55	3.00
	d	0.90	R. mangle	2.55	2.50
13	a	0.33	R. mangle	1.91	2.50
	b	0.77	R. mangle	4.46	3.00
	c	3.03	R. mangle	3.02	3.50
	d	1.87	R. mangle	2.86	2.00
14	a	0.72	R. mangle	0.95	1.50
	b	1.19	R. mangle	3.82	3.00
	c	1.14	A. germinans	3.18	4.00
	d	1.99	R. mangle	2.86	3.50
15	a	0.71	R. mangle	2.39	4.00
	b	0.94	R. mangle	3.50	4.00
	c	0.83	A. germinans	3.34	4.50
	d	0.74	R. mangle	1.27	2.00
16	a	1.16	R. mangle	2.55	4.00
	b	0.74	A. germinans	1.59	2.50
	c	1.01	L. racemosa	2.39	3.00
	d	1.48	R. mangle	1.75	2.50

continued overleaf

Sampling Point	Quarter	Distance (m)	Species	dbh (cm)	Height (m)
17	a	0.59	R. mangle	3.18	3.00
	b	0.96	L. racemosa	1.91	2.00
	c	0.86	L. racemosa	2.71	4.00
	d	1.48	R. mangle	3.82	4.00
18	a	0.70	R. mangle	2.07	3.00
	b	0.94	R. mangle	3.02	3.00
	c	2.56	R. mangle	2.23	3.50
	d	0.46	A. germinans	2.23	2.50
19	a	1.43	R. mangle	3.02	3.00
	b	1.02	A. germinans	3.02	4.00
	c	0.86	R. mangle	2.23	3.50
	d	1.63	R. mangle	3.02	3.50
20	a	0.65	R. mangle	1.75	2.50
	b	0.62	L. racemosa	3.50	7.00
	c	0.61	A. germinans	3.50	4.00
	d	2.20	R. mangle	3.02	4.00

Summary

Table 12.5 Summary data Burnt site 1992 (1994)

Mangrove Species	Relative Density	Relative Dominance	Relative Frequency	Importance Value	IV Rank	Mean Tree Height (m)	Mean Tree dbh (cm)
A. germinans	44.0	7.1	45.9	97.1	2	7.63	8.7
R. mangle	55.0	92.8	51.4	199.2	1	6.94	4.2
L. racemosa	1.0	0.1	2.7	3.8	3	7.50	10.2

Table 12.6 Summary data Texaco site 1994

Mangrove Species	Relative Density	Relative Dominance	Relative Frequency	Importance Value	IV Rank	Mean Tree Height (m)	Mean Tree dbh (cm)
A. germinans	33.0	4.5	35.7	73.2	3	16.24	17.8
R. mangle	45.0	25.7	38.1	108.8	2	11.17	10.9
L. racemosa	22.0	69.8	26.2	118.0	1	14.68	13.7

Table 12.7 Summary data Punta del Este site 1994

Mangrove Species	Relative Density	Relative Dominance	Relative Frequency	Importance Value	IV Rank	Mean Tree Height (m)	Mean Tree dbh (cm)
A. germinans	23.0	12.2	38.5	73.6	2	4.64	4.0
R. mangle	71.0	83.4	51.3	205.6	1	2.97	2.5
L. racemosa	6.0	4.5	10.3	20.7	3	5.20	3.5

Calculations

The methods of calculation and worked examples[1] are given in Cintrón & Novelli (1984) to which the reader is referred. Given below however, are the formulae required for interpreting the values given in the summary tables:

$$\text{Relative Density} = \frac{\text{Number of individuals of a species}}{\text{Total number of individuals}} \times 100$$

$$\text{Relative Dominance} = \frac{\text{Dominance of a species}}{\text{Dominance for all species}} \times 100$$

$$\text{Relative Frequency} = \frac{\text{Frequency of a species}}{\text{Sum frequency of all species}} \times 100$$

These three relative measures can be combined to give the importance value (IV) of Curtis (1959), which reaches 300 in monospecific stands:

Importance Value = Relative Density + Relative Dominance + Relative Frequency.

[1] Although it should be noted that in their worked examples they miscalcalculate the value obtained for the mean basal area of *Rhizophora mangle*. They quote a figure of 0.0604, but this is the sum basal area, and should be divided by the number of specimens (5) to give a final value of 0.0121. This has a knock-on effect on many of the later calculations too!

Appendix 2: Analytical methods & equipment

The analytical methods are separated into field measurements and laboratory techniques, then further subdivided into soil, gas and water analyses. A brief outline of the technique is given, together with a source giving the method in full. References to the HACH spectrophotometer method numbers, are consistent with those given in the DR2000 Manual published by HACH Co.(1991). These descriptions are followed by two diagrams. The first shows the mangrove soil corer built for this project, and the second details the field water sampling technique.

FIELD MEASUREMENTS

Soil samples

Colour

Measured immediately after coring in direct near overhead sunlight using a revised Munsell® Soil Colour Chart (1994 Edition), with additional tropical pages.
[Macbeth Division, Kollmorgan Instruments Corporation, 405 Little Britain Road, New Windsor, NY 12553, USA.]

Field pH

Measured using an ORION 290A meter connected to a ROSS 81-55 glass combination electrode. The electrode was inserted into the soil core whilst still in the corer to minimise changes resulting from oxidation of the sample.
[Orion Research Inc. 529 Main Street, Boston, MA, USA.]

Field redox potential

Measured using an ORION 290A meter connected to a ROSS 97-78 direct reading glass combination electrode with a ceramic frit junction. Readings were corrected for temperature and pH using the standard corrections published in the ORION electrode instruction manual and Rowell (1994) respectively. The electrode was inserted into the soil core whilst still in the corer to minimise changes resulting from oxidation of the sample.

Semi-quantitative measurement of soil nitrate

Merck NO_3-N Merckoquant® 10020/10050 Semi-quantitative nitrate test strips were used to determine soil nitrate and nitrite levels in the mangrove soils of the Burnt 1992 fieldsite. Range 0 - 500 mgl^{-1} NO_3-N, in 5 100 mgl^{-1} steps.
[E.Merck, Postfach 4119, 6100 Darmstadt, Germany]

Inorganic nitrogen soil extracts

Extracts for the determination of soil nitrate-N and ammonium-N were taken from samples immediately after collection. To 30g fresh weight of soil, 50ml of 1M potassium chloride was added and the mixture shaken by hand for an hour. This solution was filtered and stabilised with the addition of 1M hydrochloric acid and mercuric chloride. Upon return to the UK these samples were analysed by flow injection, with the level of ammonium-N measured by reaction with a sodium dihydrogen phosphate indicator solution, and nitrate-N by reaction with sulphanilamide and 1-naphtyl-ethyleneamide.

Flow Injection facilities were generously provided by the Department of Geography, University of Bristol.

Gas samples

Nitrous oxide flux

Measurements of the rate of nitrous oxide gas evolved from the soil surface was made using cover tins, after the method of Hutchinson & Mosier (1981). These were placed over areas of soil, previously cleared of litter. The soil cover encloses a fixed volume of gas and samples are withdrawn from the cover 45 minutes later using a hypodermic syringe inserted into a rubber Subaseal™ fitted into the top of the corer. Two 5ml samples of the gases were taken, and injected into evacuated 7ml test tubes, creating a positive pressure difference to minimise the risk of contamination during transportation. Replicate samples were taken, as well as measurements of background levels of the nitrous oxide in the air at the time of measurement. The level of nitrous oxide in each vial was determined by gas chromatography, and the resulting flux of nitrous oxide measured as ng N_2O-N m^{-2} s^{-1}, calculated using the formula:

$$\text{Nitrous oxide flux} = \frac{\text{sample } N_2O \text{ concentration (ppm)} \times 1.16 \times 10^6 \times \text{Cover tin volume } (m^3)}{\text{Cover tin area } (m^2) \times \text{time (s)}}$$

The equipment for this analysis and the facilities for carrying out the gas chromatography were generously provided by the Scottish Agricultural College.

Water samples

Field pH
As for soil pH.

Field redox potential
As for soil redox.

Conductivity
Measured in 1992 using an EIL Model MC1 MkV portable conductivity measuring set, using a sample cell of k=1.0, with manual temperature compensation. Values are the results of two sets of readings at different temperatures, following the procedure outlined in the instruction manual. Measurements in 1994 were made using a Mettler-Toledo Corning Checkmate M90 digital stick conductivity meter with automatic temperature compensation.
[Electronic Instruments Ltd, Chertsey, Surrey, England.]
[Mettler-Toledo Ltd. 64 Boston Road, Beaumont Leys, Leicester, LE4 1AW, England]

Total dissolved solids (TDS)
Total dissolved solids measurements were made using a Corning Checkmate M90 digital stick meter.

Dissolved oxygen content
Measured in 1992 using a Hanna HI 8543 portable dissolved oxygen meter. Measured in 1994 using a Corning Checkmate M90 digital stick meter.
[Hanna Instruments Inc. 584 Industrial Park East Drive, Woonsocket, RI, USA.]

LABORATORY METHODS

Soil samples

Fraction greater than 2 mm/less than 2 mm e.p.s.
Samples were air dried at 40°C ground using a pestle and mortar to break up large lumps of clay then passed through a British Standard 2 mm mesh stainless steel sieve. Values are expressed as a percentage of the total sample weight.

Moisture content/dry matter
Soil moisture content was determined following the method outlined in Allen (1989). The percent moisture was found using the formula:

$$\text{Moisture (\%)} = \frac{\text{loss in weight on oven drying at } 105^{\circ}\text{C (g)} \times 100}{\text{initial sample weight (g)}}$$

The percent dry matter was obtained from the formula:

$$\text{Dry Matter (\%)} = \frac{\text{oven dry weight at } 105^{\circ}\text{C (g)} \times 100}{\text{initial sample weight (g)}}$$

% Weight loss on Ignition

Soil weight loss on ignition was determined following the method outlined in Allen (1989). 1 g of oven-dried material was placed in a muffle furnace and the temperature brought up to 550°C. It was maintained at this temperature for 2 hours, then allowed to cool and the samples removed to a desiccator before re-weighing. The percentage loss on ignition was calculated from the formula:

$$\text{Loss on Ignition (\%)} = \frac{\text{weight loss after ignition at } 550^{\circ}\text{C (g)} \times 100}{\text{oven dry weight (g)}}$$

% Organic carbon

Soil organic carbon content was determined using a modification of the Walkley-Black wet oxidation method, (Black *et al.* 1965). Potassium dichromate and concentrated sulphuric acid were added to 0.2 g of air dried soil. The dichromate ion is reduced by organic matter present in the soil, this reaction occurs using heat provided by the reaction of the concentrated sulphuric acid with the water in the dichromate solution. After leaving the resultant solution to cool, it was diluted with distilled water, centrifuged for 10 minutes at 2000 rpm and the supernatant analysed with a colorimeter at 600 nm.

Extractable cations

5 g of air dried soil was extracted with 125 ml of 1M ammonium acetate, buffered to pH 7. The solution was filtered and the filtrate used for analysis of manganese, sodium, potassium, calcium and magnesium levels, using procedures detailed in Whiteside (1979).

Manganese

A sample of the filtrate was used directly for manganese AAS (atomic absorption spectrophotometer) analysis. The AAS settings were as follows:

	Wavelength	Bandpass	Lamp Current	Fuel
Manganese	279.5 nm	0.2 nm	9 mA	air-acetylene

Sodium and potassium

A sample of the filtrate was used directly for sodium and potassium flame emission analysis using a gas flame photometer, settings as detailed below:

	Wavelength	Fuel
Sodium	589.5 nm	natural gas
Potassium	766.5.5 nm	natural gas

Calcium and magnesium

A 20ml sample of the extract was diluted to 100 ml, with the addition of de-ionised water and an acidified lanthanum chloride solution (0.4% La^{3+}) to suppress interferences from aluminium, silicon and phosphorus. This solution was then used for AAS analysis of calcium and magnesium levels, with the settings below:

	Wavelength	Bandpass	Lamp Current	Fuel
Calcium	422.7 nm	0.4 nm	8 mA	air-acetylene
Magnesium	285.2 nm	0.4 nm	4 mA	air-acetylene

Available phosphorus

Sodium molybdate, bicarbonate extract method (HACH Method No. 8182)

A bicarbonate soil extract is combined with sodium molybdate, an indicator which yields a blue colour when it forms a complex with the phosphate ions. Ascorbic acid is added which reduces the phosphate complex to form a heteropoly blue species. The intensity of the blue colour can be used as a measure of the available phosphorus in the soil, determined colorimetrically using the DR/2000 spectrophotometer set at 890 nm.

[HACH Co., PO Box 389, Loveland, CO 80539, USA]

Total iron

1,10 Phenanthroline method (HACH Method No. 8145)

Iron present in 0.1N Hydrochloric Acid soil extract is reacted with a reducing agent, to convert all forms of iron (including precipitated and suspended iron) into the ferrous state. The 1,10 phenanthroline produces an orange colour with ferrous iron. The amount of total iron in the sample is proportional to the intensity of this orange colour, which is measured colorimetrically using the DR/2000 spectrophotometer set at 510 nm.

Soil sulphate-sulphur

Calcium phosphate method (Modified from HACH Method No. 8188)

Soluble sulphate, plus a fraction of absorbed sulphate is extracted from a 1:100 soil:water mix, with a 500 mgl^{-1} P solution of calcium phosphate. Phosphate ions displace the absorbed sulphate and calcium ions depress the extraction of organic matter, eliminating contamination from extractable organic sulphur. Activated, decolourizing charcoal is slurried with the extracting solution before filtration to give a clear colourless extract. Sulphate ions in the sample are reacted with barium to form insoluble barium turbidity. The amount of turbidity formed is proportional to the sulphate concentration, measured colorimetrically using the DR/2000 spectrophotometer set at 450 nm.

Water samples

Chloride

Mercuric thiocyanate method (HACH Method No. 8113)

Chloride ions in a 25 ml water sample react with mercuric thiocyanate to form mercuric chloride and liberate thiocyanate ion. Thiocyanate ions react with ferric ions to form an orange coloured ferric thiocyanate complex. The amount of this complex is proportional to the chloride concentration, measured colorimetrically using the DR/2000 spectrophotometer set at 455 nm.

Nitrate-nitrogen

Cadmium reduction method (HACH Method No. 8039)

Cadmium reduces nitrate-N present in the sample to nitrite-N. This reacts in an acidic medium with sulphanilic acid to yield a diazonium salt. This salt couples with gentisic acid to form an amber coloured product. The intensity of the colour is proportional to the nitrate-N concentration, measured colorimetrically using the DR/2000 spectrophotometer set at 400 nm.

Reactive phosphorous (orthophosphate)

Molybdovanadate method (HACH Method No. 8114)

Orthophosphate in a 25 ml water sample reacts with molybdate in an acid medium to produce a phosphomolybdate complex. In the presence of vanadium, yellow vanadomolybdophosphoric acid is formed. The intensity of the yellow colour is proportional to the phosphate concentration, measured colorimetrically using the DR/2000 spectrophotometer set at 430 nm.

Sulphate

Barium chloride method (HACH Method No. 8051)

Sulphate ions in a 25 ml water sample react with an added barium salt to form white insoluble barium turbidity. The amount of turbidity formed is proportional to the sulphate concentration, measured colorimetrically using the DR/2000 spectrophotometer set at 450 nm.

Suspended solids (nonfilterable residue)

Photometric method (HACH Method No. 8006)

The amount of suspended material in a water sample previously agitated for 2 minutes using a domestic food processor is measured directly using the DR/2000 spectrophotometer set at 810 nm.

Turbidity

Absorptometric method (HACH Method No. 8237)

The turbidity of the water sample is estimated by measuring an optical property of the water resulting from the scattering and absorbing of light by the particulate matter present. The amount of turbidity registered is dependent on variables such as the size, shape and refractive properties of the particles. The spectrophotometer, set at 450 nm, is pre-calibrated using formazin turbidity standards, yielding readings in formazin turbidity units (FTU). FTU are equivalent to the standard NTU (nephelometric turbidity units) when measured on a nephelometer.

SAMPLING EQUIPMENT

Overleaf, are diagrams of the soil corer and water sampling device used in the field.

Figure 12.10 The mangrove soil corer

The main body of the corer is a stainless steel tube, approx 1200 mm long, internal diameter 59 mm, external diameter 63 mm.

20 holes, each 20 mm diameter are drilled 25 mm apart in a double spiral along its length. The spacing of these holes is such that when the sleeve is pushed up, no holes are exposed, if the sleeve is pulled down, holes can be exposed, one pair at a time.

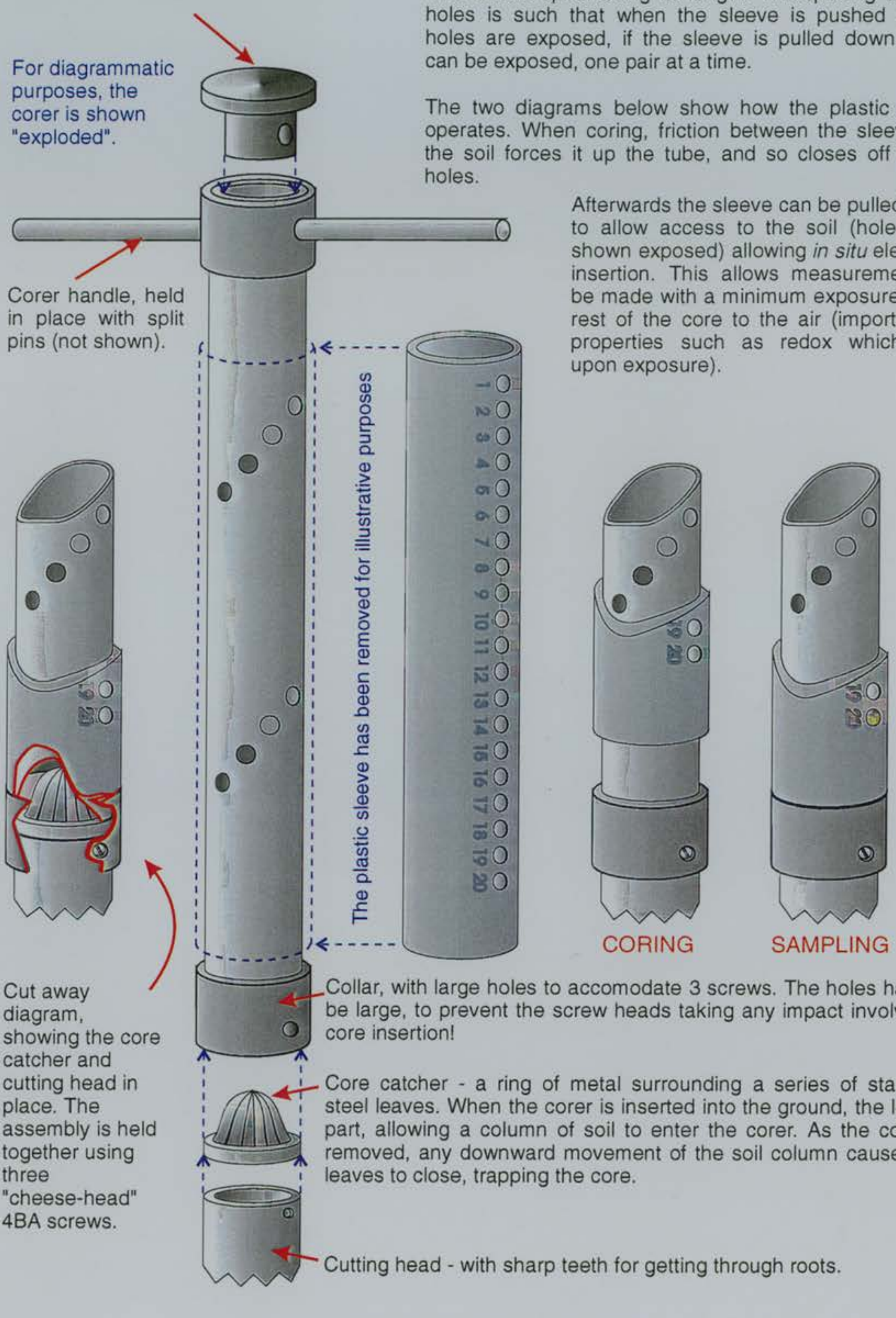
The two diagrams below show how the plastic sleeve operates. When coring, friction between the sleeve and the soil forces it up the tube, and so closes off all the holes.

Afterwards the sleeve can be pulled down to allow access to the soil (hole 20 is shown exposed) allowing *in situ* electrode insertion. This allows measurements to be made with a minimum exposure of the rest of the core to the air (important for properties such as redox which alter upon exposure).

Aluminium driving cap, held in place by the solid corer handle. It can be hit with a hammer to drive the corer into the ground.

For diagrammatic purposes, the corer is shown "exploded".

Corer handle, held in place with split pins (not shown).



Cut away diagram, showing the core catcher and cutting head in place. The assembly is held together using three "cheese-head" 4BA screws.

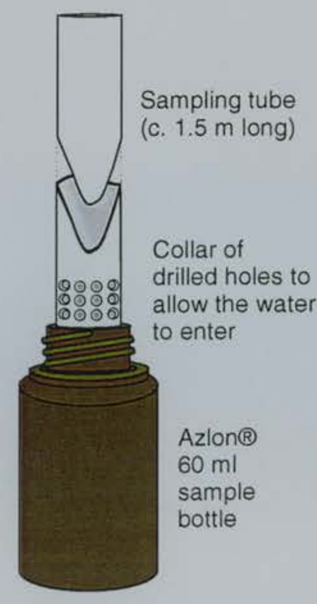
Collar, with large holes to accomodate 3 screws. The holes have to be large, to prevent the screw heads taking any impact involved in core insertion!

Core catcher - a ring of metal surrounding a series of stainless steel leaves. When the corer is inserted into the ground, the leaves part, allowing a column of soil to enter the corer. As the corer is removed, any downward movement of the soil column causes the leaves to close, trapping the core.

Cutting head - with sharp teeth for getting through roots.

This corer is heavily modified from a design published in Boto (1984).

Figure 12.11 Water sampling methods

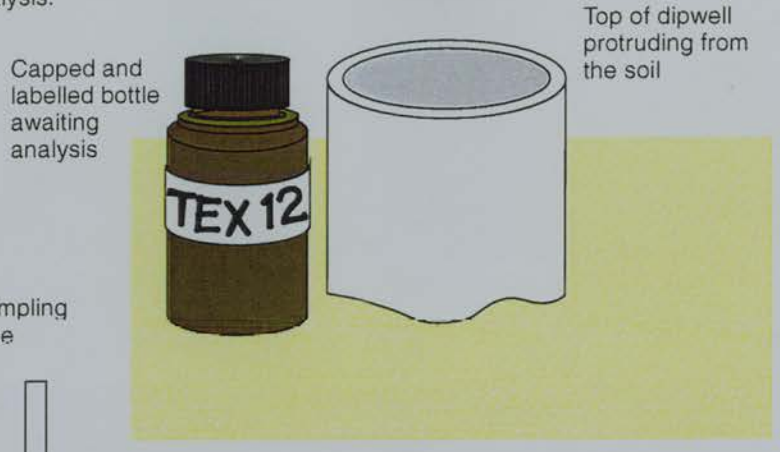


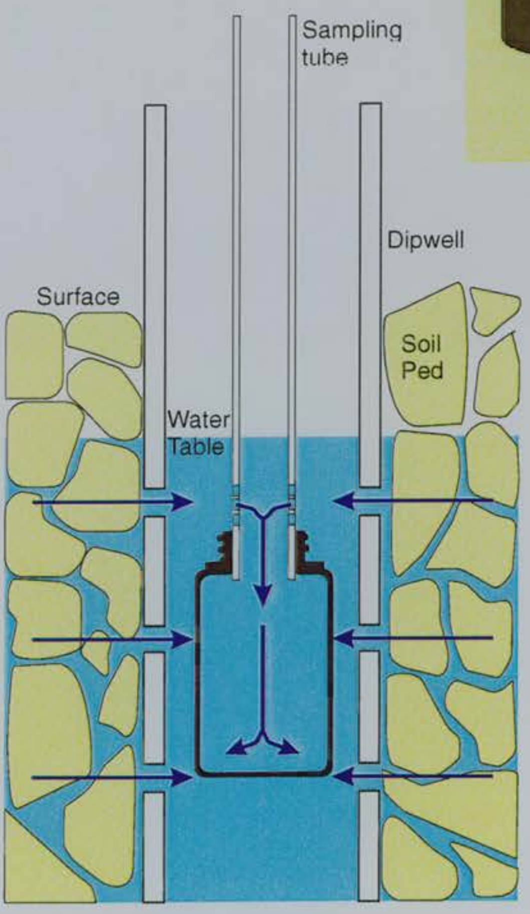
Groundwater samples were taken from dipwells, which were partially inserted into the mangrove soil at each sample site.

The dipwells were made from c.75 cm lengths of PVC pipe, with small (3 mm diameter) holes drilled along their length. Approximately 7 cm of each pipe was left protruding from the ground surface in an attempt to prevent crabs from falling down into the water.

Samples were collected several days after dipwell insertion, using Azlon® "Amber" 60 ml sample bottles, placed on the end of a narrow sample collection tube.

These bottles were selected because they provided a very good seal (important during transportation) and their dark walls prevent light from entering, minimising biological alteration before analysis.





CROSS-SECTIONAL VIEW

This shows a dipwell at the time of sampling, with the sample bottle and tube already inserted.

Some time after the initial insertion of the dipwell, the water level inside returns to equilibrium with that of the surrounding groundwater, by perculating through the holes. Sediments disturbed during the insertion process soon settle out, leaving the water clear for sampling.

A sample bottle is uncapped and fitted onto the sampling tube. This assembly is then lowered carefully into the dipwell until the ring of holes around the collar of the sampling tube are below the water surface, allowing water to flow in. When the sample bottle is full, the tube is pulled up and the bottle removed and capped.

Appendix 3: Statistical methods

The Mann-Whitney U test

This is a test which searches for possible differences between two datasets. It does not require these datasets to be normally distributed. It begins by combining the two datasets (x and y) and awarding each point an overall ranking, from lowest (rank=1) to highest (rank=$n_x + n_y$). Identical values are each given the arithmetic mean of the ranks they span. The datasets are then separated and the sum of rankings is calculated for each sample: $\sum r_x$ and $\sum r_y$. A test statistic (U) is then calculated for each sample set from a combination of these ranking totals and the number of samples:

$$U_x = n_x n_y + \frac{n_x(n_x + 1)}{2} - \sum r_x$$

$$U_y = n_x n_y + \frac{n_y(n_y + 1)}{2} - \sum r_y$$

Critical values of U for a given level of significance can then be determined from tables. The null hypothesis is rejected if the calculated value of U is less than or equal to the critical value at the chosen significance level.

Three alternative hypotheses can be tested for:

1. $X \neq Y$ (sample x and sample y come from populations with different mean ranks, but the test doesn't specify which of the mean ranks is believed to be the larger). This non-directional test is two-tailed. The test uses the smaller U value of the two (U_x and U_y).
2. $X > Y$ (sample x and sample y come from populations which have different mean ranks, and that the mean rank of population X is greater than the mean rank of population Y). A one-tailed test, it uses the U value found for sample x, (U_x).
3. $X < Y$ (the opposite of the above). It uses the U value for sample y, (U_y).

As discussed in chapter five, the two-tailed test is used in this research, hypothesis one above.

Based on Ebdon (1985).

One-way analysis of variance (ANOVA)

This test, also known as the F-distribution, can be used to decide whether two samples were drawn from the same population. The F statistic is calculated from two samples (datasets) of size n_1 and n_2 by comparing the estimates of the population variance from each sample:

$$F_{n_{1-1},\, n_{2-1}} = \frac{\text{estimate of the population variance based on sample 1}}{\text{estimate of the population variance based on sample 2}}$$

The population variance (σ^2) is calculated using the standard formula:

$$\sigma^2 = \frac{\sum X^2 - \frac{\sum X^2}{N}}{N-1}$$

where

X is an individual member of the population
N is the number of individuals in the population.

The "estimates" of the population variance are obtained by substituting the n_1 and n_2 sample members (x) from the two sample datasets. The calculated F-value is then compared with critical values published in tables, for a value of F with $(n_1\text{-}1)$ and $(n_2\text{-}1)$ degrees of freedom.

This test has three assumptions:

1. The two populations are drawn from populations with the same variance.

2. The two samples are drawn at random.
3. The population from which the samples are drawn are normally distributed.

Significantly large F values indicates that at least one of the above assumptions does not hold. If we can be sure that the sample population is normally distributed and that the samples were selected randomly, then we can reject the first assumption and conclude that the two samples were drawn from populations with different variances, i.e. the two samples are drawn from different populations.

Similar to the Man Whitney-U test, one- and two-tailed tests can be carried out, depending whether *a priori* assumptions are made about which sample is likely to show the larger variance. The validity of one-tailed tests has been questioned, and two-tailed tests are used throughout this work. To calculate the F-statistic for a two-tailed test there are two possible ways of arranging the calculation:

$$F\ n_{1\text{-}1},\ n_{2\text{-}1} = \frac{\text{estimate of the population variance based on sample 1}}{\text{estimate of the population variance based on sample 2}}$$

$$F\ n_{2\text{-}1},\ n_{2\text{-}1} = \frac{\text{estimate of the population variance based on sample 2}}{\text{estimate of the population variance based on sample 1}}$$

Both methods are used and the larger value is chosen as the F-statistic.

After Meddis (1975).

Normality testing

The question of method

To investigate whether different statistical methods may yield conflicting decisions concerning the data's distribution function, three common tests of normality are compared below, using data from the surface layer of the 1992 Burnt Site. The tests considered are the Kolmogorov-Smirnov test (using the less rigorous Lilliefors version, which does not assume a particular value for the sample mean or standard deviation[2], (SYSTAT Inc., 1993)) the Anderson-Darling test and the Ryan-Joiner test. The latter is very similar to the more common Shapiro-Wilks test (MINITAB Inc., 1993), often used for small sample sizes, (SAS Institute Inc., 1982).

For each of the three tests, the probability that the measured variable's distribution significantly differs from the theoretical normal (gaussian) distribution was tested, using a 5% level of significance. This was felt to be a suitably sensitive threshold for rejection. The full results of the normality testing are given in appendix three. Each measured variable's distribution has been classified using one of three terms defined below:

Test's p-value > 0.100 Retain the null hypothesis[3] - data distribution is labelled as NORMAL.
$0.050 \leq$ p-value ≥ 0.100 Validity of null hypothesis is questioned, data labelled as NEAR NORMAL
$0.000 \leq$ p-value ≥ 0.049 Reject the null hypothesis at $\alpha = 0.05$ - data NOT NORMALLY distributed (for clarity of comparison, the "NOT NORMAL" label has been omitted from the table below).

In essence, this classification is a normality test at the 5% level of significance, considering whether to retain the null hypothesis that "the distribution function of the measured variable does *not* differ

[2] Very rigorous tests of normality compare the distribution against a normal distribution with a mean of zero and a standard deviation of one. For the data given here to pass such a test, it is likely it would have to first undergo a statistical standardisation procedure, such as subtracting the mean from each individual value, then dividing the result by the standard deviation of the population.

[3] The more cautious term "retain" is used here in place of the more common "accept" when referring to the perceived validity of the null hypothesis. This accords with the recommendations of Williams (1986, p669) who notes that a failure to reject a null hypothesis is not in itself proof of its validity, merely that "the data do not provide sufficient evidence that the null is faulty."

significantly from a normal distribution". Thus if the test yields a high p-value and a distribution is labelled as "NORMAL" we can have 95% confidence in this classification. The class "NEAR NORMAL" refers to a slightly less convincing retention of the null hypothesis (where $\alpha = 0.10$, yielding 90% confidence). The introduction of this intermediate classification reflects the probabilistic, rather than absolute nature of the decision process employed in these tests.

Table 12.8 A comparison of three different tests of normality, applied to data from the 1992 Burnt site

Measured property	Zone	Kolmogorov-Smirnov	Anderson-Darling	Ryan-Joiner
x	Cleared	0.143 - NORMAL	0.029	0.0819 - NEAR NORMAL
	Forest	0.150 - NORMAL	0.108 - NORMAL	0.0987 - NEAR NORMAL
	Transition	1.000 - NORMAL	0.568 - NORMAL	>0.1000 - NORMAL
y	Cleared	0.048	0.019	0.0500 - NEAR NORMAL
	Forest	0.442 - NORMAL	0.270 - NORMAL	>0.1000 - NORMAL
	Transition	0.358 - NORMAL	0.192 - NORMAL	>0.1000 - NORMAL
z	Cleared	0.175 - NORMAL	0.056 - NEAR NORMAL	0.0440
	Forest	0.155 - NORMAL	0.363 - NORMAL	>0.1000 - NORMAL
	Transition	0.179 - NORMAL	0.175 - NORMAL	>0.1000 - NORMAL
Layer Thickness	Cleared	0.165 - NORMAL	0.277 - NORMAL	>0.1000 - NORMAL
	Forest	0.173 - NORMAL	0.325 - NORMAL	>0.1000 - NORMAL
	Transition	0.930 - NORMAL	0.791 - NORMAL	>0.1000 - NORMAL
Mean Layer Depth	Cleared	0.165 - NORMAL	0.277 - NORMAL	>0.1000 - NORMAL
	Forest	0.173 - NORMAL	0.325 - NORMAL	>0.1000 - NORMAL
	Transition	0.930 - NORMAL	0.791 - NORMAL	>0.1000 - NORMAL
Bulk Density	Cleared	0.002	0.000	0.0359
	Forest	0.920 - NORMAL	0.531 - NORMAL	>0.1000 - NORMAL
	Transition	0.358 - NORMAL	0.438 - NORMAL	>0.1000 - NORMAL
% Moisture w/w	Cleared	0.042	0.004	0.0474
	Forest	0.343 - NORMAL	0.368 - NORMAL	>0.1000 - NORMAL
	Transition	1.000 - NORMAL	0.652 - NORMAL	>0.1000 - NORMAL
% Dry Matter w/w	Cleared	0.042	0.004	0.0474
	Forest	0.343 - NORMAL	0.368 - NORMAL	>0.1000 - NORMAL
	Transition	1.000 - NORMAL	0.652 - NORMAL	>0.1000 - NORMAL
% > 2 mm	Cleared	0.002	0.000	0.0359
	Forest	0.000	0.000	0.0453
	Transition	0.818 - NORMAL	0.442 - NORMAL	>0.1000 - NORMAL
% < 2 mm	Cleared	0.002	0.000	0.0359
	Forest	0.002	0.000	0.0453
	Transition	0.818 - NORMAL	0.442 - NORMAL	>0.1000 - NORMAL
% Wt. Loss on Ignition	Cleared	0.155 - NORMAL	0.407 - NORMAL	>0.1000 - NORMAL
	Forest	0.078 - NEAR NORMAL	0.065 - NEAR NORMAL	0.0466
	Transition	0.060 - NORMAL	0.011	0.0458
% Organic C	Cleared	0.266 - NORMAL	0.407 - NORMAL	>0.1000 - NORMAL
	Forest	0.095 - NEAR NORMAL	0.017	0.0438
	Transition	1.000 - NORMAL	0.695 - NORMAL	>0.1000 - NORMAL
Field Soil pH	Cleared	0.172 - NORMAL	0.515 - NORMAL	>0.1000 - NORMAL
	Forest	0.004	0.001	0.0473
	Transition	0.106 - NORMAL	0.183 - NORMAL	>0.1000 - NORMAL
Field Water pH	Cleared	0.215 - NORMAL	0.205 - NORMAL	>0.1000 - NORMAL
	Forest	0.215 - NORMAL	0.103 - NORMAL	>0.1000 - NORMAL
	Transition	0.098 - NEAR NORMAL	0.107 - NORMAL	>0.1000 - NORMAL
Redox potential	Cleared	0.000	0.000	0.0305
	Forest	0.001	0.000	0.0407
	Transition	0.217 - NORMAL	0.246 - NORMAL	>0.1000 - NORMAL
Water Conductivity	Cleared	0.047	0.017	>0.1000 - NORMAL
	Forest	0.004	0.000	0.0378
	Transition	0.084 - NEAR NORMAL	0.173 - NORMAL	>0.1000 - NORMAL
Dissolved Oxygen	Cleared	0.295 - NORMAL	0.239 - NORMAL	>0.1000 - NORMAL
	Forest	0.011	0.002	>0.1000 - NORMAL
	Transition	0.001	0.004	>0.1000 - NORMAL
Exch. Ca	Cleared	0.010	0.022	0.0751 - NEAR NORMAL
	Forest	0.002	0.000	0.0401
	Transition	0.001	0.000	0.0392
Exch. Mg	Cleared	0.306 - NORMAL	0.042	0.0457
	Forest	0.949 - NORMAL	0.896 - NORMAL	>0.1000 - NORMAL
	Transition	0.822 - NORMAL	0.627 - NORMAL	>0.1000 - NORMAL
Exch. K	Cleared	0.069 - NEAR NORMAL	0.376 - NORMAL	>0.1000 - NORMAL
	Forest	0.068 - NEAR NORMAL	0.178 - NORMAL	>0.1000 - NORMAL
	Transition	0.426 - NORMAL	0.559 - NORMAL	>0.1000 - NORMAL
Exch. Na	Cleared	0.578 - NORMAL	0.440 - NORMAL	>0.1000 - NORMAL
	Forest	0.116 - NORMAL	0.225 - NORMAL	>0.1000 - NORMAL
	Transition	0.283 - NORMAL	0.418 - NORMAL	>0.1000 - NORMAL
Exch. Mn	Cleared	0.014	0.006	0.0489
	Forest	0.000	0.000	0.0489
	Transition	0.220 - NORMAL	0.122 - NORMAL	0.0955 - NEAR NORMAL

continued overleaf

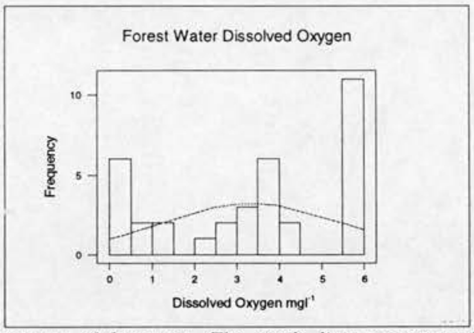
Measured property	Zone	Kolmogorov-Smirnov	Anderson-Darling	Ryan-Joiner
Extr P	Cleared	0.355 - NORMAL	0.332 - NORMAL	>0.1000 - NORMAL
	Forest	0.526 - NORMAL	0.180 - NORMAL	0.0962 - NEAR NORMAL
	Transition	0.496 - NORMAL	0.502 - NORMAL	>0.1000 - NORMAL
Soil NH_4-N	Cleared	0.144 - NORMAL	0.015	0.0484
	Forest	0.266 - NORMAL	0.241 - NORMAL	>0.1000 - NORMAL
	Transition	0.035	0.018	0.0489

Sample sizes: Forest and Cleared, n=35; Transition Zone, n=8.

Interpretation: which test to use?

The testing reveals that there is generally remarkably little difference between the conclusions of the three tests. Many apparent minor differences in classification (for example, whether the Transition Zone exchangeable manganese values are normally, or near normally distributed) are the result of only very small differences in the reported probability values, which happen to lie either side of a classification boundary. This is particularly true for differences between the Kolmogorov-Smirnov and Anderson-Darling tests, the Ryan-Joiner test shows a slight tendency to retain spuriously the null hypothesis, claiming the data are normally distributed when it actually is not. An example of such a case are the forest dissolved oxygen measurements, whose distribution is shown in Figure 12.12 below:

Figure 12.12 1992 Burnt site layer 1 forest zone dissolved oxygen frequency histogram



The bars in the histogram are measures of frequency. The single line represents the theoretical smoothed frequency distribution pattern of a normally distributed variable, with the same mean and standard deviation as the forest dissolved oxygen data. If this variable was normally distributed, the height of the bars would closely match the smoothed line.

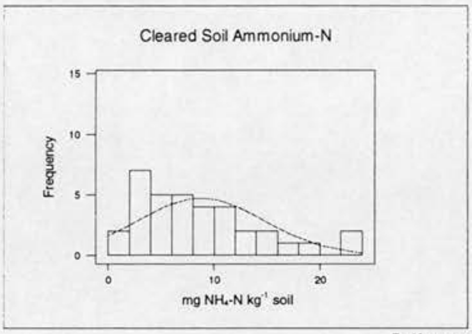
The Kolmogorov-Smirnov and Anderson-Darling tests yield a significant result, concluding that the Forest dissolved oxygen values are not normally distributed, with respective confidence levels of 98.9% and 99.8%. Conversely, the Ryan-Joiner test considers the data normally distributed, yielding a p-value greater than 0.100, suggesting that we should retain the null hypothesis of no difference, as its rejection could only be carried out with less than a 10% confidence limit of being correct.

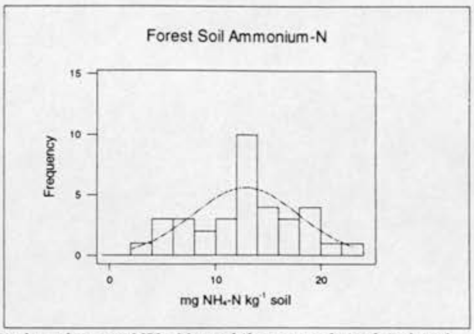
Further testing using mathematically generated data sets has shown that the Ryan-Joiner test does not differentiate clearly between binomial and normally distributed datasets. For this reason and the discrepancy noted above, it was not considered suitable for further use, reducing the choice of test to two: the Kolmogorov-Smirnov and the Anderson-Darling tests. Although the Kolmogorov-Smirnov test is more widely employed in geographical literature, for this work the Anderson-Darling test will be used, as it seems to be slightly more critical, rejecting the assumption of normality slightly more often than the other two tests. This means that the normality testing will err on the side of caution, perhaps erroneously rejecting an assumption of normality occasionally. This would mean that spatial differences in the values of such a variable would then be compared using a non-parametric test, rather than a more statistically powerful parametric method. This loss of test power is thought to be more acceptable than wrongly using a parametric test when the data actually fail to satisfy its underlying assumptions of normality. For these reasons, in this piece of research all the normality tests are carried out using the Anderson-Darling test.

Interzonal differences in the distributions

Many of the measured variables show different distribution patterns depending upon where the values are measured (i.e. in the cleared, forest or transition zone). One example of such variation is seen in the 1992 Burnt Site Layer 1 values of soil ammonium-nitrogen, which are normally distributed in the forest, but not in the cleared or transition zone. Figure 12.13a and Figure 12.13b below show the frequency histograms for soil ammonium-nitrogen levels in the cleared and forest zones.

Figure 12.13a & 12.134b - 1992 Burnt site layer 1 soil ammonium-N frequency histograms





Soil ammonium-N levels are displayed in mg NH_4-N per kilogram of air dried soil.

The cleared soil values show two sources of deviation from the theoretical normal distribution: a distinct positive skew (measured at 1.22), plus the presence of a few exceptionally high ammonium-N values, giving the distribution a long tail. The forest values do seem to fit far more closely to the normal distribution, with a much lesser degree of skew (only 0.51) giving a relatively even distribution of values around the mean. The only notable deviation from the predicted curve, is the concentration of values around the mean, giving the distribution a marked peak. This peak suggests that the ammonium-N levels may have achieved an optimum or equilibrium level centred around the mean, with only a few values varying from this.

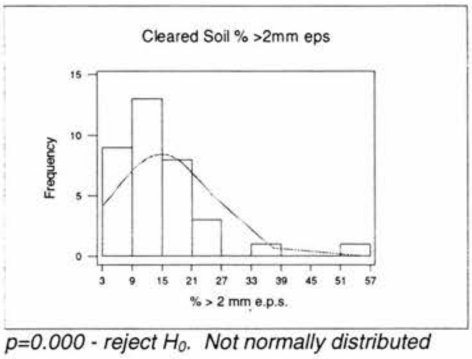
This difference in the distribution pattern in the two zones is not surprising, indeed it corroborates the hypothesis of significant difference between the cleared and forest zones. The ammonium-N values at a site reflect the balance between the production of ammonium by soil bacteria and its loss through further bacterial nitrification and plant uptake. In the forest zone, these processes should be operating in a relative equilibrium, resulting in a fairly constant value of soil ammonium, which could reasonably be expected to have an approximately normal distribution. In the disturbed, cleared zone, increased surface soil drainage favours nitrification of the ammonium, so production declines and the distribution shows a bias towards low soil ammonium levels, resulting in the positively skewed distribution shown.

Interpretation of the distribution of the transition zone values has to be made cautiously, as the small sample size means that the shape of the distribution may be strongly affected by one or two extreme values. In general, decisions about whether the data need to be transformed before parametric testing will be made using only the distribution of the two larger datasets, those from the forest and cleared zones.

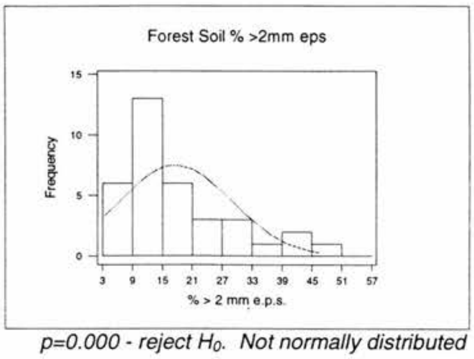
Applying transformations to some soil data

The success of transformations depends upon how similar the shapes of the forest and cleared data distributions are. This is most easily explained graphically. Figure 12.14 shows the frequency distributions of the percentage of soil greater than 2 mm equivalent particle size, for samples from the cleared area and the forest. These two distributions have a similar shape, both are positively skewed, reflecting a predominance of low sample values. Immediately below these histograms are the Anderson-Darling test results which show that neither of these distributions are normal. Superimposed upon these graphs are bell-shaped curves, which show the theoretical distribution of a normally distributed variable, with the same mean and standard deviation as the measured soil property. If the data are normally distributed, then the bars of the histograms should fit closely to the curve.

Figure 12.14 Untransformed 1992 Burnt site data, % soil w/w greater than 2 mm e.p.s.



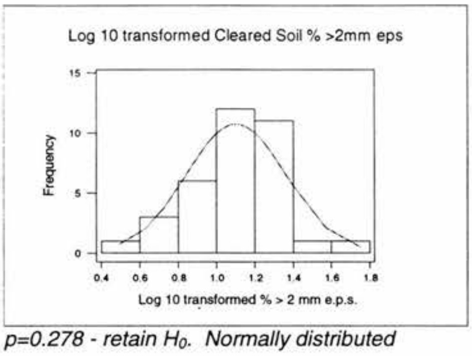
p=0.000 - reject H_0. Not normally distributed



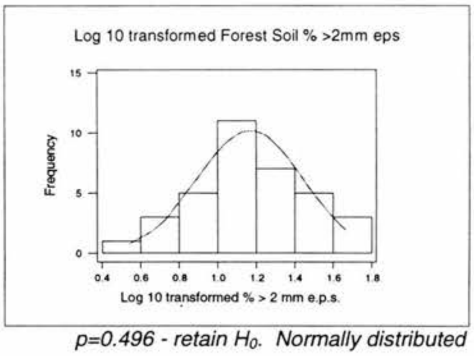
p=0.000 - reject H_0. Not normally distributed

A range of standard transformations were applied to these distributions and the resulting distribution retested for normality. Of these transformations, the log 10 transformation proved the most effective. Figure 12.15 below, shows the transformed frequency histograms, which show a more even distribution of values above and below the mean. The Anderson-Darling results show both the forest and cleared samples to be normally distributed.

Figure 12.15 Log 10 transformed 1992 Burnt site data, % soil (w/w) greater than 2 mm e.p.s.



p=0.278 - retain H_0. Normally distributed

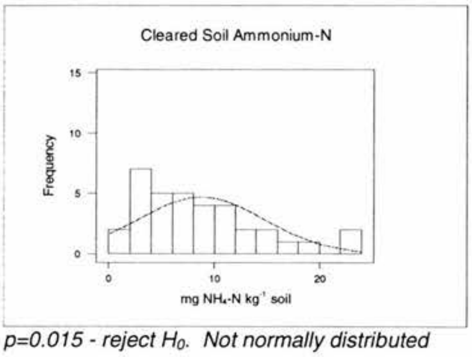


p=0.496 - retain H_0. Normally distributed

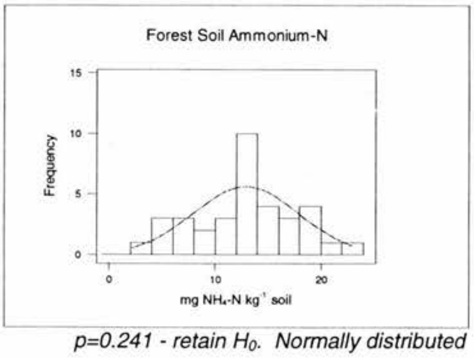
Thus this transformation has been successful - both samples are now normally distributed allowing a parametric test such as one-way analysis of variance to be applied to the log 10 transformed data.

An example of a situation where transforming data is less successful is given in Figure 12.16. This shows that the untransformed cleared soil values are not normally distributed, with a marked positive skew. However, the distribution of values from the forest is far more symmetrical and the Anderson-Darling test finds it to be normally distributed.

Figure 12.16 Untransformed 1992 Burnt site data, soil extract ammonium-N



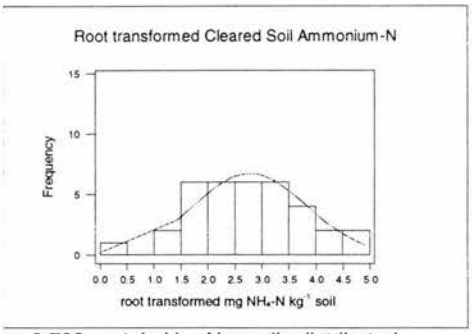
p=0.015 - reject H_0. Not normally distributed



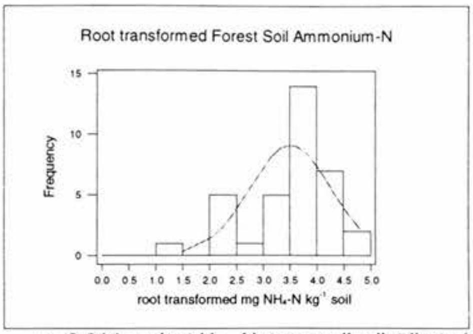
p=0.241 - retain H_0. Normally distributed

Again, a range of standard mathematical transformations were applied to the data. Figure 12.17 shows the result of a square root transformation. The transformed data from the cleared zone now appear normally distributed, having lost the earlier positive skew seen in Figure 12.16 above. However, the samples from the forest now show a negative skew, and the Anderson-Darling test rejects the null hypothesis of normality.

Figure 12.17 Square root transformed 1992 Burnt site data, soil extract ammonium-N



p=0.798 - retain H_0. Normally distributed



p=0.014 - reject H_0. Not normally distributed

In this case, with two datasets showing very differently shaped distributions, no transformation has been able to produce normally distributed datasets for both variables at once. Thus, these transformed soil ammonium-N datasets are not suitable for parametric testing, rendering the transformation process merely an added complication, with no benefit in the available testing power.

Because transformations are mathematical processes, which change the value of each sample, their use inevitably adds another "layer" of interpretation. Therefore, they should only be applied when there is an obvious benefit, such as allowing the use of a more powerful statistical test. Applying some standard transformations to abnormally distributed variables from the field data has shown that this process is only advantageous if the samples from the cleared and forest areas have very similarly shaped distributions. This is rarely the case and where it does apply, the data are unlikely to be different anyway. Therefore, transformations have not been used in the comparative tests in this work.

This decision not to transform the data, and the resulting loss in statistical power is not thought to be serious. Each dataset found above to be normally distributed and thus tested using a one-way analysis of variance technique in Chapter 6 was retested using the non-parametric Mann Whitney-U test. In every case, (a total of 36 comparisons), the same decision to reject or retain the null hypothesis was given by the two tests.

Ordination methods

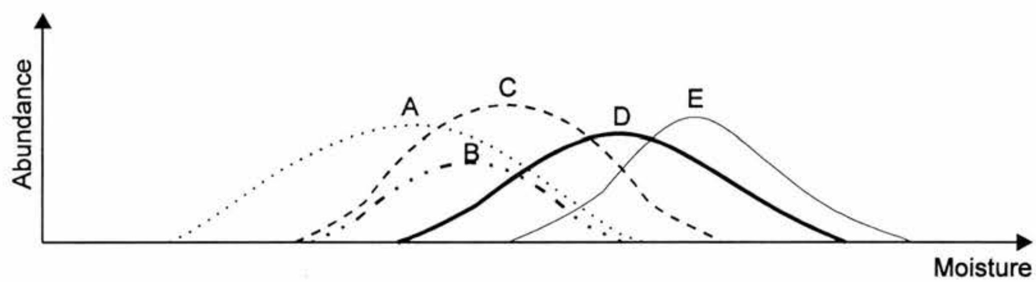
The following explanations of the two ordination techniques used in this work, detrended correspondence analysis (DCA) and canonical correspondence analysis (CCA), draw from the work of ter Braak (1987). The explanations use the terms sample "sites", "environmental variables" and plant "species" in the sense employed in traditional ecological work, and used in this work for the CCA application. The reader is reminded that the plant "species" used in this work comprised only three classes, cleared, forest and transition zone.

In ecological work, measurements at fieldsites often include recording the value of environmental variables and the composition of species at a range of locations. By calculating an average value of the environmental variable over the sites where a given plant species occurs, an estimate for the plant species optimum, or indicator value can be obtained. This is the principle behind the technique of CCA, which uses these values to discriminate between sample sites. If however, the environmental variable which determines the occurrence of a given species is unknown, or no measurements of the environmental variables were taken, then an alternative method must be used to reveal the "underlying environmental gradient" in a set of species data. This is the aim of DCA.

Detrended correspondence analysis (DCA)

DCA relies on the assumption that the plant species show bell-shaped response curves to environmental gradients. Plants will have a preferred range of values of this environmental property (e.g. moisture) and not grow in extreme conditions, whether high (flooded soils) or low (near-drought conditions). Different plant species have different response curves for the environmental variables. This is shown below in Figure 12.18, a hypothetical example based on one devised by ter Braak (1987).

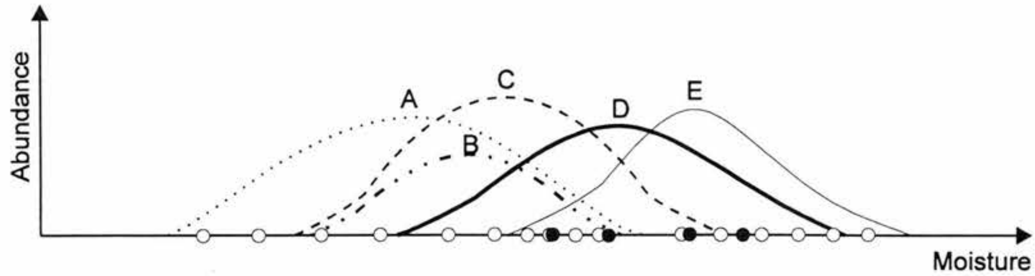
Figure 12.18 A hypothetical model of plant-environmental variable relations



This figure shows the response curves of five plant species (A-E) to the environmental property moisture. The x-axis indicates soil moisture content, with low values at the left hand side and high values to the right. Peaks in the response curves indicate conditions where (in the absence of competition) the given plant species will be most abundant. Modified from Figure 5.3 in ter Braak (1987).

Figure 12.19 below shows an example of a study where measurements of the environmental properties have been made at a range of sample sites. These sample sites are represented by dots and can be placed along the *x*-axis according to the moisture value obtained at the site. In order to show the effectiveness of later attempts to group the sites, sample sites containing one plant species (species D) are highlighted, by using black rather than open circles along the *x*-axis.

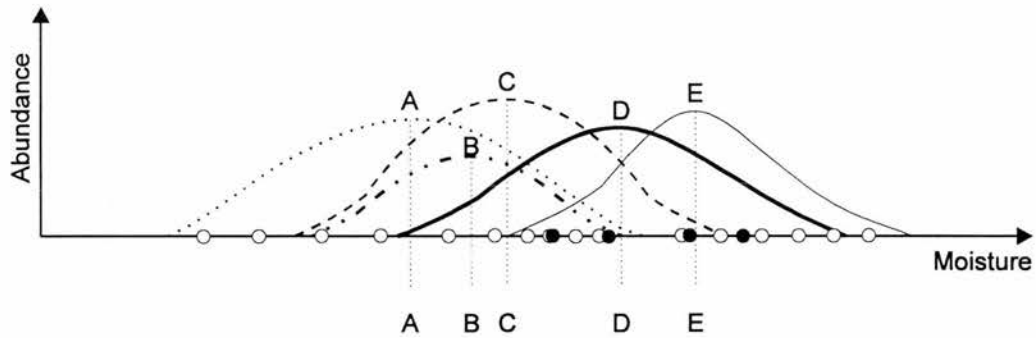
Figure 12.19 A hypothetical model showing sample sites



The dots represent the position of theoretical sample sites arranged by moisture-preference along the x-axis. They have been coloured to differentiate sites possessing plant species D (solid circles) from the others (open circles).

The first step in DCA is to obtain from these curves a measure of how well this environmental property explains the species data. The simplest way to do this is to obtain the average of the environmental property (moisture in this case) using only sites where the species is present. This average value is referred to as the species score. The position of the species scores along the environmental gradient (x-axis) is marked using dotted vertical lines in Figure 12.20 below.

Figure 12.20 A hypothetical model showing the position of calculated sample scores

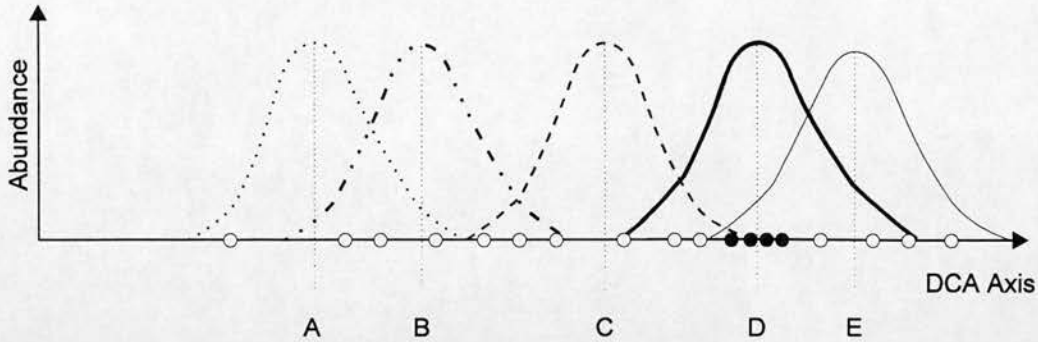


The vertical dotted lines show the species scores along the x-axis for each of the five plant species.

To measure how well moisture explains the species data, the dispersion (spread) of the species scores is calculated. If the resulting dispersion value is large, then this environmental property successfully separates the species curves and thus moisture explains the species data well. If the dispersion is small, then moisture is seen as a being less able to explain the species data.

The response of plant species data to different environmental variables can be compared in a similar way. In order to compare the explanatory power of different environmental variables, they must all be standardised. Commonly this is achieved by taking an individual value of an environmental property, subtracting the mean value of this environmental property over all the sites and dividing the result by the standard deviation. This yields a variable which has a mean of zero and a standard deviation of one. Comparing the dispersion of all the environmental properties measured at the sample sites may still not provide the best possible explanation for the species data. Detrended correspondence analysis attempts to construct a new theoretical variable which best explains the species data. This is achieved by choosing a theoretical value for each site that maximises the dispersion of the species scores, using a mathematical iterative process known as reciprocal, or two-way weighted averaging. This process is described fully in Hill (1973). The results of such a process are shown diagramatically in Figure 12.21 below.

Figure 12.21 A hypothetical model showing dispersion along a new, theoretical axis



The reciprocal averaging routine has created a new hypothetical variable, whose value increases along the x-axis. Sample sites can be plotted along this axis as for moisture. Their new position depends upon the calculated value for this variable at each sampling site. The colouring of the sample sites is as before. It shows that sites with the same plant cover are grouped together and those with different plant species are well-dispersed. Thus the DCA routine is able to explain the species data using this hypothetical variable.

This theoretical variable is used as the first DCA ordination axis in an x-y scatterplot. Sampling sites are plotted along this axis according to their site scores. A second DCA ordination axis can be calculated using the same routine, but stipulating that the resulting site scores along this second axis are uncorrelated to the site scores along the first DCA axis. This ensures that this second axes expresses new information about the species distribution. Further DCA axes can be produced if required, as long as each one is uncorrelated with the previous axes.

Detrended correspondence analysis, differs from the simpler correspondence analysis, in the method of generating the second and subsequent ordination axes. CA often suffers from a "fault", where the second axis, although statistically uncorrelated, still shows a systematic, often quadratic relationship with the first axis. This criticism has been termed the "arch effect". Hill & Gauch (1980) developed a technique to eliminate this, known as detrending. This method ensures that for any point along the first ordination axis, the mean value of the site scores on the subsequent axes is near to zero (and thus they are truly mathematically unrelated). This is achieved by dividing the first ordination axis up into segments and within each segment adjusting the site scores for points along later ordination axes, by subtracting their mean value.

The DCA ordination diagram, which will reveal the dispersion amongst the site and species data, is created by plotting the site scores and the species scores of one ordination axis against those of another.

Plant species are plotted in the ordination diagram using the species scores (akin to optimal values) for each of the two hypothetical variables, represented by the two DCA ordination axes. Species are therefore plotted as points. An individual sampling site is plotted on the ordination diagram at the point which represents the centroid of the points of species that occur there. Sample sites that lie close to the point of a plant species are thus likely to have a high abundance of that plant species (although this can be moderated by competition effects). Sites plotting close together are therefore likely to contain similar plant species. Because DCA is a good approximation to fitting a bell-shaped response curve (surface) to the species data, the points where the species occur in the ordination diagram is close to the optima of these surfaces. Thus the expected abundance (or probability of occurrence) decreases with distance away from the species point. The arrangement of the sample sites and species in this ordination space can thus be used to infer environmental gradients, which account for the dispersion in the data.

The maximised dispersion of the species scores along each DCA ordination axis (thus a measure of the axes' importance) is termed the eigenvalue. Because the species abundance data have been standardised, eigenvalues have a value between zero and one, where one indicates complete dispersion and thus total explanation of the species data. DCA ordination axis one has the highest eigenvalue, axis two the second highest, and so on. Eigenvalues over 0.5 are often used to denote an axis which achieves a good separation of the species data.

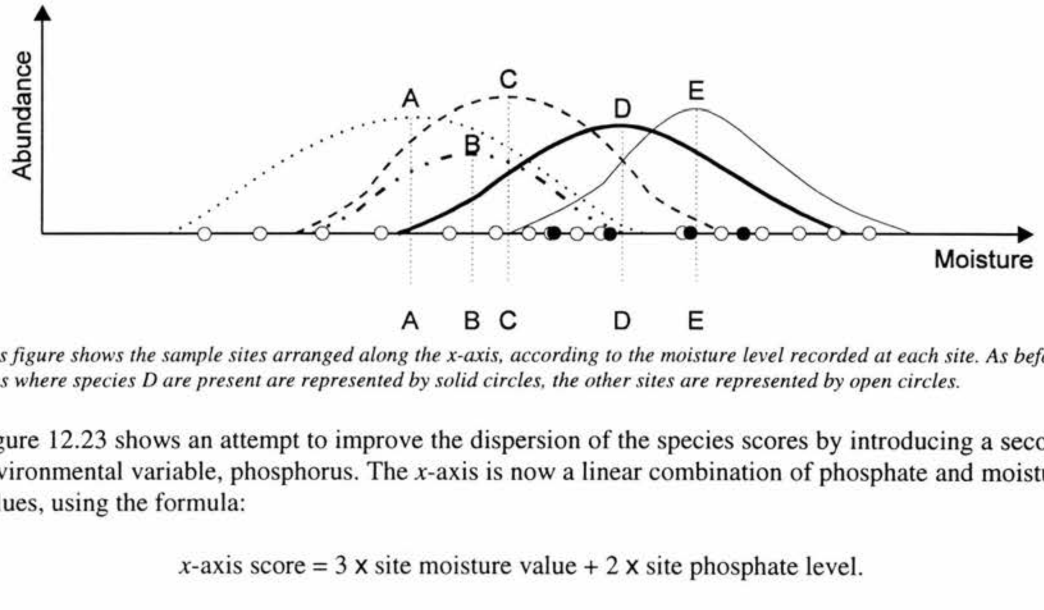
DCA can be applied to sites where there is only information regarding the species data. The routines will attempt to detect an assumed underlying environmental gradient in the species data by applying the reciprocal averaging process, starting with arbitrary initial values for the environmental values. Hill has shown mathematically that using the process of reciprocal averaging, the outcome of repeated iterations eventually converges upon a set of values for the sites and species that does not depend on the initial (arbitrary) values (Hill, 1973). These values yield a set of site and species scores which when arranged in ordination space, maximise the dispersion in the species dataset.

Canonical correlation analysis (CCA)

This method follows on from DCA and involves the integration of two statistical techniques: regression (measuring how one variable's value may be dependent at least in part upon those of another) and ordination (rearranging multivariate data which acts across multiple dimensions, so that it can be displayed across only one or two axes, whilst maintaining as much of the original information as possible). They combine to form a true multivariate direct gradient analysis technique: canonical (or constrained) ordination.

Similar to DCA, it attempts to "explain" variations in the "species" data using the environmental data, but differs in its method. CCA constructs it's new theoretical variables using linear *combinations* of all the environmental variables. The results are displayed graphically in an ordination diagram where the principal axes of such a diagram use the values of these theoretical variables. The process begins by standardising the environmental variable values to a mean of zero and a variance of one. Then, as before, species scores are calculated for each environmental variable and used as a measure of dispersion. To show how this method differs from DCA, the simple example above, using species showing different responses to soil moisture is continued in Figure 12.22 below.

Figure 12.22 Hypothetical plant-moisture response curves

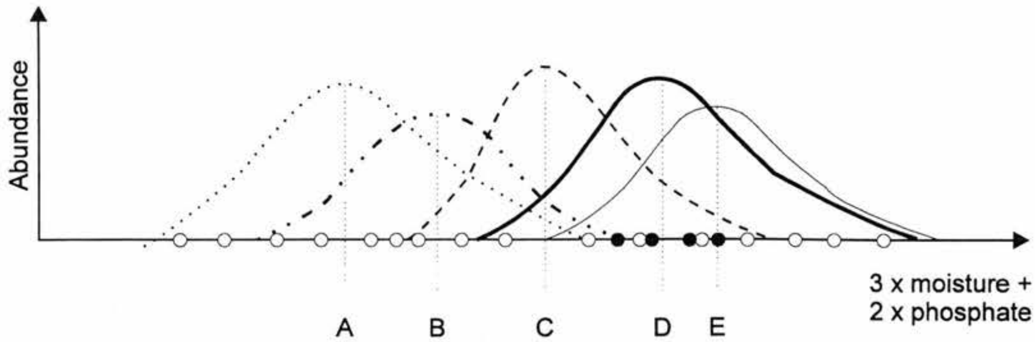


This figure shows the sample sites arranged along the x-axis, according to the moisture level recorded at each site. As before, sites where species D are present are represented by solid circles, the other sites are represented by open circles.

Figure 12.23 shows an attempt to improve the dispersion of the species scores by introducing a second environmental variable, phosphorus. The x-axis is now a linear combination of phosphate and moisture values, using the formula:

$$x\text{-axis score} = 3 \times \text{site moisture value} + 2 \times \text{site phosphate level.}$$

Figure 12.23 Dispersion along an axis relating to a combination of moisture and phosphate levels

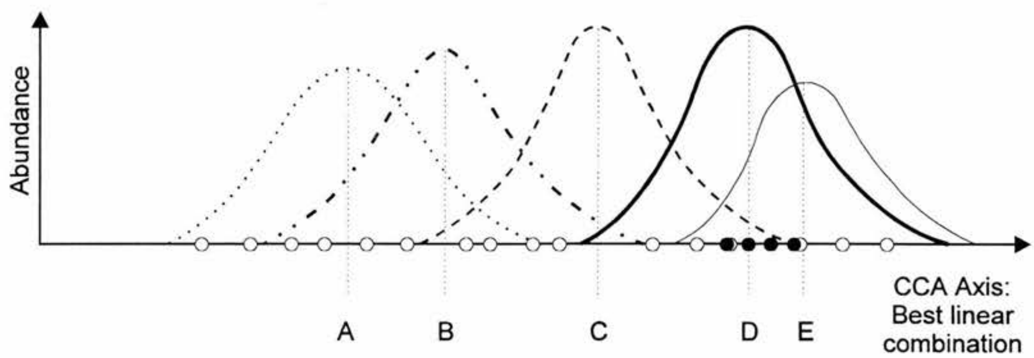


Modified from Figure 5.18 in ter Braak (1987).

This combination of phosphorus and moisture has been selected only for illustrative purposes, the choice of these particular variables and the exact value of the weightings are *not* important in this example. Looking at the diagram, the plant species response curves can be seen to overlap less, indicating that this classification is more effective in separating sites according to their species cover. Looking at the distribution of sites containing species D (shown as solid circles in this diagram), it can be seen that these sites are now arranged more closely.

Changing the weightings of these environmental variables, and/or including more environmental variables to calculate the x-axis will affect the dispersion of sites. Some combinations will group similar sites more closely together (interpreted as representing a relationship occurring in the real world), others will produce weaker, or spurious clusters. CCA provides a method of calculating the linear combination of variables which maximises site dispersion. Figure 12.24 shows the sample sites arranged along an x-axis which has been selected by CCA to be the best linear combination of all the environmental variables measured at the sample sites.

Figure 12.24 Dispersion along the new, canonical axis



It can be seen that the response curves are more peaked and thus more distinct and that the sites containing species D (shown as solid circles) are tightly clustered. This shows that the CCA algorithms can use differences in the environmental data to successfully explain variation in the plant species present at each sample site.

In CCA, the theoretical variable which comprises the *x*-axis is produced by considering all possible linear combinations of the weighted sums of the environmental variables, i.e.

$$x_i = c_0 + c_1 z_{1i} + c_2 z_{2i} \ldots + c_q z_{qi}$$

where

z_{ji} is the value of environmental variable *j* at site *i*.

c_j is the weight (positive or negative) belonging to that variable

x_i is the value of the resulting compound environmental variable at site *i*.

Through a series of mathematical iterations[4], CCA selects the particular linear combination (weightings) of environmental variables that maximises the dispersion of the species scores. This means that samples of the same species have similar compound environmental variable scores [x_i] and samples with different species cover have very different compound environmental variable scores. The values of the compound environmental variables that maximises the dispersion of the species scores is used as the first canonical axis on the ordination diagram.

The second (and possibly, further) canonical axes are chosen in a similar method, as linear combinations of the environmental variables that also maximise the dispersion of the species scores. However they also have to satisfy one further criterion, they must be uncorrelated with the previous canonical axes.

Using the canonical axes, an ordination space can be created. Usually these are restricted to two-dimensions, using only the first two canonical axes. The resulting ordination space can be represented as an x-y scattergram. The sites can be positioned as points in this space, according to the value of the environmental properties measured there. Similarly the species scores (which can be thought of as a "preferred" value for each environmental property) allow the plant species to be plotted as points in this space. To complete the diagram, each environmental variable can be plotted, but they are commonly represented by arrows rather than points. This reflects the fact that they are themselves an axis, and species points are arranged along the environmental axis in an order which corresponds to the ranking of the weighting of the species average for this environmental property. Therefore the location of sample sites relative to the environmental arrow indicates the value of this property at the sample site. Sites plotting near the arrow head will have high values of this property, sites near the tail of the arrow will have low values. The location of sample sites relative to a given species point in ordination space indicates its abundance. Sample sites with a high abundance value for a certain plant species tend to plot very near the point representing that species in the ordination diagram. The arrangement of the species around the environmental arrows indicates environmental conditions favoured (or tolerated) by the plants.

The maximised dispersion of the species scores along each canonical axis (thus a measure of the axes' importance) is termed the eigenvalue and, because the environmental variables are standardised has a value between zero and one, where one indicates complete dispersion and thus total explanation of the species data. Canonical axis one has the highest eigenvalue, axis two the second highest, etc. Eigenvalues over 0.5 are often used to denote an axis which achieves a good separation of the species data.

Drawn from the discussion in ter Braak (1987) and ter Braak (1987-1992).

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[4] A modified version of the two-way weighted averaging algorithm used in correspondence analysis (CA).

Appendix 4: Sample data

Data contained in this appendix are arranged chronologically by fieldsite.

1992 Burnt fieldsite data

Sampling sites are identified using a combination of numbers and letters, e.g. **C12**, **LT1**.

For the areal (stratified random) sampling, the letter(s) indicate the zone in which the sample lies:

C Cleared zone
TZ Transition zone
F Forest zone

The number which follows identifies the sample within the zone, but their ordering is not significant.

For the transect sampling, the first two letters indicate to which transect line the sample belongs:

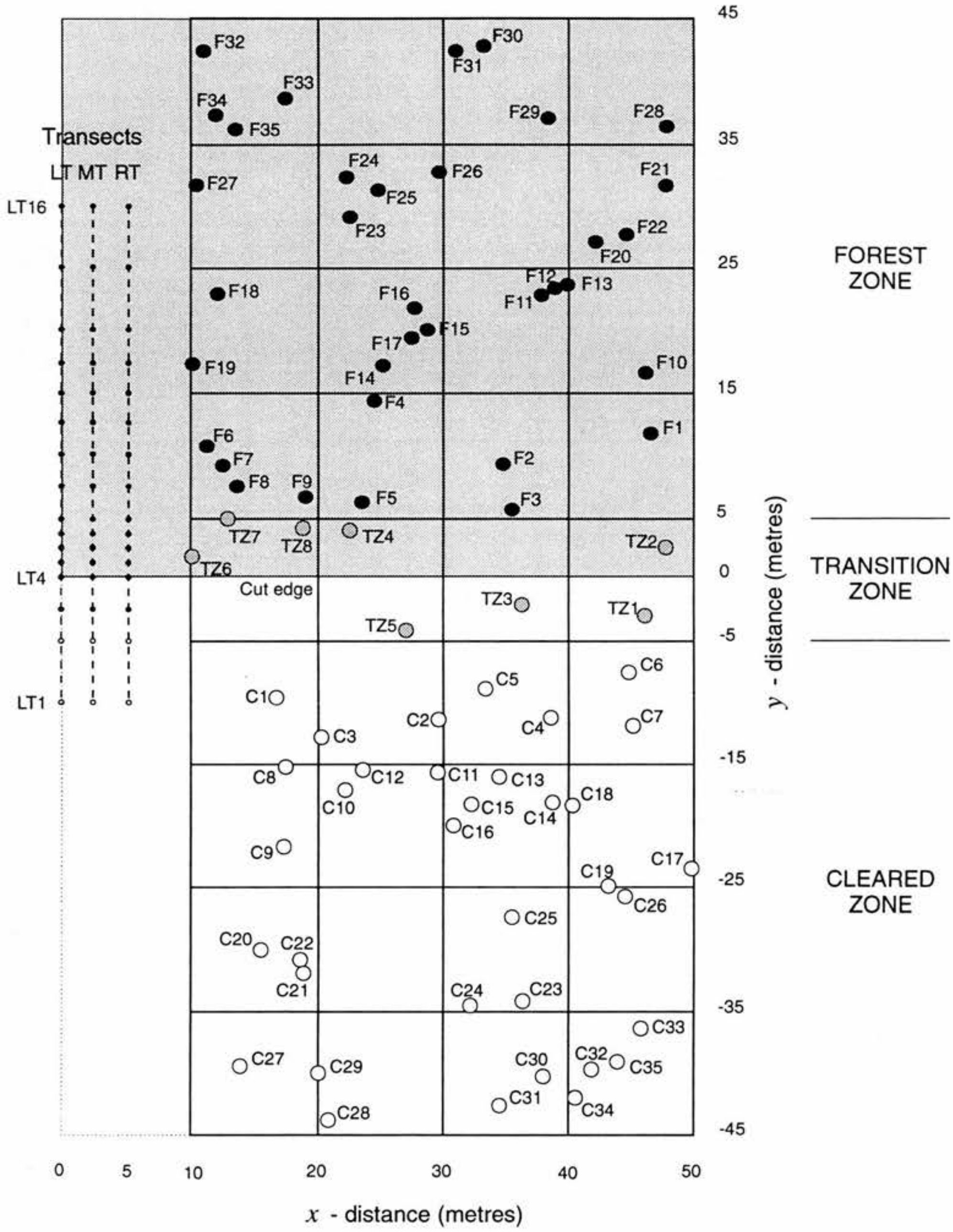
LT Left transect
MT Middle transect
RT Right transect

The number indicates the sample point's position along the sample line. Sample points with a suffix of 1 (i.e. **LT1**, **MT1** and **RT1**) lie furthest into the cleared zone, sample points with a suffix of 4 lie on the cut edge and sample points with a suffix of 16 are 30 metres into the forest.

Where samples have been taken at different depths, they are differentiated using a further set of numbers. For example at site **C1**, the sample nearest the surface is sample **C1/1**, below this lies sample **C1/2**, below that sample **C1/3**, etc. The arrangement of these sample points in space is shown in Figure 12.25.

The data are arranged as follows:
Table 12.9 Positional data - layer 1 samples, Burnt site 1992
Table 12.10 Positional data - layer 2 samples, Burnt site 1992
Table 12.11 Positional data for the 50 locating markers, Burnt site 1992
Table 12.12 Physical properties and carbon content, layer 1 samples, Burnt site 1992
Table 12.13 Physical properties and carbon content, layer 2 samples, Burnt site 1992
Table 12.14 Soil exchangeable cation levels, layer 1 samples, Burnt site 1992
Table 12.15 Soil exchangeable cation levels, layer 2 samples, Burnt site 1992
Table 12.16 Soil exchangeable manganese, extractable phosphorus and inorganic N levels, layer 1 samples, Burnt site 1992
Table 12.17 Soil exchangeable manganese, extractable phosphorus and inorganic N levels, layer 2 samples, Burnt site 1992
Table 12.18 Soil pH and redox potential (Eh_7), layer 1 samples, Burnt site 1992
Table 12.19 Soil pH and redox potential (Eh_7), layer 2 samples, Burnt site 1992
Table 12.20 Plant root abundancy, layer 1 samples, Burnt site 1992
Table 12.21 Plant root abundancy, layer 2 samples, Burnt site 1992
Table 12.22 Dominant soil colour, layers 1 & 2, Burnt site 1992
Table 12.23 Water pH, conductivity and dissolved oxygen content, Burnt site 1992
Table 12.24 Soil sulphate-sulphur and total iron levels, Burnt site 1992
Table 12.25 Transect litter depth and insolation data, Burnt site 1992

Figure 12.25 The position of the 1992 Burnt site sampling points



This diagram shows the 1992 Burnt field site in plan view. The three linear transects are marked with dashed lines, the dots on each line indicate a sampling point. The large rectangle marks out the region used for areal sampling. The grey shaded area represents the fraction of the site still covered by mangrove.

Sampling sites have been coloured to represent the zone in which they lie: Points in the forest are marked with solid black circles, points in the transition zone with grey circles and points in the cleared zone are marked with open circles.

The distance scale marked is that used for locating the sampling points in the field, using an arbitrary point (0,0).

Table 12.9 Positional data - layer 1 samples, Burnt site 1992

Sample number	x (m)	y (m)	z (m)	thickness (cm)	depth (cm)	Sample number	x (m)	y (m)	z (m)	thickness (cm)	depth (cm)
C1/1	16.82	-9.74	-0.11	14.00	7.00	F1/1	46.67	11.63	-0.03	12.00	6.00
C2/1	29.66	-11.47	-0.08	11.00	5.50	F2/1	34.95	9.11	-0.06	14.50	7.25
C3/1	20.36	-12.89	-0.15	12.00	6.00	F3/1	35.48	5.49	-0.05	13.00	6.50
C4/1	38.67	-11.38	-0.10	7.00	3.50	F4/1	24.45	14.34	-0.08	14.00	7.00
C5/1	33.42	-8.94	-0.12	5.00	2.50	F5/1	23.48	6.04	-0.06	13.00	6.50
C6/1	44.92	-7.67	-0.14	11.00	5.50	F6/1	11.36	10.53	-0.08	15.50	7.75
C7/1	45.31	-12.01	-0.04	10.00	5.00	F7/1	12.43	8.98	-0.09	14.00	7.00
C8/1	17.55	-15.30	-0.10	10.00	5.00	F8/1	13.50	7.45	-0.11	15.00	7.50
C9/1	17.29	-21.77	-0.09	8.00	4.00	F9/1	19.00	6.36	-0.05	13.00	6.50
C10/1	22.30	-17.02	-0.06	10.00	5.00	F10/1	46.19	16.49	-0.03	15.00	7.50
C11/1	29.67	-15.63	-0.12	8.00	4.00	F11/1	37.94	22.68	0.06	12.00	6.00
C12/1	23.66	-15.63	-0.06	10.00	5.00	F12/1	38.97	23.45	0.00	13.00	6.50
C13/1	34.50	-16.10	-0.12	13.00	6.50	F13/1	39.91	23.64	-0.05	8.00	4.00
C14/1	38.68	-18.16	-0.10	9.00	4.50	F14/1	25.28	17.05	-0.10	14.00	7.00
C15/1	32.39	-18.26	-0.08	12.00	6.00	F15/1	28.65	19.95	-0.11	14.00	7.00
C16/1	30.89	-19.98	-0.06	12.00	6.00	F16/1	27.77	21.52	-0.13	11.00	5.50
C17/1	49.92	-23.67	-0.06	10.00	5.00	F17/1	27.48	19.72	-0.12	12.00	6.00
C18/1	40.40	-18.35	-0.15	10.00	5.00	F18/1	12.08	22.92	-0.10	11.00	5.50
C19/1	43.27	-25.00	-0.13	13.00	6.50	F19/1	10.07	17.25	-0.11	12.00	6.00
C20/1	15.48	-30.21	-0.07	11.00	5.50	F20/1	42.18	27.01	-0.18	12.00	6.00
C21/1	18.85	-32.06	-0.08	12.00	6.00	F21/1	47.83	31.63	-0.12	12.00	6.00
C22/1	18.76	-30.96	-0.07	11.00	5.50	F22/1	44.52	27.54	-0.16	10.00	5.00
C23/1	36.46	-34.30	-0.15	9.00	4.50	F23/1	22.55	29.06	-0.18	10.00	5.00
C24/1	32.27	-34.60	-0.13	12.00	6.00	F24/1	22.38	32.19	-0.11	13.00	6.50
C25/1	35.57	-27.46	-0.11	9.50	4.75	F25/1	24.89	31.18	-0.10	12.00	6.00
C26/1	44.68	-25.86	-0.09	11.00	5.50	F26/1	29.69	32.77	-0.16	11.50	5.75
C27/1	13.87	-39.55	-0.08	8.50	4.25	F27/1	10.31	31.65	-0.17	9.50	4.75
C28/1	20.99	-43.90	-0.16	11.00	5.50	F28/1	48.01	36.34	-0.18	11.50	5.75
C29/1	20.09	-40.04	-0.09	13.00	6.50	F29/1	38.44	37.09	-0.10	10.00	5.00
C30/1	38.12	-40.28	0.07	15.00	7.50	F30/1	33.31	42.73	-0.17	12.50	6.25
C31/1	34.58	-42.70	-0.03	13.00	6.50	F31/1	30.94	42.41	-0.11	10.00	5.00
C32/1	41.92	-39.82	-0.13	10.00	5.00	F32/1	10.81	42.50	-0.11	9.50	4.75
C33/1	45.91	-36.46	-0.13	10.00	5.00	F33/1	17.49	38.58	-0.15	13.00	6.50
C34/1	40.60	-42.09	-0.12	11.00	5.50	F34/1	11.79	37.38	-0.19	12.00	6.00
C35/1	43.95	-39.19	-0.14	9.00	4.50	F35/1	13.40	36.15	-0.14	10.50	5.25
TZ1/1	46.26	-3.05	-0.13	13.00	6.50	TZ5/1	27.12	-4.31	-0.12	12.00	6.00
TZ2/1	47.78	2.50	-0.14	14.00	7.00	TZ6/1	10.07	1.81	-0.15	10.00	5.00
TZ3/1	36.32	-2.24	-0.14	15.00	7.50	TZ7/1	12.87	4.95	-0.12	16.00	8.00
TZ4/1	22.54	3.84	-0.08	13.00	6.50	TZ8/1	18.91	4.14	-0.12	14.00	7.00
LT1/1	0.00	-10.00	-0.15	13.00	6.50	MT1/1	2.50	-10.00	-0.15	13.00	6.50
LT2/1	0.00	-5.00	-0.17	13.00	6.50	MT2/1	2.50	-5.00	-0.15	13.00	6.50
LT3/1	0.00	-2.50	-0.14	15.00	7.50	MT3/1	2.50	-2.50	-0.15	15.00	7.50
LT4/1	0.00	0.00	-0.15	14.00	7.00	MT4/1	2.50	0.00	-0.06	17.00	8.50
LT5/1	0.00	1.25	-0.16	14.00	7.00	MT5/1	2.50	1.25	-0.10	15.00	7.50
LT6/1	0.00	2.50	-0.14	19.00	9.50	MT6/1	2.50	2.50	-0.14	14.00	7.00
LT7/1	0.00	3.75	-0.13	13.00	6.50	MT7/1	2.50	3.75	-0.13	13.00	6.50
LT8/1	0.00	5.00	-0.06	14.00	7.00	MT8/1	2.50	5.00	-0.07	17.00	8.50
LT9/1	0.00	7.50	-0.15	14.00	7.00	MT9/1	2.50	7.50	-0.12	12.00	6.00
LT10/1	0.00	10.00	-0.16	13.00	6.50	MT10/1	2.50	10.00	-0.09	13.00	6.50
LT11/1	0.00	12.50	-0.13	13.00	6.50	MT11/1	2.50	12.50	-0.07	13.00	6.50
LT12/1	0.00	15.00	-0.14	13.00	6.50	MT12/1	2.50	15.00	-0.11	17.00	8.50
LT13/1	0.00	17.50	-0.06	8.00	4.00	MT13/1	2.50	17.50	-0.07	13.00	6.50
LT14/1	0.00	20.00	-0.12	13.00	6.50	MT14/1	2.50	20.00	-0.09	13.00	6.50
LT15/1	0.00	25.00	-0.09	10.00	5.00	MT15/1	2.50	25.00	-0.09	14.00	7.00
LT16/1	0.00	30.00	-0.08	13.00	6.50	MT16/1	2.50	30.00	-0.10	10.00	5.00
RT1/1	5.00	-10.00	-0.13	16.00	8.00	RT9/1	5.00	7.50	-0.09	13.00	6.50
RT2/1	5.00	-5.00	-0.13	14.00	7.00	RT10/1	5.00	10.00	-0.09	13.00	6.50
RT3/1	5.00	-2.50	-0.14	13.50	6.75	RT11/1	5.00	12.50	-0.09	12.00	6.00
RT4/1	5.00	0.00	-0.07	14.00	7.00	RT12/1	5.00	15.00	-0.10	13.00	6.50
RT5/1	5.00	1.25	-0.11	11.00	5.50	RT13/1	5.00	17.50	-0.09	11.00	5.50
RT6/1	5.00	2.50	-0.07	18.00	9.00	RT14/1	5.00	20.00	-0.07	14.00	7.00
RT7/1	5.00	3.75	-0.05	12.00	6.00	RT15/1	5.00	25.00	-0.05	13.00	6.50
RT8/1	5.00	5.00	-0.06	13.00	6.50	RT16/1	5.00	30.00	-0.05	17.00	8.50

Table 12.10 Positional data - layer 2 samples, Burnt site 1992

Sample number	x (m)	y (m)	z (m)	thickness (cm)	depth (cm)	Sample number	x (m)	y (m)	z (m)	thickness (cm)	depth (cm)
C1/2	16.82	-9.74	-0.25	15.00	21.50	F1/2	46.67	11.63	-0.15	13.00	18.50
C2/2	29.66	-11.47	-0.19	13.00	17.50	F2/2	34.95	9.11	-0.20	13.50	21.25
C3/2	20.36	-12.89	-0.27	11.00	17.50	F3/2	35.48	5.49	-0.18	16.00	21.00
C4/2	38.67	-11.38	-0.17	7.00	10.50	F4/2	24.45	14.34	-0.22	12.00	20.00
C5/2	33.42	-8.94	-0.17	8.00	9.00	F5/2	23.48	6.04	-0.19	13.00	19.50
C6/2	44.92	-7.67	-0.25	12.00	17.00	F6/2	11.36	10.53	-0.24	13.50	22.25
C7/2	45.31	-12.01	-0.14	15.00	17.50	F7/2	12.43	8.98	-0.23	14.00	21.00
C8/2	17.55	-15.30	-0.20	15.00	17.50	F8/2	13.50	7.45	-0.26	16.00	23.00
C9/2	17.29	-21.77	-0.17	12.00	14.00	F9/2	19.00	6.36	-0.18	13.00	19.50
C10/2	22.30	-17.02	-0.16	12.00	16.00	F10/2	46.19	16.49	-0.18	14.00	22.00
C11/2	29.67	-15.63	-0.20	7.00	11.50	F11/2	37.94	22.68	-0.06	12.00	18.00
C12/2	23.66	-15.63	-0.16	15.00	17.50	F12/2	38.97	23.45	-0.13	11.00	18.50
C13/2	34.50	-16.10	-0.25	11.50	18.75	F13/2	39.91	23.64	-0.13	11.00	13.50
C14/2	38.68	-18.16	-0.19	11.00	14.50	F14/2	25.28	17.05	-0.24	15.00	21.50
C15/2	32.39	-18.26	-0.20	10.00	17.00	F15/2	28.65	19.95	-0.25	17.00	22.50
C16/2	30.89	-19.98	-0.18	14.00	19.00	F16/2	27.77	21.52	-0.24	13.00	17.50
C17/2	49.92	-23.67	-0.16	8.00	14.00	F17/2	27.48	19.72	-0.24	11.00	17.50
C18/2	40.40	-18.35	-0.25	11.50	15.75	F18/2	12.08	22.92	-0.21	6.00	14.00
C19/2	43.27	-25.00	-0.26	10.00	18.00	F19/2	10.07	17.25	-0.23	9.00	16.50
C20/2	15.48	-30.21	-0.18	12.50	17.25	F20/2	42.18	27.01	-0.30	10.00	17.00
C21/2	18.85	-32.06	-0.20	21.50	22.75	F21/2	47.83	31.63	-0.24	13.00	18.50
C22/2	18.76	-30.96	-0.18	12.00	17.00	F22/2	44.52	27.54	-0.26	6.00	13.00
C23/2	36.46	-34.30	-0.24	11.50	14.75	F23/2	22.55	29.06	-0.28	11.00	15.50
C24/2	32.27	-34.60	-0.25	10.00	17.00	F24/2	22.38	32.19	-0.24	13.00	19.50
C25/2	35.57	-27.46	-0.20	11.00	15.00	F25/2	24.89	31.18	-0.22	14.50	19.25
C26/2	44.68	-25.86	-0.20	12.00	17.00	F26/2	29.69	32.77	-0.27	12.50	17.75
C27/2	13.87	-39.55	-0.17	9.50	13.25	F27/2	10.31	31.65	-0.26	9.50	14.25
C28/2	20.99	-43.90	-0.27	13.00	17.50	F28/2	48.01	36.34	-0.29	13.00	18.00
C29/2	20.09	-40.04	-0.22	10.00	18.00	F29/2	38.44	37.09	-0.20	14.00	17.00
C30/2	38.12	-40.28	-0.08	9.00	19.50	F30/2	33.31	42.73	-0.29	12.00	18.50
C31/2	34.58	-42.70	-0.16	9.00	17.50	F31/2	30.94	42.41	-0.21	10.00	15.00
C32/2	41.92	-39.82	-0.23	10.00	15.00	F32/2	10.81	42.50	-0.20	10.50	14.75
C33/2	45.91	-36.46	-0.23	13.00	16.50	F33/2	17.49	38.58	-0.28	12.00	19.00
C34/2	40.60	-42.09	-0.23	17.00	19.50	F34/2	11.79	37.38	-0.31	11.00	17.50
C35/2	43.95	-39.19	-0.23	11.00	14.50	F35/2	13.40	36.15	-0.24	11.50	16.25
TZ1/2	46.26	-3.05	-0.26	12.00	19.00	TZ5/2	27.12	-4.31	-0.24	11.00	17.50
TZ2/2	47.78	2.50	-0.28	12.50	20.25	TZ6/2	10.07	1.81	-0.25	7.00	13.50
TZ3/2	36.32	-2.24	-0.29	12.00	21.00	TZ7/2	12.87	4.95	-0.28	11.00	21.50
TZ4/2	22.54	3.84	-0.21	12.00	19.00	TZ8/2	18.91	4.14	-0.26	14.00	21.00
LT1/2	0.00	-10.00	-0.28	15.00	20.50	MT1/2	2.50	-10.00	-0.28	13.00	19.50
LT2/2	0.00	-5.00	-0.30	14.00	20.00	MT2/2	2.50	-5.00	-0.28	14.00	20.00
LT3/2	0.00	-2.50	-0.29	14.00	22.00	MT3/2	2.50	-2.50	-0.30	13.00	21.50
LT4/2	0.00	0.00	-0.29	13.00	20.50	MT4/2	2.50	0.00	-0.23	6.00	20.00
LT5/2	0.00	1.25	-0.30	14.00	21.00	MT5/2	2.50	1.25	-0.25	15.00	22.50
LT6/2	0.00	2.50	-0.33	13.00	25.50	MT6/2	2.50	2.50	-0.28	15.00	21.50
LT7/2	0.00	3.75	-0.26	15.00	20.50	MT7/2	2.50	3.75	-0.26	14.00	20.00
LT8/2	0.00	5.00	-0.20	13.00	20.50	MT8/2	2.50	5.00	-0.24	15.00	24.50
LT9/2	0.00	7.50	-0.29	13.00	20.50	MT9/2	2.50	7.50	-0.24	16.00	20.00
LT10/2	0.00	10.00	-0.29	13.00	19.50	MT10/2	2.50	10.00	-0.22	14.00	20.00
LT11/2	0.00	12.50	-0.26	12.00	19.00	MT11/2	2.50	12.50	-0.20	18.00	22.00
LT12/2	0.00	15.00	-0.27	16.00	21.00	MT12/2	2.50	15.00	-0.28	10.00	22.00
LT13/2	0.00	17.50	-0.14	6.00	11.00	MT13/2	2.50	17.50	-0.20	15.00	20.50
LT14/2	0.00	20.00	-0.25	9.00	17.50	MT14/2	2.50	20.00	-0.22	12.00	19.00
LT15/2	0.00	25.00	-0.19	18.00	19.00	MT15/2	2.50	25.00	-0.23	11.00	19.50
LT16/2	0.00	30.00	-0.21	11.00	18.50	MT16/2	2.50	30.00	-0.20	15.00	17.50
RT1/2	5.00	-10.00	-0.29	15.00	23.50	RT9/2	5.00	7.50	-0.22	14.00	20.00
RT2/2	5.00	-5.00	-0.27	15.00	21.50	RT10/2	5.00	10.00	-0.22	15.00	20.50
RT3/2	5.00	-2.50	-0.27	16.50	21.75	RT11/2	5.00	12.50	-0.21	12.00	18.00
RT4/2	5.00	0.00	-0.21	14.00	21.00	RT12/2	5.00	15.00	-0.23	10.00	18.00
RT5/2	5.00	1.25	-0.22	15.00	18.50	RT13/2	5.00	17.50	-0.20	8.00	15.00
RT6/2	5.00	2.50	-0.25	7.00	21.50	RT14/2	5.00	20.00	-0.21	15.00	21.50
RT7/2	5.00	3.75	-0.17	18.00	21.00	RT15/2	5.00	25.00	-0.18	12.00	19.00
RT8/2	5.00	5.00	-0.19	16.00	21.00	RT16/2	5.00	30.00	-0.22	13.50	23.75

Table 12.11 Positional data for the 50 locating markers, Burnt site 1992

Sample number	x (m)	y (m)	z (m)
Pole 1	10.00	45.00	-0.10
Pole 2	20.00	45.00	-0.07
Pole 3	30.00	45.00	-0.12
Pole 4	40.00	45.00	-0.15
Pole 5	50.00	45.00	-0.14
Pole 6	10.00	35.00	-0.17
Pole 7	20.00	35.00	-0.16
Pole 8	30.00	35.00	-0.15
Pole 9	40.00	35.00	-0.15
Pole 10	50.00	35.00	-0.14
Pole 11	10.00	25.00	-0.08
Pole 12	20.00	25.00	-0.15
Pole 13	30.00	25.00	-0.08
Pole 14	40.00	25.00	-0.04
Pole 15	50.00	25.00	-0.09
Pole 16	10.00	15.00	-0.06
Pole 17	20.00	15.00	-0.03
Pole 18	30.00	15.00	-0.04
Pole 19	40.00	15.00	-0.02
Pole 20	50.00	15.00	-0.08
Pole 21	10.00	5.00	-0.08
Pole 22	20.00	5.00	0.07
Pole 23	30.00	5.00	-0.03
Pole 24	40.00	5.00	-0.01
Pole 25	50.00	5.00	-0.06

Sample number	x (m)	y (m)	z (m)
Pole 26	10.00	-5.00	-0.15
Pole 27	20.00	-5.00	-0.14
Pole 28	30.00	-5.00	-0.12
Pole 29	40.00	-5.00	-0.08
Pole 30	50.00	-5.00	-0.13
Pole 31	10.00	-15.00	-0.12
Pole 32	20.00	-15.00	-0.06
Pole 33	30.00	-15.00	-0.15
Pole 34	40.00	-15.00	-0.17
Pole 35	50.00	-15.00	-0.08
Pole 36	10.00	-25.00	-0.11
Pole 37	20.00	-25.00	-0.12
Pole 38	30.00	-25.00	-0.12
Pole 39	40.00	-25.00	-0.17
Pole 40	50.00	-25.00	-0.16
Pole 41	10.00	-35.00	-0.13
Pole 42	20.00	-35.00	-0.14
Pole 43	30.00	-35.00	-0.15
Pole 44	40.00	-35.00	-0.16
Pole 45	50.00	-35.00	-0.12
Pole 46	10.00	-45.00	-0.15
Pole 47	20.00	-45.00	-0.07
Pole 48	30.00	-45.00	-0.13
Pole 49	40.00	-45.00	-0.17
Pole 50	50.00	-45.00	-0.13

Fifty numbered sampling poles were used to mark out a 10 m grid in the field. This was used for locational purposes during the fieldwork. It corresponds to the heavy grid superimposed onto the terrain models of chapter six. Only x, y and z data were measured at these poles.

The three tables above all give relative positional data. The heights are expressed relative to the observed lagoon level, which remained constant throughout the 1992 field season. The x and y co-ordinates for all the points are measured from the nominal point (0,0) which is the corner of the field area nearest to the road and furthest from the cut forest edge. Transect line **LT** runs along the line x=0.

Table 12.12 Physical properties and carbon content, layer 1 samples, Burnt site 1992

Sample number	Bulk ρ g cm^{-3}	Moisture %	% >2mm	%Wt LoI	%Org C	Sample number	Bulk ρ g cm^{-3}	Moisture %	% >2mm	%Wt LoI	%Org C
C1/1	0.40	50.8	55.8	9.7	2.9	F1/1	0.30	61.5	14.0	17.3	4.0
C2/1	0.32	60.9	12.0	14.2	6.1	F2/1	0.29	63.5	26.5	25.2	8.2
C3/1	1.02	58.0	19.2	11.4	4.7	F3/1	0.38	50.4	16.6	12.1	2.5
C4/1	0.32	46.8	6.5	5.4	1.4	F4/1	0.43	57.2	46.3	13.9	4.0
C5/1	0.55	64.0	4.1	16.5	5.0	F5/1	0.36	60.5	16.3	12.2	5.8
C6/1	0.35	74.4	8.2	16.4	7.9	F6/1	0.42	64.1	10.8	18.8	8.7
C7/1	0.45	56.8	17.9	9.8	3.8	F7/1	0.30	55.6	27.2	19.1	5.0
C8/1	0.40	56.8	17.9	16.0	6.1	F8/1	0.53	56.7	31.4	12.2	4.5
C9/1	0.47	59.6	7.7	14.4	5.8	F9/1	0.33	61.8	36.7	11.1	4.2
C10/1	0.39	62.6	15.9	16.0	6.1	F10/1	0.31	64.9	28.7	10.6	5.2
C11/1	0.46	55.8	7.6	13.9	5.0	F11/1	0.09	74.1	9.4	28.0	9.0
C12/1	0.30	60.0	12.4	13.4	3.8	F12/1	0.26	62.3	40.1	17.5	6.0
C13/1	0.30	56.5	8.7	13.7	4.0	F13/1	0.34	67.2	3.5	15.9	10.5
C14/1	0.49	58.1	25.0	15.7	6.4	F14/1	0.26	63.4	18.1	15.7	4.8
C15/1	0.40	61.1	24.4	14.3	4.1	F15/1	0.19	67.8	16.5	19.2	6.7
C16/1	0.31	62.0	11.7	17.7	4.7	F16/1	0.21	63.6	9.8	15.8	7.7
C17/1	0.41	64.6	3.1	16.8	4.4	F17/1	0.22	69.3	12.7	28.4	8.3
C18/1	0.46	54.0	14.8	11.5	4.1	F18/1	0.30	75.5	14.1	39.9	17.5
C19/1	0.36	55.4	37.4	15.0	3.2	F19/1	0.39	64.1	8.3	13.7	4.7
C20/1	0.52	40.2	10.6	15.0	4.6	F20/1	0.35	71.7	14.0	23.7	7.6
C21/1	0.40	60.3	13.4	13.6	4.4	F21/1	0.41	62.2	16.8	10.1	4.7
C22/1	0.46	56.4	18.9	10.4	3.1	F22/1	0.36	62.8	11.1	21.7	4.7
C23/1	0.40	57.2	11.6	16.0	4.7	F23/1	0.37	56.0	13.0	15.5	6.0
C24/1	0.35	59.8	13.2	14.6	5.2	F24/1	0.22	66.5	13.7	20.2	10.0
C25/1	0.48	59.9	16.8	14.0	4.7	F25/1	0.21	66.3	13.6	17.4	5.1
C26/1	0.46	59.0	16.6	17.1	7.7	F26/1	0.55	58.7	7.9	19.6	5.4
C27/1	0.62	51.0	13.1	10.4	5.1	F27/1	0.44	63.4	14.1	20.3	11.2
C28/1	0.53	61.1	12.6	14.1	5.5	F28/1	0.52	58.0	4.5	18.2	5.7
C29/1	0.38	60.9	17.9	11.5	4.2	F29/1	0.43	59.8	21.2	17.6	7.4
C30/1	0.48	60.1	24.8	11.8	3.8	F30/1	0.34	50.2	23.1	10.6	2.7
C31/1	0.30	59.5	12.3	20.7	3.8	F31/1	0.25	60.2	9.6	20.1	5.9
C32/1	0.48	47.8	9.7	11.3	1.6	F32/1	0.31	66.5	5.2	21.9	7.0
C33/1	0.36	63.6	5.3	16.1	4.2	F33/1	0.22	63.1	44.6	24.8	9.3
C34/1	0.48	59.5	14.4	16.0	5.9	F34/1	0.57	60.0	15.5	14.3	6.6
C35/1	0.67	48.8	4.3	9.8	2.9	F35/1	0.28	62.8	5.5	16.6	7.0
TZ1/1	0.44	63.3	17.6	30.1	7.0	TZ5/1	0.34	52.6	19.2	7.6	1.7
TZ2/1	0.38	52.7	26.5	8.7	5.5	TZ6/1	0.37	58.3	9.1	6.9	2.9
TZ3/1	0.35	59.5	10.5	8.9	1.0	TZ7/1	0.30	58.3	9.1	12.4	4.1
TZ4/1	0.38	66.0	18.5	13.5	3.7	TZ8/1	0.35	70.0	14.6	4.9	1.1
LT1/1	0.41	55.1	19.3	7.8	3.9	MT1/1	0.59	56.5	32.8	8.7	4.3
LT2/1	0.55	57.6	14.5	11.0	3.3	MT2/1	0.63	58.6	30.2	12.4	5.2
LT3/1	0.69	55.6	32.3	8.0	3.6	MT3/1	0.54	60.5	56.4	14.3	5.2
LT4/1	0.45	55.6	32.3	9.0	4.0	MT4/1	0.32	58.7	22.7	12.5	7.3
LT5/1	0.51	56.6	13.3	9.3	3.4	MT5/1	0.30	59.1	89.0	10.5	5.6
LT6/1	0.40	45.9	48.6	7.0	2.6	MT6/1	0.38	46.2	76.1	8.7	3.9
LT7/1	0.29	54.1	16.8	10.1	5.5	MT7/1	0.23	59.6	97.7	10.8	5.1
LT8/1	0.20	59.3	17.1	12.2	4.5	MT8/1	0.11	61.9	57.6	19.0	8.7
LT9/1	0.25	50.3	32.9	9.2	4.9	MT9/1	0.47	59.8	7.5	19.1	6.0
LT10/1	0.46	59.5	19.6	15.9	8.0	MT10/1	0.31	59.1	57.6	10.5	5.0
LT11/1	0.24	63.0	11.0	16.3	8.9	MT11/1	0.23	55.3	35.6	42.0	11.4
LT12/1	0.47	67.7	12.3	17.4	9.5	MT12/1	0.28	70.7	67.2	34.8	13.4
LT13/1	0.17	58.4	14.6	16.1	8.9	MT13/1	0.12	64.3	39.3	11.1	5.2
LT14/1	0.23	58.7	13.9	20.5	6.8	MT14/1	0.31	49.4	12.7	30.7	9.2
LT15/1	0.15	63.7	14.5	21.4	8.7	MT15/1	0.24	68.6	49.1	23.7	8.0
LT16/1	0.16	72.0	7.4	24.8	10.5	MT16/1	0.25	53.9	35.2	11.1	4.4
RT1/1	0.26	56.0	24.3	14.1	5.0	RT9/1	0.34	59.3	21.4	12.5	4.4
RT2/1	0.57	57.4	23.6	9.1	5.4	RT10/1	0.33	68.2	10.4	21.7	8.7
RT3/1	0.45	53.2	37.6	12.9	3.7	RT11/1	0.14	64.3	8.2	22.3	7.8
RT4/1	0.42	56.4	21.3	14.5	3.0	RT12/1	0.26	59.8	52.3	12.0	5.8
RT5/1	0.31	59.9	12.6	11.2	4.0	RT13/1	0.20	71.7	11.2	27.0	9.2
RT6/1	0.39	59.0	32.2	3.4	5.5	RT14/1	0.23	59.3	23.8	24.0	9.2
RT7/1	0.30	66.7	9.8	18.7	5.4	RT15/1	0.16	71.2	50.2	24.2	9.2
RT8/1	0.35	70.4	27.1	20.2	6.9	RT16/1	0.10	61.5	22.3	23.8	7.8

Bulk ρ = *bulk density*

Table 12.13 Physical properties and carbon content, layer 2 samples, Burnt site 1992

Sample number	Moisture %	% >2mm	%Wt Lol	%Org C	Sample number	Moisture %	% >2mm	%Wt Lol	%Org C
C1/2	36.1	17.9	4.5	1.9	F1/2	50.2	32.6	11.7	4.0
C2/2	36.4	13.0	5.0	1.4	F2/2	46.4	13.1	7.6	3.2
C3/2	38.6	11.3	2.5	1.4	F3/2	35.0	32.1	4.0	1.5
C4/2	36.8	12.1	5.8	1.6	F4/2	45.0	27.3	4.3	2.8
C5/2	45.2	5.6	6.6	3.2	F5/2	45.8	30.6	9.1	3.5
C6/2	45.2	3.1	4.8	2.5	F6/2	50.5	9.2	9.7	3.5
C7/2	37.9	9.6	2.8	1.3	F7/2	38.1	12.2	3.5	2.0
C8/2	37.8	17.0	5.7	2.5	F8/2	32.9	16.8	3.9	1.5
C9/2	35.3	9.7	3.3	2.2	F9/2	44.1	16.7	6.7	2.0
C10/2	35.0	5.4	5.1	1.7	F10/2	31.5	22.8	4.3	1.5
C11/2	42.2	6.9	5.5	2.5	F11/2	71.6	3.7	28.6	16.5
C12/2	35.8	16.9	4.0	1.6	F12/2	44.8	43.4	10.4	1.8
C13/2	37.8	14.1	3.5	1.6	F13/2	53.5	21.0	13.8	4.2
C14/2	32.0	36.4	2.2	0.8	F14/2	58.6	25.9	14.1	7.0
C15/2	38.1	24.5	4.9	1.7	F15/2	55.9	40.6	12.4	5.5
C16/2	34.1	27.2	2.6	1.1	F16/2	58.9	7.6	13.9	5.5
C17/2	54.2	7.0	10.3	4.4	F17/2	66.6	7.3	21.9	9.7
C18/2	42.3	17.2	5.7	2.2	F18/2	67.4	2.1	43.2	15.5
C19/2	39.1	21.2	4.9	1.9	F19/2	47.8	5.1	8.2	3.3
C20/2	40.2	16.8	6.3	1.9	F20/2	54.8	6.7	12.0	4.4
C21/2	40.9	18.0	6.7	2.2	F21/2	42.1	15.2	5.6	2.5
C22/2	39.2	25.4	4.8	1.7	F22/2	51.0	9.2	10.2	4.0
C23/2	44.5	31.3	5.8	2.0	F23/2	38.9	17.5	7.0	2.5
C24/2	39.3	24.2	4.7	2.5	F24/2	45.2	20.1	6.5	2.7
C25/2	35.2	29.4	2.1	8.5	F25/2	46.0	17.8	8.5	3.1
C26/2	40.0	13.6	6.1	1.6	F26/2	42.9	20.5	4.3	2.2
C27/2	31.3	22.1	1.5	0.3	F27/2	45.9	9.6	7.2	3.3
C28/2	32.3	15.0	2.8	1.2	F28/2	39.9	22.6	5.3	1.9
C29/2	45.0	17.1	4.2	3.3	F29/2	37.9	33.6	5.2	2.1
C30/2	32.4	9.8	3.9	1.2	F30/2	33.4	13.2	4.1	0.5
C31/2	42.8	14.1	5.7	1.3	F31/2	40.7	17.5	4.7	2.1
C32/2	35.9	11.3	6.2	1.6	F32/2	54.7	14.9	12.4	7.1
C33/2	44.1	12.2	6.7	2.5	F33/2	51.6	28.3	8.1	5.3
C34/2	32.7	6.4	2.6	2.1	F34/2	45.5	25.9	5.8	2.5
C35/2	44.6	13.6	5.1	2.1	F35/2	55.0	39.8	11.0	4.0
TZ1/2	37.0	18.2	5.7	1.4	TZ5/2	36.0	14.3	7.1	2.5
TZ2/2	31.9	19.0	5.5	1.1	TZ6/2	60.2	2.9	22.0	4.8
TZ3/2	46.7	10.8	5.8	1.0	TZ7/2	39.0	14.2	4.4	1.4
TZ4/2	47.1	13.9	7.4	3.1	TZ8/2	47.0	9.8	9.9	3.1
LT1/2	36.7	7.1	3.3	2.1	MT1/2	32.1	5.0	3.2	2.3
LT2/2	38.5	13.9	3.0	2.1	MT2/2	38.3	8.0	2.3	3.3
LT3/2	35.5	7.8	3.8	2.8	MT3/2	35.2	26.1	4.2	2.1
LT4/2	38.5	10.6	4.4	1.8	MT4/2	30.8	17.1	3.6	2.0
LT5/2	38.6	11.2	4.7	1.8	MT5/2	31.3	66.5	4.2	2.1
LT6/2	30.5	1.3	3.8	1.5	MT6/2	28.6	54.1	1.9	1.2
LT7/2	22.3	7.8	5.2	2.3	MT7/2	33.7	29.6	4.1	1.5
LT8/2	33.9	6.3	3.9	2.6	MT8/2	34.1	25.6	4.4	1.8
LT9/2	35.0	10.6	3.3	2.6	MT9/2	32.3	32.7	3.8	1.5
LT10/2	45.4	6.8	6.6	4.3	MT10/2	43.0	12.9	4.8	2.7
LT11/2	43.4	11.3	7.2	3.1	MT11/2	37.1	35.8	5.7	1.7
LT12/2	41.6	26.9	6.3	3.7	MT12/2	46.5	10.6	8.2	2.0
LT13/2	37.2	2.8	3.6	2.1	MT13/2	37.3	74.6	5.6	2.1
LT14/2	44.3	2.4	6.9	3.0	MT14/2	37.8	21.6	5.2	1.7
LT15/2	42.1	9.0	8.2	3.0	MT15/2	46.0	12.4	11.3	3.5
LT16/2	61.9	13.9	13.3	7.8	MT16/2	34.2	21.6	3.1	2.3
RT1/2	38.5	4.2	4.9	3.2	RT9/2	33.2	13.3	1.5	2.3
RT2/2	31.3	32.1	1.8	1.8	RT10/2	48.2	32.6	6.8	3.3
RT3/2	44.2	10.9	6.6	2.3	RT11/2	42.5	26.7	3.4	2.0
RT4/2	33.2	20.8	2.4	1.8	RT12/2	41.3	6.9	5.7	2.1
RT5/2	42.1	27.6	15.4	2.3	RT13/2	68.8	3.6	16.7	12.9
RT6/2	39.2	17.7	5.3	2.3	RT14/2	40.6	93.3	5.3	2.3
RT7/2	55.1	9.8	12.2	6.7	RT15/2	45.4	40.4	7.6	1.8
RT8/2	46.6	44.9	7.7	10.6	RT16/2	36.7	4.5	5.8	2.9

Table 12.14 Soil exchangeable cation levels, layer 1 samples, Burnt site 1992

Sample number	Exch. Ca $cmol_c\ kg^{-1}$	Exch. Mg $cmol_c\ kg^{-1}$	Exch. K $cmol_c\ kg^{-1}$	Exch. Na $cmol_c\ kg^{-1}$	Sample number	Exch. Ca $cmol_c\ kg^{-1}$	Exch. Mg $cmol_c\ kg^{-1}$	Exch. K $cmol_c\ kg^{-1}$	Exch. Na $cmol_c\ kg^{-1}$
C1/1	2.74	3.99	0.56	16.34	F1/1	2.02	4.07	1.01	31.84
C2/1	2.81	4.15	0.76	26.45	F2/1	2.85	4.31	1.57	46.65
C3/1	3.07	4.15	1.03	33.18	F3/1	1.72	3.96	0.92	27.12
C4/1	1.56	3.56	0.49	8.26	F4/1	3.24	4.16	1.19	40.59
C5/1	3.92	4.17	0.88	31.84	F5/1	2.28	4.07	1.15	37.22
C6/1	3.68	4.38	1.35	45.31	F6/1	3.11	4.32	1.33	45.98
C7/1	2.02	3.90	0.63	17.69	F7/1	6.08	4.28	1.33	45.98
C8/1	3.90	4.23	1.15	33.86	F8/1	4.79	4.21	1.39	39.92
C9/1	2.76	4.12	0.92	29.14	F9/1	2.87	4.20	1.37	43.29
C10/1	2.70	4.09	0.90	31.16	F10/1	2.15	4.06	1.37	37.22
C11/1	2.57	4.10	0.92	27.12	F11/1	3.29	4.26	1.60	51.37
C12/1	2.54	4.05	0.88	25.10	F12/1	2.20	4.10	1.15	37.90
C13/1	2.39	4.02	0.90	25.10	F13/1	2.44	4.08	1.35	35.20
C14/1	2.46	4.04	0.88	25.10	F14/1	2.41	4.13	1.46	40.59
C15/1	2.70	4.06	0.92	26.45	F15/1	2.78	4.28	1.71	53.39
C16/1	2.61	4.10	0.99	29.14	F16/1	2.54	4.18	1.33	44.63
C17/1	3.22	4.12	1.10	29.82	F17/1	3.24	4.29	1.42	52.72
C18/1	2.78	4.10	0.97	30.49	F18/1	4.16	4.38	2.07	61.47
C19/1	2.46	3.98	0.88	20.39	F19/1	2.48	4.12	1.06	39.92
C20/1	2.74	4.10	0.92	26.45	F20/1	3.63	4.47	1.87	59.45
C21/1	3.79	4.16	0.97	29.14	F21/1	2.04	4.04	1.17	31.84
C22/1	2.09	3.94	0.70	19.04	F22/1	2.85	4.22	1.69	41.27
C23/1	3.00	4.24	1.10	33.18	F23/1	1.93	3.96	0.97	27.12
C24/1	2.70	4.16	1.06	28.47	F24/1	2.78	4.13	1.39	38.57
C25/1	2.54	4.04	0.81	22.41	F25/1	2.41	4.09	1.33	39.25
C26/1	2.17	4.01	0.85	23.08	F26/1	2.81	4.16	1.28	36.55
C27/1	2.41	3.90	0.74	18.37	F27/1	2.59	4.15	1.19	39.25
C28/1	3.33	4.23	1.08	35.20	F28/1	1.96	4.16	1.10	39.92
C29/1	2.54	4.11	0.92	29.82	F29/1	1.85	3.99	1.26	35.88
C30/1	2.41	4.05	0.88	26.45	F30/1	1.48	3.96	1.03	25.77
C31/1	2.52	3.95	0.79	19.04	F31/1	2.02	4.06	1.12	31.84
C32/1	1.83	3.93	0.72	21.06	F32/1	2.04	3.88	0.88	20.39
C33/1	2.11	4.11	1.03	35.20	F33/1	2.85	4.17	1.60	36.55
C34/1	2.50	4.07	1.03	29.82	F34/1	2.57	4.18	1.33	34.53
C35/1	1.80	3.97	0.74	24.43	F35/1	2.00	3.94	1.33	27.12
TZ1/1	1.89	4.21	0.36	32.13	TZ5/1	1.79	4.05	0.46	23.08
TZ2/1	1.57	4.15	0.38	29.87	TZ6/1	10.29	4.41	0.86	45.16
TZ3/1	2.08	4.26	0.46	44.03	TZ7/1	2.93	4.41	0.62	47.42
TZ4/1	2.60	4.35	0.60	47.42	TZ8/1	3.22	4.46	0.71	58.75
LT1/1	2.12	4.28	0.38	31.57	MT1/1	2.93	4.30	0.36	29.30
LT2/1	2.28	4.22	0.50	38.36	MT2/1	5.91	4.27	0.58	36.66
LT3/1	2.44	4.12	0.57	33.83	MT3/1	2.73	4.28	0.62	38.36
LT4/1	2.60	4.19	0.53	36.10	MT4/1	2.12	4.13	0.71	28.74
LT5/1	3.32	4.23	0.50	35.53	MT5/1	2.34	4.22	0.64	31.57
LT6/1	3.25	4.16	0.48	25.91	MT6/1	1.69	4.08	0.51	26.47
LT7/1	2.41	4.23	0.58	36.10	MT7/1	4.90	4.35	0.64	36.66
LT8/1	2.12	4.10	0.57	25.91	MT8/1	6.56	4.45	0.86	46.86
LT9/1	2.47	4.15	0.53	34.40	MT9/1	2.70	4.26	0.64	32.13
LT10/1	4.68	4.37	0.58	43.46	MT10/1	2.47	4.27	0.45	32.70
LT11/1	11.23	4.44	0.74	47.42	MT11/1	3.22	4.39	0.65	44.03
LT12/1	2.76	4.26	0.67	40.63	MT12/1	3.70	4.53	0.86	53.65
LT13/1	1.99	4.11	0.64	19.68	MT13/1	2.51	4.30	0.51	35.53
LT14/1	2.12	4.19	0.51	26.47	MT14/1	3.06	4.40	0.58	44.03
LT15/1	2.99	4.37	0.53	38.93	MT15/1	3.35	4.36	0.72	45.72
LT16/1	2.73	4.30	0.71	47.42	MT16/1	2.28	4.27	0.58	32.70
RT1/1	2.38	4.29	0.38	32.13	RT9/1	2.63	4.25	0.53	29.87
RT2/1	2.25	4.29	0.43	36.10	RT10/1	3.19	4.42	0.53	46.29
RT3/1	2.86	4.29	0.46	34.97	RT11/1	2.34	4.27	0.53	41.19
RT4/1	1.47	3.91	0.41	19.11	RT12/1	2.15	4.25	0.67	40.63
RT5/1	2.02	4.19	0.55	33.83	RT13/1	3.09	4.44	0.76	49.12
RT6/1	2.63	4.33	0.65	39.50	RT14/1	2.76	4.32	0.57	40.63
RT7/1	2.96	4.39	0.58	45.72	RT15/1	3.19	4.43	0.71	57.05
RT8/1	3.02	4.33	0.57	42.33	RT16/1	2.25	4.31	0.50	47.99

Table 12.15 Soil exchangeable cation levels, layer 2 samples, Burnt site 1992

Sample number	Exch. Ca $cmol_c\ kg^{-1}$	Exch. Mg $cmol_c\ kg^{-1}$	Exch. K $cmol_c\ kg^{-1}$	Exch. Na $cmol_c\ kg^{-1}$	Sample number	Exch. Ca $cmol_c\ kg^{-1}$	Exch. Mg $cmol_c\ kg^{-1}$	Exch. K $cmol_c\ kg^{-1}$	Exch. Na $cmol_c\ kg^{-1}$
C1/2	1.89	4.04	0.63	24.43	F1/2	1.74	4.10	0.97	37.90
C2/2	1.54	3.95	0.61	21.06	F2/2	1.78	4.11	0.97	39.25
C3/2	2.87	3.95	0.74	24.43	F3/2	1.15	3.86	0.65	23.08
C4/2	5.36	3.63	0.67	9.61	F4/2	2.22	3.98	0.76	29.14
C5/2	1.61	1.32	0.67	19.71	F5/2	1.80	4.01	0.99	30.49
C6/2	1.67	4.10	0.85	33.18	F6/2	3.79	4.22	0.81	39.25
C7/2	1.48	3.91	0.74	21.73	F7/2	2.39	3.93	0.76	28.47
C8/2	1.83	3.90	0.63	22.41	F8/2	1.48	3.86	0.58	21.06
C9/2	1.28	3.80	0.65	18.37	F9/2	2.22	4.02	0.81	31.16
C10/2	1.63	4.02	0.74	29.82	F10/2	0.93	3.79	0.67	21.73
C11/2	1.83	3.93	0.72	22.41	F11/2	3.02	4.37	1.75	64.84
C12/2	1.48	3.90	0.67	23.75	F12/2	1.48	3.95	0.94	29.82
C13/2	1.45	3.81	0.70	17.69	F13/2	1.67	3.94	1.35	30.49
C14/2	0.95	3.72	0.56	15.67	F14/2	2.44	4.31	1.28	51.37
C15/2	1.48	3.91	0.81	23.08	F15/2	2.72	4.23	1.30	48.67
C16/2	1.04	3.73	0.61	14.32	F16/2	2.52	4.22	1.19	47.33
C17/2	2.70	4.12	1.03	31.84	F17/2	3.29	4.40	1.57	61.47
C18/2	2.00	3.99	0.81	25.10	F18/2	4.38	4.49	2.00	68.21
C19/2	1.59	3.90	0.79	22.41	F19/2	1.85	4.07	0.79	36.55
C20/2	1.85	4.00	0.76	23.08	F20/2	2.61	4.30	1.24	50.02
C21/2	1.87	3.94	0.70	20.39	F21/2	1.28	3.92	0.79	27.79
C22/2	1.43	3.86	0.67	18.37	F22/2	2.17	4.17	1.12	39.92
C23/2	2.30	4.07	0.81	26.45	F23/2	1.72	3.96	0.65	29.14
C24/2	1.41	3.92	0.83	20.39	F24/2	1.52	3.99	0.92	33.18
C25/2	1.26	3.79	0.70	13.65	F25/2	1.69	4.05	0.92	33.86
C26/2	1.43	3.99	0.81	22.41	F26/2	1.56	3.99	0.83	29.82
C27/2	1.30	3.72	0.58	15.00	F27/2	2.26	4.07	0.99	33.86
C28/2	1.22	3.75	0.56	15.00	F28/2	1.32	3.91	0.83	25.77
C29/2	1.89	3.97	0.72	25.77	F29/2	1.48	3.87	0.79	25.10
C30/2	1.32	3.83	0.65	18.37	F30/2	0.93	3.88	0.79	22.41
C31/2	1.35	3.84	0.72	21.73	F31/2	1.26	3.90	0.79	25.10
C32/2	1.78	4.04	0.85	29.82	F32/2	2.33	4.13	1.12	39.92
C33/2	2.13	4.06	0.97	31.16	F33/2	2.13	4.16	1.08	36.55
C34/2	1.13	3.89	0.79	21.73	F34/2	2.72	4.12	0.83	34.53
C35/2	1.37	3.92	0.76	25.77	F35/2	2.02	3.95	1.15	27.12
TZ1/2	1.24	4.10	0.29	28.74	TZ5/2	1.73	4.14	0.36	29.30
TZ2/2	0.85	4.02	0.32	24.77	TZ6/2	3.93	4.36	0.64	50.82
TZ3/2	2.05	4.29	0.31	36.10	TZ7/2	1.44	4.14	0.36	30.44
TZ4/2	2.47	4.35	0.41	40.63	TZ8/2	1.66	4.19	0.32	36.10
LT1/2	1.40	4.10	0.31	20.81	MT1/2	1.34	4.00	0.27	17.98
LT2/2	1.76	4.13	0.27	27.60	MT2/2	2.54	4.13	0.36	26.47
LT3/2	2.25	4.04	0.27	23.64	MT3/2	2.31	4.06	0.32	25.91
LT4/2	2.25	4.11	0.27	27.04	MT4/2	1.14	3.98	0.29	21.38
LT5/2	2.31	4.11	0.32	24.77	MT5/2	1.14	3.95	0.29	19.11
LT6/2	1.21	4.05	0.22	17.98	MT6/2	1.21	3.89	0.27	16.85
LT7/2	2.47	4.07	0.31	26.47	MT7/2	1.86	4.04	0.27	23.08
LT8/2	1.24	4.01	0.29	21.38	MT8/2	1.66	4.07	0.27	24.77
LT9/2	2.18	4.08	0.32	23.08	MT9/2	1.50	4.10	0.22	22.51
LT10/2	4.81	4.24	0.38	32.70	MT10/2	1.76	4.10	0.31	27.04
LT11/2	3.51	4.27	0.41	33.83	MT11/2	1.34	4.09	0.32	25.34
LT12/2	1.95	4.10	0.32	27.60	MT12/2	1.53	4.07	0.32	26.47
LT13/2	1.31	4.02	0.32	23.64	MT13/2	1.63	4.15	0.29	26.47
LT14/2	2.05	4.27	0.31	36.66	MT14/2	1.50	4.13	0.32	29.30
LT15/2	1.76	4.20	0.32	28.17	MT15/2	2.34	4.29	0.43	42.33
LT16/2	3.09	4.40	0.55	51.95	MT16/2	1.31	4.19	0.29	27.60
RT1/2	1.63	4.19	0.24	27.60	RT9/2	1.73	4.11	0.29	23.08
RT2/2	1.24	3.95	0.25	19.11	RT10/2	2.34	4.28	0.34	33.27
RT3/2	2.25	4.17	0.50	28.17	RT11/2	1.50	4.12	0.34	30.44
RT4/2	1.47	4.01	0.29	24.21	RT12/2	1.57	4.11	0.34	30.44
RT5/2	1.69	4.13	0.39	32.70	RT13/2	2.31	4.31	0.60	51.39
RT6/2	1.63	4.18	0.34	31.00	RT14/2	1.24	4.00	0.32	25.91
RT7/2	2.89	4.44	0.41	50.25	RT15/2	1.82	4.24	0.41	40.06
RT8/2	1.95	4.26	0.36	35.53	RT16/2	1.76	4.21	0.31	28.17

Table 12.16 Soil exchangeable manganese, extractable phosphorus and inorganic N levels, layer 1 samples, Burnt site 1992

Sample number	Exch. Mn $cmol_c\ kg^{-1}$	Extr P $mg\ P\ kg^{-1}$	NH_4-N $mg\ NH_4\text{-}N\ kg^{-1}$	Sample number	Exch. Mn $cmol_c\ kg^{-1}$	Extr P $mg\ P\ kg^{-1}$	NH_4-N $mg\ NH_4\text{-}N\ kg^{-1}$
C1/1	0.007	320	5.69	F1/1	0.007	500	16.16
C2/1	0.010	470	8.15	F2/1	0.007	670	12.72
C3/1	0.009	400	3.84	F3/1	0.006	500	7.11
C4/1	0.008	310	0.00	F4/1	0.010	340	5.08
C5/1	0.011	470	9.41	F5/1	0.006	490	13.78
C6/1	0.011	510	7.80	F6/1	0.013	590	15.98
C7/1	0.008	480	17.32	F7/1	0.014	490	13.48
C8/1	0.015	490	10.36	F8/1	0.014	1000	2.20
C9/1	0.012	490	23.27	F9/1	0.009	490	6.00
C10/1	0.009	440	6.24	F10/1	0.006	630	21.32
C11/1	0.008	520	3.48	F11/1	0.009	880	23.01
C12/1	0.007	560	2.82	F12/1	0.006	360	4.96
C13/1	0.007	580	6.40	F13/1	0.009	130	13.00
C14/1	0.008	600	5.96	F14/1	0.007	650	12.71
C15/1	0.010	540	7.41	F15/1	0.007	120	14.62
C16/1	0.009	480	3.55	F16/1	0.007	180	10.81
C17/1	0.007	570	2.84	F17/1	0.009	190	4.21
C18/1	0.007	450	19.98	F18/1	0.011	1210	18.57
C19/1	0.007	580	15.68	F19/1	0.007	880	6.00
C20/1	0.010	400	5.32	F20/1	0.014	650	18.19
C21/1	0.015	810	4.55	F21/1	0.008	520	11.04
C22/1	0.008	430	10.96	F22/1	0.012	390	13.91
C23/1	0.010	440	8.92	F23/1	0.006	340	9.84
C24/1	0.009	530	10.44	F24/1	0.009	740	14.71
C25/1	0.008	580	10.49	F25/1	0.007	350	15.05
C26/1	0.006	380	9.14	F26/1	0.008	440	11.93
C27/1	0.009	430	3.67	F27/1	0.007	460	19.76
C28/1	0.012	120	1.99	F28/1	0.008	310	13.80
C29/1	0.008	650	13.61	F29/1	0.007	570	13.96
C30/1	0.007	450	7.71	F30/1	0.006	150	9.80
C31/1	0.010	230	2.21	F31/1	0.006	550	12.36
C32/1	0.008	670	5.66	F32/1	0.006	190	17.01
C33/1	0.009	390	12.39	F33/1	0.010	490	13.41
C34/1	0.011	640	23.88	F34/1	0.010	270	18.15
C35/1	0.006	520	15.77	F35/1	0.006	530	16.08
TZ1/1	0.007	690	7.90	TZ5/1	0.005	360	7.52
TZ2/1	0.003	320	7.12	TZ6/1	0.017	530	7.38
TZ3/1	0.007	350	7.28	TZ7/1	0.008	620	9.38
TZ4/1	0.006	850	12.49	TZ8/1	0.010	930	11.98
LT1/1	0.006	280	2.78	MT1/1	0.010	380	3.41
LT2/1	0.005	400	2.39	MT2/1	0.003	490	4.90
LT3/1	0.003	260	1.31	MT3/1	0.010	240	4.47
LT4/1	0.007	390	2.03	MT4/1	0.005	410	6.50
LT5/1	0.009	580	6.79	MT5/1	0.006	570	5.18
LT6/1	0.007	220	1.17	MT6/1	0.005	280	1.20
LT7/1	0.005	270	2.04	MT7/1	0.003	270	4.58
LT8/1	0.005	550	3.55	MT8/1	0.006	530	6.66
LT9/1	0.008	290	1.47	MT9/1	0.011	480	6.53
LT10/1	0.013	360	3.41	MT10/1	0.008	660	5.36
LT11/1	0.009	520	5.58	MT11/1	0.008	790	1.54
LT12/1	0.009	450	2.85	MT12/1	0.009	1280	4.54
LT13/1	0.006	640	5.08	MT13/1	0.007	680	2.94
LT14/1	0.003	680	4.05	MT14/1	0.011	760	4.20
LT15/1	0.006	490	3.29	MT15/1	0.003	1050	7.62
LT16/1	0.006	980	5.43	MT16/1	0.002	380	4.96
RT1/1	0.008	410	2.62	RT9/1	0.007	540	9.20
RT2/1	0.006	340	4.72	RT10/1	0.009	690	9.93
RT3/1	0.006	280	4.53	RT11/1	0.005	500	8.21
RT4/1	0.003	390	6.16	RT12/1	0.011	560	4.62
RT5/1	0.003	260	6.11	RT13/1	0.010	650	7.39
RT6/1	0.007	360	5.72	RT14/1	0.007	840	5.68
RT7/1	0.004	820	8.27	RT15/1	0.006	810	4.97
RT8/1	0.006	850	6.63	RT16/1	0.007	630	4.40

All soil nitrate-N values were below the detectable limits.

Table 12.17 Soil exchangeable manganese, extractable phosphorus and inorganic N levels, layer 2 samples, Burnt site 1992

Sample number	Exch. Mn $cmol_c\ kg^{-1}$	Extr P $mg\ P\ kg^{-1}$	NH_4-N $mg\ NH_4\text{-}N\ kg^{-1}$	Sample number	Exch. Mn $cmol_c\ kg^{-1}$	Extr P $mg\ P\ kg^{-1}$	NH_4-N $mg\ NH_4\text{-}N\ kg^{-1}$
C1/2	0.003	230	2.36	F1/2	0.004	470	5.89
C2/2	0.005	240	3.12	F2/2	0.004	320	6.90
C3/2	0.004	200	0.20	F3/2	0.002	110	9.57
C4/2	0.010	230	1.01	F4/2	0.007	280	7.84
C5/2	0.006	370	8.18	F5/2	0.005	90	3.73
C6/2	0.004	350	26.85	F6/2	0.006	330	2.03
C7/2	0.001	300	9.88	F7/2	0.005	230	8.56
C8/2	0.005	280	13.52	F8/2	0.005	250	0.24
C9/2	0.005	340	7.50	F9/2	0.005	190	13.52
C10/2	0.004	290	3.88	F10/2	0.002	260	3.64
C11/2	0.005	290	8.64	F11/2	0.007	260	31.27
C12/2	0.004	260	5.98	F12/2	0.004	220	10.77
C13/2	0.005	310	7.56	F13/2	0.006	130	6.52
C14/2	0.003	210	7.44	F14/2	0.006	90	9.61
C15/2	0.004	310	8.97	F15/2	0.006	440	9.55
C16/2	0.004	200	6.29	F16/2	0.006	70	11.47
C17/2	0.007	460	0.33	F17/2	0.007	210	11.89
C18/2	0.006	300	8.36	F18/2	0.010	500	22.53
C19/2	0.004	240	11.52	F19/2	0.006	380	8.79
C20/2	0.006	270	5.03	F20/2	0.007	350	13.17
C21/2	0.005	400	4.33	F21/2	0.004	160	4.38
C22/2	0.005	290	4.08	F22/2	0.007	550	8.45
C23/2	0.006	380	13.36	F23/2	0.004	190	3.11
C24/2	0.006	230	12.65	F24/2	0.005	180	4.34
C25/2	0.004	290	7.50	F25/2	0.004	200	10.83
C26/2	0.005	430	12.48	F26/2	0.003	200	2.73
C27/2	0.005	210	6.86	F27/2	0.004	210	9.10
C28/2	0.004	380	6.93	F28/2	0.005	340	6.23
C29/2	0.006	220	7.93	F29/2	0.004	300	10.55
C30/2	0.004	190	9.10	F30/2	0.003	300	3.66
C31/2	0.004	220	5.11	F31/2	0.003	360	11.05
C32/2	0.004	430	12.45	F32/2	0.005	610	13.34
C33/2	0.006	410	13.66	F33/2	0.006	580	14.07
C34/2	0.004	260	8.84	F34/2	0.006	330	12.93
C35/2	0.005	320	15.36	F35/2	0.007	300	18.14
TZ1/2	0.006	280	6.70	TZ5/2	0.003	150	8.40
TZ2/2	0.002	70	4.47	TZ6/2	0.007	370	9.74
TZ3/2	0.003	290	7.39	TZ7/2	0.007	240	9.28
TZ4/2	0.005	440	14.45	TZ8/2	0.004	360	9.52
LT1/2	0.003	320	1.50	MT1/2	0.003	130	4.65
LT2/2	0.003	440	1.44	MT2/2	0.003	90	4.19
LT3/2	0.006	250	0.88	MT3/2	0.003	120	2.73
LT4/2	0.003	220	2.23	MT4/2	0.002	120	1.67
LT5/2	0.004	490	3.87	MT5/2	0.003	150	1.45
LT6/2	0.003	190	1.38	MT6/2	0.004	160	1.41
LT7/2	0.004	330	2.01	MT7/2	0.004	90	1.70
LT8/2	0.004	110	2.48	MT8/2	0.003	20	3.45
LT9/2	0.004	130	2.24	MT9/2	0.005	170	3.62
LT10/2	0.005	240	3.23	MT10/2	0.005	220	3.66
LT11/2	0.008	690	3.68	MT11/2	0.005	270	1.83
LT12/2	0.004	180	2.47	MT12/2	0.003	290	1.42
LT13/2	0.003	160	4.90	MT13/2	0.004	260	3.68
LT14/2	0.013	190	3.76	MT14/2	0.003	190	3.12
LT15/2	0.004	280	4.34	MT15/2	0.007	210	3.22
LT16/2	0.004	430	9.80	MT16/2	0.003	280	2.13
RT1/2	0.004	280	6.13	RT9/2	0.006	170	4.69
RT2/2	0.000	300	1.57	RT10/2	0.005	270	4.73
RT3/2	0.005	140	3.26	RT11/2	0.003	240	15.38
RT4/2	0.003	150	3.64	RT12/2	0.002	220	6.78
RT5/2	0.003	330	3.58	RT13/2	0.009	650	6.30
RT6/2	0.003	220	5.04	RT14/2	0.005	200	10.55
RT7/2	0.004	320	6.26	RT15/2	0.003	140	7.72
RT8/2	0.003	320	6.34	RT16/2	0.003	190	6.89

All soil nitrate-N values were below the detectable limits.

Table 12.18 Soil pH and redox potential (Eh_7), layer 1 samples, Burnt site 1992

Sample number	pH	redox mV (NHE)	Sample number	pH	redox mV (NHE)
C1/1	6.10	60	F1/1	6.33	-139
C2/1	6.54	-147	F2/1	6.55	-156
C3/1	6.51	-188	F3/1	7.14	-149
C4/1	6.76	-178	F4/1	6.59	-142
C5/1	6.22	-152	F5/1	6.35	-144
C6/1	6.11	-102	F6/1	6.12	-67
C7/1	5.80	-130	F7/1	6.65	-133
C8/1	6.08	-148	F8/1	6.46	-149
C9/1	5.92	-165	F9/1	6.16	-123
C10/1	6.02	-155	F10/1	6.81	-157
C11/1	5.38	-97	F11/1	6.33	-89
C12/1	6.19	-158	F12/1	5.84	-108
C13/1	6.24	-159	F13/1	6.41	-153
C14/1	6.55	-189	F14/1	6.27	-143
C15/1	6.34	-172	F15/1	6.05	-126
C16/1	6.52	-134	F16/1	6.02	-87
C17/1	6.52	-58	F17/1	6.53	-147
C18/1	6.04	-136	F18/1	6.34	-138
C19/1	6.52	-145	F19/1	6.55	-163
C20/1	6.47	-163	F20/1	5.28	-109
C21/1	6.94	-167	F21/1	6.54	-160
C22/1	6.74	-167	F22/1	6.60	-151
C23/1	6.41	-129	F23/1	5.21	-24
C24/1	6.35	-150	F24/1	6.39	-127
C25/1	6.40	-146	F25/1	5.91	-30
C26/1	7.38	-164	F26/1	5.43	24
C27/1	7.18	-96	F27/1	5.00	-6
C28/1	7.21	-142	F28/1	5.30	-36
C29/1	7.22	-144	F29/1	5.95	-119
C30/1	7.06	-72	F30/1	6.34	-154
C31/1	7.08	-157	F31/1	6.25	-115
C32/1	7.00	-167	F32/1	6.44	-128
C33/1	6.75	-163	F33/1	6.76	-169
C34/1	6.98	-161	F34/1	6.26	-116
C35/1	6.44	-118	F35/1	6.41	-116
TZ1/1	5.71	-135	TZ5/1	6.63	-168
TZ2/1	5.43	-134	TZ6/1	6.52	-56
TZ3/1	6.22	-158	TZ7/1	6.50	-128
TZ4/1	6.59	-148	TZ8/1	6.95	-105
LT1/1	6.80	197	MT1/1	6.78	55
LT2/1	7.05	-87	MT2/1	7.05	-194
LT3/1	7.19	156	MT3/1	7.46	-237
LT4/1	7.19	77	MT4/1	6.85	95
LT5/1	7.02	34	MT5/1	7.09	74
LT6/1	6.86	107	MT6/1	6.77	101
LT7/1	7.25	80	MT7/1	7.06	183
LT8/1	7.22	250	MT8/1	7.12	40
LT9/1	6.83	232	MT9/1	7.42	253
LT10/1	7.55	254	MT10/1	6.63	285
LT11/1	6.51	254	MT11/1	6.34	326
LT12/1	6.89	-78	MT12/1	5.77	-32
LT13/1	6.86	-7	MT13/1	6.21	17
LT14/1	6.54	-95	MT14/1	6.47	1
LT15/1	6.43	-4	MT15/1	5.85	-221
LT16/1	5.83	-80	MT16/1	5.41	96
RT1/1	7.27	172	RT9/1	7.12	222
RT2/1	6.76	40	RT10/1	6.79	281
RT3/1	6.93	102	RT11/1	6.79	314
RT4/1	6.98	200	RT12/1	6.55	323
RT5/1	7.32	-155	RT13/1	6.79	-170
RT6/1	7.16	43	RT14/1	6.48	119
RT7/1	6.75	-264	RT15/1	5.41	136
RT8/1	7.39	15	RT16/1	5.80	86

Table 12.19 Soil pH and redox potential (Eh_7), layer 2 samples, Burnt site 1992

Sample number	pH	redox mV (NHE)	Sample number	pH	redox mV (NHE)
C1/2	6.01	-54	F1/2	5.83	-52
C2/2	5.98	-13	F2/2	5.46	-31
C3/2	5.94	-113	F3/2	5.80	16
C4/2	6.67	-17	F4/2	6.14	-3
C5/2	6.28	-151	F5/2	5.64	37
C6/2	6.09	-75	F6/2	5.72	16
C7/2	5.84	-122	F7/2	5.96	-30
C8/2	6.09	-16	F8/2	5.80	17
C9/2	5.96	-127	F9/2	5.59	-44
C10/2	5.73	-64	F10/2	5.84	-20
C11/2	6.11	-84	F11/2	5.70	-33
C12/2	5.80	-110	F12/2	5.59	-21
C13/2	6.06	-16	F13/2	6.17	-118
C14/2	6.34	-139	F14/2	5.32	1
C15/2	5.95	-78	F15/2	5.59	0
C16/2	6.01	-117	F16/2	5.42	21
C17/2	6.25	-114	F17/2	5.38	-16
C18/2	5.88	-44	F18/2	5.73	-21
C19/2	5.82	-75	F19/2	5.77	11
C20/2	6.29	-4	F20/2	5.51	-32
C21/2	6.31	-63	F21/2	5.49	31
C22/2	6.12	-91	F22/2	6.09	146
C23/2	6.02	-29	F23/2	5.48	64
C24/2	6.40	-50	F24/2	5.48	-18
C25/2	6.26	-73	F25/2	5.46	-14
C26/2	6.79	-53	F26/2	5.66	32
C27/2	7.18	-129	F27/2	5.46	-30
C28/2	7.04	-51	F28/2	6.00	-28
C29/2	7.03	-111	F29/2	5.37	20
C30/2	6.62	66	F30/2	6.33	-120
C31/2	7.00	-147	F31/2	5.54	67
C32/2	5.14	-9	F32/2	5.80	63
C33/2	6.18	-46	F33/2	5.86	13
C34/2	6.33	-6	F34/2	5.78	-17
C35/2	5.91	-52	F35/2	5.87	-40
TZ1/2	5.21	-38	TZ5/2	6.37	-10
TZ2/2	5.11	13	TZ6/2	6.22	-94
TZ3/2	5.26	-28	TZ7/2	5.99	-52
TZ4/2	6.05	-43	TZ8/2	5.80	38
LT1/2	6.80	-158	MT1/2	7.40	237
LT2/2	7.10	61	MT2/2	6.93	-53
LT3/2	7.26	175	MT3/2	7.29	18
LT4/2	7.13	-70	MT4/2	6.86	59
LT5/2	7.26	47	MT5/2	7.25	-80
LT6/2	6.87	7	MT6/2	6.88	26
LT7/2	7.14	77	MT7/2	6.72	0
LT8/2	7.21	114	MT8/2	7.07	30
LT9/2	7.41	231	MT9/2	6.93	265
LT10/2	7.31	272	MT10/2	7.39	274
LT11/2	6.76	302	MT11/2	7.08	289
LT12/2	6.24	-111	MT12/2	5.73	-64
LT13/2	6.81	-274	MT13/2	6.34	311
LT14/2	5.58	-193	MT14/2	5.87	78
LT15/2	6.47	-63	MT15/2	6.20	125
LT16/2	5.80	159	MT16/2	5.77	217
RT1/2	7.56	315	RT9/2	7.17	230
RT2/2	6.92	-117	RT10/2	6.89	238
RT3/2	7.07	-181	RT11/2	7.24	277
RT4/2	7.11	167	RT12/2	6.53	316
RT5/2	7.10	-68	RT13/2	6.40	-28
RT6/2	7.01	-48	RT14/2	6.03	107
RT7/2	6.78	-91	RT15/2	6.06	127
RT8/2	7.30	168	RT16/2	5.96	137

Table 12.20 Plant root abundancy, layer 1 samples, Burnt site 1992

Sample number	Very fine roots	Fine roots	Medium roots	Coarse roots	Sample number	Very fine roots	Fine roots	Medium roots	Coarse roots
C1/1	-	abundant	-	common	F1/1	abundant	common	few	-
C2/1	-	abundant	-	-	F2/1	abundant	many	few	few
C3/1	-	abundant	common	few	F3/1	-	-	few	-
C4/1	-	abundant	-	-	F4/1	abundant	-	-	-
C5/1	-	abundant	common	-	F5/1	abundant	many	-	-
C6/1	many	-	-	few	F6/1	abundant	common	-	few
C7/1	-	abundant	common	common	F7/1	-	abundant	many	few
C8/1	-	abundant	-	-	F8/1	-	abundant	common	many
C9/1	-	abundant	-	-	F9/1	-	abundant	few	few
C10/1	-	abundant	-	-	F10/1	-	abundant	-	-
C11/1	-	abundant	-	-	F11/1	abundant	few	few	-
C12/1	-	abundant	-	-	F12/1	abundant	common	few	-
C13/1	-	abundant	-	many	F13/1	abundant	few	-	few
C14/1	-	abundant	-	-	F14/1	abundant	many	-	few
C15/1	-	abundant	-	-	F15/1	abundant	common	few	-
C16/1	-	abundant	-	-	F16/1	abundant	few	-	-
C17/1	-	abundant	-	few	F17/1	abundant	many	-	-
C18/1	-	abundant	-	-	F18/1	abundant	-	many	-
C19/1	-	abundant	-	common	F19/1	abundant	-	common	-
C20/1	-	abundant	-	-	F20/1	abundant	-	common	-
C21/1	-	abundant	-	common	F21/1	abundant	few	common	-
C22/1	-	abundant	-	common	F22/1	abundant	-	many	-
C23/1	-	abundant	-	common	F23/1	abundant	-	many	-
C24/1	-	abundant	many	-	F24/1	-	abundant	common	-
C25/1	abundant	abundant	few	-	F25/1	-	-	many	-
C26/1	abundant	many	-	-	F26/1	abundant	few	-	-
C27/1	abundant	common	few	-	F27/1	abundant	-	common	-
C28/1	abundant	many	common	-	F28/1	-	abundant	common	-
C29/1	abundant	many	common	-	F29/1	abundant	many	common	-
C30/1	abundant	many	-	few	F30/1	abundant	common	many	-
C31/1	abundant	many	common	-	F31/1	-	abundant	few	-
C32/1	abundant	abundant	few	-	F32/1	abundant	common	few	-
C33/1	abundant	abundant	-	-	F33/1	-	abundant	common	-
C34/1	abundant	abundant	many	-	F34/1	-	abundant	many	-
C35/1	abundant	abundant	few	few	F35/1	abundant	abundant	-	-
TZ1/1	abundant	few	few	-	TZ5/1	abundant	many	common	-
TZ2/1	abundant	many	many	-	TZ6/1	abundant	common	common	-
TZ3/1	many	few	few	-	TZ7/1	abundant	few	many	-
TZ4/1	abundant	many	common	-	TZ8/1	abundant	many	many	-
LT1/1	abundant	many	many	-	MT1/1	abundant	many	many	-
LT2/1	abundant	many	few	-	MT2/1	abundant	many	many	-
LT3/1	abundant	many	few	-	MT3/1	abundant	common	many	-
LT4/1	abundant	many	many	few	MT4/1	abundant	few	many	-
LT5/1	abundant	few	many	-	MT5/1	abundant	-	many	-
LT6/1	abundant	many	many	-	MT6/1	abundant	common	many	-
LT7/1	abundant	few	common	-	MT7/1	abundant	many	common	-
LT8/1	abundant	many	few	-	MT8/1	abundant	many	many	-
LT9/1	abundant	many	few	few	MT9/1	abundant	many	few	-
LT10/1	abundant	many	few	-	MT10/1	abundant	abundant	many	-
LT11/1	abundant	-	few	-	MT11/1	abundant	few	-	few
LT12/1	abundant	many	many	-	MT12/1	abundant	abundant	many	-
LT13/1	many	abundant	many	-	MT13/1	abundant	many	common	-
LT14/1	abundant	-	few	-	MT14/1	abundant	-	-	-
LT15/1	abundant	few	few	few	MT15/1	abundant	many	-	few
LT16/1	abundant	many	few	-	MT16/1	abundant	few	-	few
RT1/1	abundant	few	few	-	RT9/1	abundant	many	common	-
RT2/1	abundant	common	many	many	RT10/1	abundant	many	few	-
RT3/1	many	many	few	-	RT11/1	abundant	few	many	-
RT4/1	abundant	few	many	-	RT12/1	abundant	-	few	-
RT5/1	abundant	many	few	few	RT13/1	abundant	many	few	-
RT6/1	abundant	many	many	few	RT14/1	abundant	abundant	many	-
RT7/1	abundant	common	many	-	RT15/1	abundant	many	-	-
RT8/1	abundant	many	many	many	RT16/1	abundant	many	few	few

Root abundancy classes follow those advocated by the Soil Survey of England & Wales (1976)
Hyphens indicate that no roots of the indicated size were recorded in the sample.

Table 12.21 Plant root abundancy, layer 2 samples, Burnt site 1992

Sample number	Very fine roots	Fine roots	Medium roots	Coarse roots	Sample number	Very fine roots	Fine roots	Medium roots	Coarse roots
C1/2	-	many	few	-	F1/2	abundant	common	-	-
C2/2	-	common	-	few	F2/2	abundant	few	few	-
C3/2	common	common	-	-	F3/2	-	abundant	few	few
C4/2	-	many	-	-	F4/2	abundant	common	common	-
C5/2	-	many	-	-	F5/2	abundant	common	-	-
C6/2	-	many	-	-	F6/2	abundant	few	-	-
C7/2	-	common	few	-	F7/2	-	abundant	-	-
C8/2	-	common	-	-	F8/2	abundant	common	-	-
C9/2	-	common	-	-	F9/2	abundant	-	common	-
C10/2	common	-	-	-	F10/2	-	abundant	-	few
C11/2	-	common	-	-	F11/2	abundant	few	many	few
C12/2	-	common	-	-	F12/2	abundant	-	-	common
C13/2	-	few	-	-	F13/2	-	abundant	common	-
C14/2	-	few	-	-	F14/2	abundant	-	-	few
C15/2	-	-	common	-	F15/2	abundant	common	-	-
C16/2	-	few	-	-	F16/2	abundant	few	common	-
C17/2	-	abundant	-	common	F17/2	abundant	common	few	-
C18/2	abundant	-	-	-	F18/2	abundant	common	few	-
C19/2	common	-	-	-	F19/2	abundant	-	common	few
C20/2	-	common	-	-	F20/2	abundant	-	-	-
C21/2	-	many	-	-	F21/2	abundant	many	common	-
C22/2	-	many	-	-	F22/2	abundant	-	many	-
C23/2	many	-	-	-	F23/2	abundant	-	many	-
C24/2	many	-	-	-	F24/2	-	abundant	common	few
C25/2	many	-	few	-	F25/2	-	abundant	-	few
C26/2	abundant	-	-	-	F26/2	abundant	-	common	-
C27/2	-	abundant	-	-	F27/2	abundant	-	few	-
C28/2	many	-	few	-	F28/2	abundant	-	many	-
C29/2	abundant	-	-	-	F29/2	abundant	-	many	few
C30/2	abundant	-	-	-	F30/2	many	common	-	-
C31/2	-	many	common	-	F31/2	many	-	few	-
C32/2	many	many	-	-	F32/2	abundant	-	few	-
C33/2	abundant	-	common	-	F33/2	many	few	few	-
C34/2	abundant	abundant	-	-	F34/2	many	-	-	few
C35/2	abundant	abundant	-	few	F35/2	abundant	-	common	-
TZ1/2	abundant	-	-	-	TZ5/2	many	-	-	-
TZ2/2	abundant	few	few	-	TZ6/2	abundant	few	few	-
TZ3/2	abundant	-	common	-	TZ7/2	many	common	common	-
TZ4/2	many	-	common	-	TZ8/2	abundant	few	common	-
LT1/2	abundant	many	common	-	MT1/2	many	many	many	-
LT2/2	many	many	-	-	MT2/2	-	common	few	-
LT3/2	many	-	common	-	MT3/2	many	common	few	-
LT4/2	abundant	few	few	-	MT4/2	-	common	many	-
LT5/2	many	-	common	-	MT5/2	many	many	few	-
LT6/2	many	-	-	-	MT6/2	many	common	few	-
LT7/2	many	-	-	-	MT7/2	abundant	-	-	few
LT8/2	common	-	-	-	MT8/2	many	many	common	-
LT9/2	many	-	-	-	MT9/2	-	abundant	-	few
LT10/2	many	many	common	-	MT10/2	many	few	few	-
LT11/2	many	-	many	-	MT11/2	abundant	-	few	-
LT12/2	many	many	few	-	MT12/2	abundant	abundant	few	-
LT13/2	many	-	-	-	MT13/2	abundant	-	few	-
LT14/2	abundant	many	common	-	MT14/2	abundant	many	few	-
LT15/2	abundant	-	-	-	MT15/2	many	many	-	-
LT16/2	abundant	-	-	-	MT16/2	abundant	-	-	few
RT1/2	many	few	few	-	RT9/2	many	-	common	-
RT2/2	many	many	common	-	RT10/2	abundant	-	few	-
RT3/2	common	-	few	-	RT11/2	abundant	-	few	-
RT4/2	abundant	many	few	-	RT12/2	many	few	-	-
RT5/2	abundant	many	few	-	RT13/2	abundant	few	many	many
RT6/2	many	many	few	-	RT14/2	many	-	few	-
RT7/2	many	common	common	-	RT15/2	abundant	abundant	common	-
RT8/2	many	few	many	-	RT16/2	abundant	-	few	-

Root abundancy classes follow those advocated by the Soil Survey of England & Wales (1976)
Hyphens indicate that no roots of the indicated size were recorded in the sample.

Table 12.22 Dominant soil colour, layers 1 & 2, Burnt site 1992

Sample number	Munsell colour	Sample number	Munsell colour	Sample number	Munsell colour	Sample number	Munsell colour
C1/1	10YR 3/3	F1/1	10YR 4/3	C1/2	10YR 3/3	F1/2	10YR 7/1
C2/1	10YR 2/1	F2/1	10YR 5/3	C2/2	10YR 6/1	F2/2	10YR 5/4
C3/1	10YR 3/1	F3/1	10YR 3/3	C3/2	10YR 7/1	F3/2	10YR 5/1
C4/1	10YR 3/2	F4/1	10YR 3/2	C4/2	10YR 3/2	F4/2	10YR 5/2
C5/1	10YR 3/3	F5/1	10YR 3/4	C5/2	10YR 4/2	F5/2	10YR 4/2
C6/1	10YR 3/1	F6/1	10YR 4/2	C6/2	10YR 3/3	F6/2	10YR 4/2
C7/1	10YR 2/2	F7/1	10YR 3/3	C7/2	10YR 5/2	F7/2	10YR 5/2
C8/1	10YR 3/3	F8/1	10YR 4/2	C8/2	10YR 5/3	F8/2	10YR 5/1
C9/1	10YR 3/2	F9/1	10YR 2/2	C9/2	10YR 5/1	F9/2	10YR 6/1
C10/1	10YR 3/2	F10/1	10YR 5/1	C10/2	10YR 5/1	F10/2	10YR 6/2
C11/1	10YR 4/2	F11/1	10YR 4/3	C11/2	10YR 4/3	F11/2	10YR 3/1
C12/1	10YR 4/1	F12/1	10YR 3/2	C12/2	10YR 5/2	F12/2	10YR 5/2
C13/1	10YR 3/3	F13/1	10YR 2/2	C13/2	10YR 6/1	F13/2	10YR 5/2
C14/1	10YR 4/2	F14/1	10YR 3/4	C14/2	10YR 5/1	F14/2	10YR 3/3
C15/1	10YR 3/4	F15/1	10YR 3/3	C15/2	10YR 5/1	F15/2	10YR 4/3
C16/1	10YR 3/2	F16/1	10YR 5/1	C16/2	10YR 6/1	F16/2	10YR 5/2
C17/1	10YR 8/1	F17/1	10YR 3/4	C17/2	10YR 3/3	F17/2	10YR 4/4
C18/1	10YR 5/4	F18/1	10YR 2/2	C18/2	10YR 5/3	F18/2	10YR 3/1
C19/1	10YR 4/3	F19/1	10YR 4/2	C19/2	10YR 4/2	F19/2	10YR 5/3
C20/1	10YR 3/2	F20/1	10YR 5/3	C20/2	10YR 5/2	F20/2	10YR 3/3
C21/1	10YR 3/4	F21/1	10YR 3/2	C21/2	10YR 3/3	F21/2	10YR 5/3
C22/1	10YR 3/2	F22/1	10YR 3/3	C22/2	10YR 5/2	F22/2	10YR 5/2
C23/1	10YR 4/2	F23/1	10YR 3/3	C23/2	10YR 5/2	F23/2	10YR 6/1
C24/1	10YR 3/3	F24/1	10YR 3/4	C24/2	10YR 4/1	F24/2	10YR 5/1
C25/1	10YR 3/4	F25/1	10YR 3/4	C25/2	10YR 3/2	F25/2	10YR 5/2
C26/1	10YR 3/3	F26/1	10YR 3/2	C26/2	10YR 5/3	F26/2	10YR 5/2
C27/1	10YR 3/2	F27/1	10YR 3/3	C27/2	5Y 5/1	F27/2	10YR 5/2
C28/1	10YR 3/1	F28/1	10YR 3/2	C28/2	10YR 5/1	F28/2	10YR 3/3
C29/1	10YR 4/2	F29/1	10YR 3/4	C29/2	10YR 3/3	F29/2	10YR 5/2
C30/1	10YR 3/4	F30/1	10YR 4/2	C30/2	10YR 4/1	F30/2	10YR 5/2
C31/1	10YR 3/3	F31/1	10YR 3/2	C31/2	10YR 4/1	F31/2	10YR 5/3
C32/1	10YR 3/2	F32/1	10YR 4/2	C32/2	10YR 5/1	F32/2	10YR 4/2
C33/1	10YR 4/2	F33/1	10YR 3/2	C33/2	10YR 5/2	F33/2	10YR 4/1
C34/1	10YR 3/3	F34/1	10YR 3/3	C34/2	10YR 5/1	F34/2	10YR 6/2
C35/1	10YR 4/2	F35/1	10YR 3/3	C35/2	10YR 4/2	F35/2	10YR 2/2
TZ1/1	10YR 3/3	TZ5/1	10YR 3/4	TZ1/2	10YR 6/2	TZ5/2	10YR 4/2
TZ2/1	10YR 4/3	TZ6/1	10YR 3/2	TZ2/2	10YR 5/1	TZ6/2	10YR 3/2
TZ3/1	10YR 3/3	TZ7/1	10YR 3/4	TZ3/2	10YR 5/2	TZ7/2	10YR 6/2
TZ4/1	10YR 2/2	TZ8/1	10YR 2/2	TZ4/2	10YR 4/2	TZ8/2	10YR 5/2
LT1/1	10YR 3/3	MT1/1	10YR 4/2	LT1/2	10YR 6/2	MT1/2	10YR 5/3
LT2/1	10YR 5/1	MT2/1	10YR 3/2	LT2/2	10YR 6/2	MT2/2	10YR 6/2
LT3/1	10YR 6/1	MT3/1	10YR 3/2	LT3/2	10YR 5/2	MT3/2	10YR 5/2
LT4/1	10YR 3/2	MT4/1	10YR 5/2	LT4/2	10YR 6/2	MT4/2	10YR 6/2
LT5/1	10YR 4/2	MT5/1	10YR 3/3	LT5/2	10YR 6/2	MT5/2	10YR 5/1
LT6/1	10YR 5/1	MT6/1	10YR 3/2	LT6/2	10YR 5/1	MT6/2	10YR 7/1
LT7/1	10YR 3/3	MT7/1	10YR 3/2	LT7/2	10YR 5/1	MT7/2	10YR 6/2
LT8/1	10YR 4/2	MT8/1	10YR 4/3	LT8/2	10YR 6/2	MT8/2	10YR 6/2
LT9/1	10YR 3/2	MT9/1	10YR 3/3	LT9/2	10YR 6/2	MT9/2	10YR 5/1
LT10/1	10YR 3/3	MT10/1	10YR 3/3	LT10/2	10YR 5/2	MT10/2	10YR 5/2
LT11/1	10YR 3/4	MT11/1	10YR 3/3	LT11/2	10YR 6/1	MT11/2	10YR 6/2
LT12/1	10YR 4/2	MT12/1	10YR 3/4	LT12/2	10YR 6/1	MT12/2	10YR 5/3
LT13/1	10YR 3/3	MT13/1	10YR 3/6	LT13/2	10YR 5/1	MT13/2	10YR 5/1
LT14/1	10YR 3/3	MT14/1	10YR 3/4	LT14/2	10YR 4/1	MT14/2	10YR 4/1
LT15/1	10YR 4/2	MT15/1	10YR 4/2	LT15/2	10YR 6/2	MT15/2	10YR 5/2
LT16/1	10YR 4/2	MT16/1	10YR 3/4	LT16/2	10YR 3/4	MT16/2	10YR 6/2
RT1/1	10YR 4/2	RT9/1	10YR 4/2	RT1/2	10YR 5/2	RT9/2	10YR 5/2
RT2/1	10YR 3/3	RT10/1	10YR 4/6	RT2/2	10YR 5/1	RT10/2	10YR 5/3
RT3/1	10YR 5/3	RT11/1	10YR 3/4	RT3/2	10YR 5/1	RT11/2	10YR 5/2
RT4/1	10YR 3/3	RT12/1	10YR 3/2	RT4/2	10YR 7/1	RT12/2	10YR 6/2
RT5/1	10YR 3/3	RT13/1	10YR 3/3	RT5/2	10YR 5/2	RT13/2	10YR 4/2
RT6/1	10YR 3/2	RT14/1	10YR 4/3	RT6/2	10YR 5/1	RT14/2	10YR 4/3
RT7/1	10YR 3/2	RT15/1	10YR 3/4	RT7/2	10YR 5/1	RT15/2	10YR 4/2
RT8/1	10YR 4/2	RT16/1	10YR 4/2	RT8/2	10YR 5/3	RT16/2	10YR 5/1

Table 12.23 Water pH, conductivity and dissolved oxygen content, Burnt site 1992

Sample number	Field water pH	Conductivity mS (25°C)	Dissolved O_2 mgl^{-1}	Sample number	Field water pH	Conductivity mS (25°C)	Dissolved O_2 mgl^{-1}
C1	7.39	1.36	1.10	F1	6.76	1.76	6.00
C2	7.21	1.24	0.20	F2	6.65	1.94	6.00
C3	7.23	1.33	0.20	F3	6.48	2.16	6.00
C4	7.32	1.15	0.10	F4	6.36	1.82	2.60
C5	7.22	1.26	0.10	F5	6.23	1.82	6.00
C6	7.35	1.20	2.20	F6	6.26	1.91	6.00
C7	7.16	1.22	0.10	F7	6.16	2.16	6.00
C8	7.41	1.22	2.90	F8	6.35	1.87	0.00
C9	7.28	1.29	0.80	F9	6.11	1.93	5.60
C10	7.34	1.27	1.90	F10	6.02	1.79	6.00
C11	7.41	1.34	3.70	F11	5.57	2.98	0.00
C12	7.37	1.28	2.30	F12	6.04	1.73	6.00
C13	7.39	1.35	1.10	F13	5.65	3.71	0.20
C14	7.35	1.33	1.20	F14	5.88	2.17	0.30
C15	7.27	1.36	1.20	F15	5.79	1.65	6.00
C16	7.50	1.37	0.50	F16	5.81	1.62	6.00
C17	7.37	1.36	0.70	F17	5.81	1.81	3.75
C18	7.36	1.36	0.80	F18	5.67	1.69	0.90
C19	7.31	1.37	2.20	F19	5.71	1.72	0.40
C20	7.34	1.37	3.50	F20	5.73	1.23	3.60
C21	7.30	1.42	0.40	F21	5.73	1.12	0.40
C22	7.31	1.45	0.90	F22	5.34	1.17	0.50
C23	7.36	1.37	2.80	F23	6.28	1.53	3.10
C24	7.33	1.23	0.40	F24	5.75	1.40	1.10
C25	7.41	1.23	1.40	F25	5.68	1.57	2.50
C26	7.34	1.18	1.50	F26	5.87	1.47	4.00
C27	7.36	1.24	1.20	F27	5.98	1.47	3.90
C28	7.42	1.19	1.50	F28	5.79	1.09	2.30
C29	7.31	1.27	1.80	F29	5.97	1.24	3.90
C30	7.37	1.20	1.70	F30	5.84	1.38	3.20
C31	7.27	1.22	0.10	F31	6.04	1.23	3.90
C32	7.41	1.20	2.20	F32	5.90	1.38	1.20
C33	7.42	1.20	2.40	F33	5.90	1.44	3.00
C34	7.34	1.23	1.00	F34	6.01	1.42	3.50
C35	7.42	1.15	2.00	F35	5.89	1.51	4.00
TZ1	6.69	2.02	6.00	TZ5	6.08	5.80	1.70
TZ2	6.75	1.74	6.00	TZ6	6.81	2.09	6.00
TZ3	6.67	2.19	6.00	TZ7	6.25	4.08	0.20
TZ4	5.99	4.68	2.70	TZ8	6.16	3.89	6.00
LT1	7.05	2.40	n/s	MT1	6.97	2.55	n/s
LT2	7.02	2.30	n/s	MT2	7.01	2.53	n/s
LT3	6.93	2.22	n/s	MT3	7.08	2.33	n/s
LT4	6.90	2.05	n/s	MT4	7.05	2.26	n/s
LT5	7.02	2.25	n/s	MT5	7.01	2.30	n/s
LT6	6.91	2.09	n/s	MT6	7.01	2.20	n/s
LT7	6.85	2.02	n/s	MT7	6.96	2.15	n/s
LT8	7.01	2.02	n/s	MT8	6.90	2.00	n/s
LT9	7.09	2.05	n/s	MT9	6.96	2.09	n/s
LT10	7.23	2.10	n/s	MT10	9.89	2.06	n/s
LT11	6.94	2.04	n/s	MT11	7.00	1.88	n/s
LT12	6.70	1.92	n/s	MT12	6.92	1.71	n/s
LT13	6.89	1.72	n/s	MT13	6.91	1.87	n/s
LT14	7.09	1.82	n/s	MT14	6.87	1.78	n/s
LT15	6.76	1.61	n/s	MT15	6.77	1.64	n/s
LT16	6.97	1.46	n/s	MT16	6.77	1.66	n/s
RT1	6.79	2.52	n/s	RT9	6.89	2.03	n/s
RT2	6.99	2.46	n/s	RT10	6.85	1.98	n/s
RT3	6.98	2.21	n/s	RT11	6.94	1.80	n/s
RT4	6.86	2.05	n/s	RT12	6.92	1.79	n/s
RT5	6.98	2.16	n/s	RT13	6.82	1.56	n/s
RT6	6.64	2.14	n/s	RT14	6.83	1.56	n/s
RT7	6.66	1.84	n/s	RT15	6.45	1.50	n/s
RT8	6.79	2.00	n/s	RT16	6.91	1.47	n/s

n/s = *not sampled*

Table 12.24 Soil sulphate-sulphur and total iron levels, Burnt site 1992

Sample number	SO_4-S g kg^{-1} soil	Total Fe g Fe kg^{-1}	Sample number	SO_4-S g kg^{-1} soil	Total Fe g Fe kg^{-1}
RT1/1	5.13	1.92	RT1/2	4.38	2.24
RT2/1	6.00	4.43	RT2/2	3.25	1.93
RT3/1	6.25	2.95	RT3/2	5.50	5.21
RT4/1	3.38	0.83	RT4/2	4.50	4.80
RT5/1	3.75	1.26	RT5/2	4.38	2.05
RT6/1	5.00	0.76	RT6/2	4.75	3.19
RT7/1	3.25	0.44	RT7/2	6.00	1.22
RT8/1	5.75	0.25	RT8/2	4.50	1.28
RT9/1	3.25	0.82	RT9/2	4.00	2.82
RT10/1	5.00	1.07	RT10/2	4.75	1.44
RT11/1	3.50	0.68	RT11/2	3.75	1.70
RT12/1	5.50	2.50	RT12/2	4.25	1.41
RT13/1	6.25	0.51	RT13/2	5.25	1.11
RT14/1	5.13	1.65	RT14/2	4.25	4.83
RT15/1	7.00	0.66	RT15/2	6.50	6.58
RT16/1	5.25	1.77	RT16/2	4.50	2.09

Table 12.25 Transect litter depth and insolation data, Burnt site 1992

Sample number	Litter depth (cm)	Insolation (nominal)	Sample number	Litter depth (cm)	Insolation (nominal)	Sample number	Litter depth (cm)	Insolation (nominal)
LT1/1	0.00	11.0	MT1/1	0.00	11.0	RT1/1	0.00	12.0
LT2/1	0.00	11.0	MT2/1	0.00	10.0	RT2/1	0.00	13.0
LT3/1	0.00	11.5	MT3/1	0.00	11.0	RT3/1	0.50	11.0
LT4/1	0.50	11.0	MT4/1	0.50	9.0	RT4/1	0.50	8.0
LT5/1	0.50	10.0	MT5/1	0.50	12.0	RT5/1	0.50	12.0
LT6/1	0.50	11.5	MT6/1	0.50	8.0	RT6/1	0.50	11.0
LT7/1	0.50	10.0	MT7/1	0.50	12.0	RT7/1	0.50	9.0
LT8/1	0.50	9.5	MT8/1	0.50	11.5	RT8/1	0.50	9.0
LT9/1	0.50	8.5	MT9/1	0.50	8.5	RT9/1	0.50	8.5
LT10/1	0.50	10.0	MT10/1	0.50	11.0	RT10/1	0.50	10.5
LT11/1	0.50	10.5	MT11/1	1.00	11.5	RT11/1	1.00	12.0
LT12/1	1.00	9.0	MT12/1	1.00	9.0	RT12/1	1.00	9.0
LT13/1	1.50	9.5	MT13/1	1.50	9.5	RT13/1	1.50	10.5
LT14/1	1.00	9.0	MT14/1	1.50	8.5	RT14/1	2.00	10.0
LT15/1	2.00	13.0	MT15/1	1.00	11.0	RT15/1	2.00	10.0
LT16/1	2.00	12.0	MT16/1	1.00	8.0	RT16/1	1.50	8.5

1994 Field site data

The data gathered along the 1994 transects are presented below. Three transects, 2.5 m apart were laid out at the Punta del Este field site, and one each at the Texaco and Burnt field sites. At the Texaco and Burnt sites, some measurements were repeated on different occasions. Sampling sites are identified using a combination of numbers and letters, e.g. **PLT12**, **TEX1**.

The letters indicate the field site and transect line along which the sample lies:

PLT Punta del Este field site, left transect
PMT Punta del Este field site, middle transect
PRT Punta del Este field site, right transect

TEX Texaco field site transect
BC Burnt site transect.

The number indicates the sample point's position along the sample line. Sample points with a suffix of 1 (i.e. **PLT1**, **TEX1** and **BC1**) lie furthest into the cleared zone, sample points with a suffix of 7 lie on the cut edge and sample points with a suffix of 13 are furthest into the forest.

Where sampling at the same location has been repeated on different days, measurements are differentiated using a further set of letters. For example at the Texaco site, the first water sulphate sample taken at the cut edge is labelled as sample **TEX1a**, returning the next day, the sample gathered at the same location is labelled as **TEX1b**.

Where soil samples have been taken at different depths, they are differentiated using a further set of numbers. For example at site **PLT1**, the sample nearest the surface is sample **PLT1/1**, below this lies sample **PLT1/2**, below that sample **PLT1/3**, etc.

The data are arranged as follows:

Table 12.26 Soil pH and redox potential, 1994 field sites
Table 12.27 Soil colour and root abundance, layer 1 samples, 1994 field sites
Table 12.28 Soil colour and root abundance, layer 2 samples, 1994 field sites
Table 12.29 Surface litter cover and mean soil layer thickness, 1994 field sites
Table 12.30 Nitrous oxide flux and crude root biomass, 1994 field sites
Table 12.31 Water pH, redox potential, conductivity & dissolved oxygen content, 1994 field sites
Table 12.32 Levels of dissolved anions, 1994 field sites
Table 12.33 Water turbidity and suspended solid content, 1994 field sites

Table 12.26 Soil pH and redox potential, 1994 field sites

Sample number	Soil pH surface	layer /1	layer /2
PLT1	7.24	6.80	6.95
PLT2	7.02	6.89	6.86
PLT3	6.81	6.80	6.80
PLT4	6.69	6.70	6.71
PLT5	6.01	5.92	5.97
PLT6	6.46	6.11	5.26
PLT7	6.31	6.64	6.72
PLT8			
PLT9	7.14	5.54	6.43
PLT10	7.12	6.74	6.74
PLT11	6.24	5.63	5.95
PLT12	6.31	5.87	5.96
PLT13	6.20	5.74	5.74
PMT1	7.11	7.10	7.05
PMT2	6.91	6.90	6.82
PMT3	6.77	6.71	6.67
PMT4	6.61	6.45	6.54
PMT5	5.81	5.64	5.67
PMT6	5.82	4.75	5.29
PMT7		3.88	3.79
PMT8			
PMT9	7.16	6.65	6.61
PMT10	7.46	6.18	5.92
PMT11	6.50	5.82	5.51
PMT12	6.41	5.80	5.85
PMT13	6.29	5.76	5.43
PRT1	6.94	6.96	6.84
PRT2	7.04	6.96	6.88
PRT3	6.95	6.90	6.85
PRT4	6.54	5.90	5.86
PRT5	6.19	5.90	5.65
PRT6	5.62	5.07	5.67
PRT7		6.67	
PRT8			
PRT9	7.14	6.93	6.80
PRT10	7.31	5.84	6.03
PRT11	6.28	6.01	5.88
PRT12	6.41	5.81	5.80
PRT13	6.37	5.60	5.73
BC1	7.98	5.79	5.45
BC2	7.80	5.92	5.98
BC3	8.29	6.04	6.05
BC4	7.69	6.55	5.92
BC5	8.51	6.20	6.01
BC6	7.45	6.49	6.33
BC7	5.78	6.04	5.68
BC8	6.40	4.93	4.94
BC9	5.06	5.55	5.61
BC10	6.55	4.74	5.25
BC11	6.39	4.81	5.12
BC12	6.51	5.84	5.60
BC13	6.59	5.30	5.49
TEX1	4.93	6.08	6.15
TEX2	5.76	6.98	6.05
TEX3	5.97	5.98	5.97
TEX4	6.57	6.37	6.48
TEX5	6.42	6.62	6.49
TEX6	6.17	6.01	5.86
TEX7	5.60	5.73	6.18
TEX8	6.22	4.98	5.38
TEX9	6.26	6.01	6.21
TEX10	6.31	5.83	6.37
TEX11	5.31	6.79	6.39
TEX12	6.24	6.60	6.38
TEX13	5.79	6.14	6.14

Sample number	Soil redox Eh_7 mV (NHE) surface	layer /1	layer /2
PLT1	220	224	230
PLT2	213	185	231
PLT3	129	266	189
PLT4	272	268	117
PLT5	125	44	192
PLT6	141	58	-42
PLT7	55	36	62
PLT8			
PLT9	194	171	-118
PLT10	120	136	130
PLT11	207	139	142
PLT12	119	137	141
PLT13	134	160	121
PMT1	260	261	232
PMT2	208	193	195
PMT3	96	-3	90
PMT4	213	185	180
PMT5	57	21	162
PMT6	116	98	132
PMT7	108	247	213
PMT8			
PMT9	146	211	223
PMT10	116	175	121
PMT11	146	168	212
PMT12	133	120	144
PMT13	131	143	122
PRT1	211	220	179
PRT2	223	243	-62
PRT3	270	267	73
PRT4	132	71	56
PRT5	-15	131	127
PRT6	181	106	92
PRT7	118	161	296
PRT8			
PRT9	125	201	85
PRT10	144	145	104
PRT11	157	115	142
PRT12	134	143	180
PRT13	133	175	153
BC1	98	46	70
BC2	321	316	31
BC3	23	158	-55
BC4	187	599	345
BC5	-158	36	73
BC6	-18	61	160
BC7	97	171	119
BC8	362	434	84
BC9	295	351	180
BC10	448	-47	158
BC11	437	444	451
BC12	442	389	402
BC13	404	261	94
TEX1	414	30	194
TEX2	206	209	267
TEX3	387	502	204
TEX4	376	379	479
TEX5	182	119	98
TEX6	133	315	79
TEX7	372	146	176
TEX8	277	111	68
TEX9	219	146	338
TEX10	129	329	62
TEX11	186	-26	160
TEX12	271	349	367
TEX13	424	370	275

Table 12.27 Soil colour and root abundance, layer 1 samples, 1994 field sites

Sample number	Munsell colour	Very fine roots	Fine roots	Medium roots	Coarse roots
PLT1/1	10YR 5/1	many	-	common	-
PLT2/1	10YR 3/2	abundant	common	common	-
PLT3/1	7.5YR 3/1	abundant	few	-	few
PLT4/1	7.5YR 2.5/1	abundant	many	few	few
PLT5/1	7.5YR 3/2	abundant	common	many	common
PLT6/1	5YR 2.5/1	abundant	many	many	-
PLT7/1	7.5YR 2.5/1	abundant	common	many	few
PLT8/1	7.5YR 3/2	abundant	many	common	few
PLT9/1	7.5YR 2.5/1	abundant	many	common	-
PLT10/1	7.5YR 3/2	abundant	few	common	many
PLT11/1	7.5YR 3/2	abundant	abundant	few	-
PLT12/1	7.5YR 2.5/1	abundant	few	common	-
PLT13/1	7.5YR 3/2	abundant	abundant	few	few
PMT1/1	10YR 3/4	abundant	common	few	few
PMT2/1	10YR 3/2	abundant	few	many	few
PMT3/1	7.5YR 2.5/1	abundant	common	few	-
PMT4/1	7.5YR 4/1	abundant	common	few	-
PMT5/1	7.5YR 2.5/1	abundant	-	common	-
PMT6/1	10YR 2/1	abundant	abundant	few	-
PMT7/1	7.5YR 2.5/1	abundant	common	many	-
PMT8/1	5YR 2.5/1	abundant	few	common	-
PMT9/1	7.5YR 3/2	abundant	many	many	few
PMT10/1	7.5YR 2.5/1	abundant	many	many	few
PMT11/1	7.5YR 2.5/1	abundant	abundant	few	few
PMT12/1	7.5YR 3/2	abundant	abundant	many	common
PMT13/1	7.5YR 3/2	abundant	abundant	many	-
PRT1/1	10YR 3/2	abundant	common	-	-
PRT2/1	7.5YR 3/1	abundant	many	-	few
PRT3/1	7.5YR 2.5/1	abundant	few	few	-
PRT4/1	5Y 3/2	abundant	few	many	few
PRT5/1	7.5YR 3/2	abundant	many	many	common
PRT6/1	2.5YR 2.5/1	abundant	few	many	few
PRT7/1	7.5YR 3/2	abundant	many	many	few
PRT8/1	7.5YR 3/2	abundant	many	many	many
PRT9/1	7.5YR 2.5/1	abundant	abundant	common	-
PRT10/1	7.5TY 2.5/1	abundant	abundant	many	few
PRT11/1	7.5TY 2.5/1	abundant	abundant	many	common
PRT12/1	7.5YR 3/2	abundant	abundant	many	few
PRT13/1	7.5YR 3/2	abundant	abundant	many	few
BC1/1	10YR 3/1	many	many	common	-
BC2/1	10YR 4/1	many	many	few	-
BC3/1	7.5R 2.5/0	many	many	-	-
BC4/1	5Y 2.5/1	many	many	few	-
BC5/1	7.5R 2.5/0	common	common	-	-
BC6/1	7.5R 2.5/0	many	many	few	-
BC7/1	10YR 3/2	many	many	common	common
BC8/1	7.5YR 2.5/1	many	many	common	common
BC9/1	7.5YR 4/2	many	many	few	common
BC10/1	7.5YR 3/2	abundant	abundant	common	many
BC11/1	7.5YR 3/2	abundant	abundant	many	common
BC12/1	7.5R 2.5/0	abundant	abundant	many	many
BC13/1	7.5YR 2.5/1	abundant	abundant	many	many
TEX1/1	7.5YR 3/1	-	many	few	few
TEX2/1	7.5YR 2.5/1	-	many	few	-
TEX3/1	10YR 2/1	-	many	common	-
TEX4/1	10YR 3/1	-	many	common	-
TEX5/1	10YR 3/1	-	many	few	-
TEX6/1	10YR 3/2	-	many	few	few
TEX7/1	2.5Y 2.5/1	-	many	few	few
TEX8/1	10YR 3/2	-	many	common	-
TEX9/1	10YR 3/1	-	many	many	few
TEX10/1	7.5R 2.5/0	-	many	many	-
TEX11/1	N 2.5/	-	few	few	few
TEX12/1	7.5YR 2.5/1	-	few	few	few
TEX13/1	10YR 2/1	-	many	few	few

Table 12.28 Soil colour and root abundance, layer 2 samples, 1994 field sites

Sample number	Munsell colour	Very fine roots	Fine roots	Medium roots	Coarse roots
PLT1/2	10YR 3/2	abundant	few	common	common
PLT2/2	10YR 4/3	abundant	many	many	-
PLT3/2	7.5YR 5/1	abundant	many	few	many
PLT4/2	7.5YR 5/1	abundant	many	many	few
PLT5/2	2.5YR 4/1	many	common	many	few
PLT6/2	2.5YR 3/1	abundant	many	many	many
PLT7/2	2.5Y 4/1	abundant	many	few	many
PLT8/2	2.5Y 4/1	abundant	common	many	few
PLT9/2	5Y 4/1	abundant	abundant	common	few
PLT10/2	5Y 4/1	abundant	few	many	many
PLT11/2	5Y 4/1	abundant	few	many	common
PLT12/2	2.5Y 5/2	abundant	common	many	common
PLT13/2	2.5Y 5/1	abundant	abundant	many	few
PMT1/2	10YR 4/2	abundant	many	many	common
PMT2/2	10YR 3/2	abundant	few	many	few
PMT3/2	7.5YR 3/1	abundant	many	few	few
PMT4/2	7.5YR 5/1	abundant	many	-	-
PMT5/2	2.5Y 4/1	abundant	many	many	many
PMT6/2	7.5YR 3/2	abundant	many	many	common
PMT7/2	2.5YR 3/1	abundant	many	many	few
PMT8/2	2.5TY 4/1	abundant	many	-	common
PMT9/2	10YR 2/2	abundant	many	many	-
PMT10/2	7.5YR 2.5/2	many	few	few	-
PMT11/2	2.5Y 5/1	abundant	abundant	many	many
PMT12/2	5Y 5/1	abundant	abundant	many	few
PMT13/2	10YR 4/1	abundant	abundant	many	many
PRT1/2	7.5YR 2.5/3	abundant	many	-	-
PRT2/2	7.5YR 3/2	abundant	many	common	few
PRT3/2	7.5YR 3/2	many	many	few	many
PRT4/2	2.5Y 3/2	abundant	many	many	many
PRT5/2	2.5YR 4/1	many	common	common	-
PRT6/2	5Y 4/1	abundant	many	many	few
PRT7/2	5Y 5/2	abundant	many	many	many
PRT8/2	5Y 4/1	abundant	many	many	few
PRT9/2	7.5YR 4/1	abundant	abundant	many	many
PRT10/2	5YR 2.5/2	abundant	abundant	many	few
PRT11/2	5Y 6/1	abundant	abundant	many	common
PRT12/2	5Y 5/1	abundant	abundant	many	many
PRT13/2	5Y 5/1	abundant	abundant	many	many
BC1/2	5Y 4/2	many	common	few	-
BC2/2	10YR 3/2	common	common	-	-
BC3/2	5Y 3/1	many	many	few	-
BC4/2	10YR 3/2	many	many	-	-
BC5/2	10YR 4/1	common	common	-	-
BC6/2	10YR 3/2	many	many	few	-
BC7/2	10YR 5/1	common	common	common	-
BC8/2	7.5YR 2.5/1	many	many	many	many
BC9/2	5Y 5/2	few	few	few	-
BC10/2	2.5Y 5/2	many	many	few	-
BC11/2	10YR 4/1	abundant	abundant	many	common
BC12/2	2.5YR 3/2	many	many	few	few
BC13/2	7.5YR 3/2	few	few	few	common
TEX1/2	2.5Y 4/2	few	few	-	-
TEX2/2	2.5Y 5/2	common	common	common	common
TEX3/2	2.5Y 5/2	common	many	common	few
TEX4/2	5Y 5/1	many	many	common	-
TEX5/2	2.5Y 4/2	common	common	few	few
TEX6/2	2.5Y 5/2	many	many	few	few
TEX7/2	2.5Y 6/2	common	common	few	-
TEX8/2	2.5Y 4/1	many	many	common	few
TEX9/2	5Y 4/1	few	few	-	few
TEX10/2	5Y 4/1	common	common	few	-
TEX11/2	5.GY 4/1	few	few	few	few
TEX12/2	2.5Y 5/2	common	few	few	few
TEX13/2	1OYR 5/1	few	few	few	few

Table 12.29 Surface litter cover and mean soil layer thickness, 1994 field sites

Sample number	%Litter Cover	Sample number	Thickness layer 1 (cm)	Sample number	Thickness layer 2 (cm)
PLT1	100	PLT1/1	9.00	PLT1/2	17.00
PLT2	100	PLT2/1	9.00	PLT2/2	22.00
PLT3	100	PLT3/1	12.00	PLT3/2	12.00
PLT4	100	PLT4/1	11.00	PLT4/2	13.00
PLT5	100	PLT5/1	10.00	PLT5/2	20.00
PLT6	100	PLT6/1	10.00	PLT6/2	20.00
PLT7	80	PLT7/1	15.00	PLT7/2	16.00
PLT8	85	PLT8/1	9.00	PLT8/2	24.00
PLT9	55	PLT9/1	7.00	PLT9/2	17.00
PLT10	70	PLT10/1	14.00	PLT10/2	22.00
PLT11	95	PLT11/1	7.00	PLT11/2	22.00
PLT12	80	PLT12/1	11.00	PLT12/2	19.00
PLT13	60	PLT13/1	11.00	PLT13/2	19.00
PMT1	100	PMT1/1	7.50	PMT1/2	18.50
PMT2	100	PMT2/1	8.00	PMT2/2	21.00
PMT3	100	PMT3/1	12.00	PMT3/2	13.00
PMT4	100	PMT4/1	8.00	PMT4/2	7.00
PMT5	100	PMT5/1	10.00	PMT5/2	21.00
PMT6	100	PMT6/1	7.00	PMT6/2	19.00
PMT7	80	PMT7/1	10.00	PMT7/2	16.00
PMT8	75	PMT8/1	8.00	PMT8/2	23.00
PMT9	60	PMT9/1	8.00	PMT9/2	16.00
PMT10	75	PMT10/1	9.00	PMT10/2	16.00
PMT11	60	PMT11/1	11.00	PMT11/2	19.00
PMT12	60	PMT12/1	9.00	PMT12/2	17.00
PMT13	75	PMT13/1	13.00	PMT13/2	27.00
PRT1	100	PRT1/1	8.50	PRT1/2	19.50
PRT2	100	PRT2/1	11.00	PRT2/2	16.00
PRT3	100	PRT3/1	18.00	PRT3/2	10.00
PRT4	100	PRT4/1	30.00	PRT4/2	29.00
PRT5	100	PRT5/1	30.00	PRT5/2	30.00
PRT6	100	PRT6/1	12.00	PRT6/2	21.00
PRT7	70	PRT7/1	12.00	PRT7/2	14.00
PRT8	95	PRT8/1	10.00	PRT8/2	20.00
PRT9	80	PRT9/1	10.00	PRT9/2	21.00
PRT10	80	PRT10/1	11.00	PRT10/2	17.00
PRT11	60	PRT11/1	14.00	PRT11/2	20.00
PRT12	75	PRT12/1	9.00	PRT12/2	20.00
PRT13	95	PRT13/1	10.00	PRT13/2	24.00
BC1	0	BC1/1	15.00	BC1/2	49.00
BC2	0	BC2/1	9.00	BC2/2	9.00
BC3	0	BC3/1	5.00	BC3/2	11.00
BC4	0	BC4/1	14.00	BC4/2	42.00
BC5	0	BC5/1	15.00	BC5/2	43.00
BC6	10	BC6/1	15.00	BC6/2	38.00
BC7	60	BC7/1	17.00	BC7/2	33.00
BC8	80	BC8/1	7.00	BC8/2	31.00
BC9	60	BC9/1	19.00	BC9/2	46.00
BC10	70	BC10/1	18.00	BC10/2	36.00
BC11	100	BC11/1	7.00	BC11/2	25.00
BC12	100	BC12/1	28.00	BC12/2	11.00
BC13	100	BC13/1	5.00	BC13/2	16.00
TEX1	0	TEX1/1	16.00	TEX1/2	57.00
TEX2	5	TEX2/1	21.00	TEX2/2	22.00
TEX3	0	TEX3/1	6.00	TEX3/2	66.00
TEX4	0	TEX4/1	8.00	TEX4/2	71.00
TEX5	10	TEX5/1	3.00	TEX5/2	74.00
TEX6	20	TEX6/1	20.00	TEX6/2	52.00
TEX7	5	TEX7/1	12.00	TEX7/2	58.00
TEX8	10	TEX8/1	6.00	TEX8/2	16.00
TEX9	5	TEX9/1	13.00	TEX9/2	62.00
TEX10	10	TEX10/1	9.00	TEX10/2	69.00
TEX11	40	TEX11/1	10.00	TEX11/2	33.00
TEX12	60	TEX12/1	9.00	TEX12/2	66.00
TEX13	80	TEX13/1	5.00	TEX13/2	16.00

Table 12.30 Nitrous oxide flux and crude root biomass, 1994 field sites

Sample number	N_2O flux ng N_2O-N m^{-2} s^{-1}	Sample number	N_2O flux ng N_2O-N m^{-2} s^{-1}	Sample number	Crude root biomass g cm^{-3}
PMT1	0.00	TEX1	1.87	BC1	0.10
PMT2	0.00	TEX2	3.18	BC2	0.07
PMT3	0.13	TEX3	6.92	BC3	0.07
PMT4	0.18	TEX4	4.15	BC4	0.06
PMT5	0.02	TEX5	1.18	BC5	0.03
PMT6	0.17	TEX6	1.38	BC6	0.04
PMT7	0.46	TEX7	0.08	BC7	0.08
PMT8	0.08	TEX8	0.71	BC8	0.11
PMT9	0.08	TEX9	0.12	BC9	0.17
PMT10	0.02	TEX10	0.06	BC10	0.14
PMT11	0.36	TEX11	0.00	BC11	0.24
PMT12	0.68	TEX12	0.49	BC12	0.24
PMT13	0.55	TEX13	0.30	BC13	0.20
BC1a	0.69	BC1b	1.87		
BC2a	0.48	BC2b	9.55		
BC3a	0.71	BC3b	0.47		
BC4a	0.29	BC4b	0.32		
BC5a	0.33	BC5b	0.20		
BC6a	0.28	BC6b	0.10		
BC7a	0.33	BC7b	0.26		
BC8a	0.05	BC8b	0.00		
BC9a	0.15	BC9b	0.26		
BC10a	0.03	BC10b	0.07		
BC11a	0.05	BC11b	0.01		
BC12a	0.00	BC12b	0.13		
BC13a	0.03	BC13b	0.00		

*The second sampling at the Burnt site (*BC1b - BC13b*) was repeated immediately after rain.*

Table 12.31 Water pH, redox potential, conductivity & dissolved oxygen content, 1994 field sites

Sample number	Water pH	Water redox mV (NHE)	Conductivity mS (25°C)	Dissolved O_2 mgl^{-1}
PLT1	4.84	-91	63.92	0.00
PLT2	4.99	-188	56.84	0.10
PLT3	5.06	-253	51.08	0.00
PLT4	4.82	-247	56.00	0.00
PLT5	4.81	-71	52.48	0.00
PLT6		68	54.04	0.00
PLT7	4.96	-250	70.72	0.00
PLT8	4.92	-61	68.76	0.00
PLT9	4.99	-219	64.76	0.00
PLT10	4.85	-163	71.84	0.00
PLT11	4.89	-194	78.24	0.00
PLT12	4.88	53	66.32	0.00
PLT13	4.78	-43	67.80	0.00
PMT1	4.98	-222	60.84	0.00
PMT2	5.03	-249	69.40	0.00
PMT3	4.91	-212	47.24	0.00
PMT4	4.89	-101	60.48	0.00
PMT5	4.75	149	44.12	0.00
PMT6		-33	65.52	0.00
PMT7	4.85	-111	60.80	0.00
PMT8	4.86	-121	62.40	0.00
PMT9	4.91	-122	75.04	0.00
PMT10	4.88	59	60.40	0.00
PMT11	4.74	-184	70.40	0.00
PMT12	4.86	-6	64.64	0.00
PMT13	4.72	-184	52.04	0.00

continued overleaf

Sample number	Water pH	Water redox mV (NHE)	Conductivity mS (25°C)	Dissolved O_2 mgl^{-1}
PRT1	4.84	-206	79.96	0.00
PRT2	5.10	-196	60.24	0.00
PRT3	4.99	-230	45.00	0.00
PRT4	4.80	-194	56.68	0.00
PRT5	5.06	-6	18.04	0.40
PRT6	4.79	-74	47.84	0.00
PRT7	5.26	35	34.64	0.30
PRT8	4.94	-90	58.00	0.00
PRT9	5.06	-77	65.28	0.00
PRT10	4.76	-112	60.08	0.00
PRT11	4.88	-190	74.12	0.00
PRT12	4.72	-179	72.32	0.00
PRT13	4.80	20	69.36	0.00
BC1a	6.06	311	31.24	0.20
BC2a	5.94	252	41.28	0.00
BC3a	6.17	279	21.60	0.00
BC4a	6.13	268	23.08	0.00
BC5a	6.11	198	26.84	0.00
BC6a	5.76	45	49.20	0.00
BC7a	5.59	106	46.44	0.00
BC8a	5.75	122	50.00	0.00
BC9a	5.43	161	42.04	0.00
BC10a	5.32	156	35.40	0.00
BC11a	4.72	-38	58.68	0.00
BC12a	4.93	127	44.20	0.00
BC13a	5.21	169	43.40	0.10
BC1b	6.08	206	54.68	0.20
BC2b	6.27	287	44.92	0.60
BC3b	6.48	252	38.56	0.60
BC4b	6.40	108	52.40	0.10
BC5b	6.15	279	50.00	0.60
BC6b	5.82	218	58.44	0.30
BC7b	5.62	251	55.84	0.10
BC8b	5.82	251	58.28	0.00
BC9b	5.38	300	50.28	0.50
BC10b	5.36	272	54.88	0.20
BC11b	4.85	354	53.68	0.70
BC12b	4.93	350	47.68	0.30
BC13b	5.21	311	47.20	0.20
TEX1a	6.29	191	37.36	0.40
TEX2a	6.19	232	39.52	0.50
TEX3a	6.78	320	42.76	1.00
TEX4a	6.74	143	40.16	0.30
TEX5a	6.94	314	53.60	0.80
TEX6a	7.06	183	65.40	0.40
TEX7a	6.76	177	78.76	0.40
TEX8a	6.65	178	75.40	0.50
TEX9a	6.92	291	77.76	0.40
TEX10a	6.69	130	80.45	0.40
TEX11a	7.33	94	69.60	0.40
TEX12a	6.97	187	74.44	0.40
TEX13a	6.83	293	78.64	0.50
TEX1b	6.18	220	36.68	1.50
TEX2b	6.02	345	36.80	2.20
TEX3b	6.46	357	40.92	2.10
TEX4b	6.58	344	52.24	1.40
TEX5b	6.78	370	54.76	2.00
TEX6b	6.55	62	65.20	0.90
TEX7b	6.97	263	73.96	1.50
TEX8b	6.76	303	76.32	1.60
TEX9b	6.80	322	78.60	1.40
TEX10b	6.82	273	77.32	1.10
TEX11b	6.81	175	69.08	1.00
TEX12b	6.67	240	70.24	0.80
TEX13b	6.52	277	72.60	2.10

Table 12.32 Levels of dissolved anions, 1994 field sites

Sample number	Water react. P mg P l^{-1}	Water NO_3-N mg NO_3-N l^{-1}	Water Cl mg Cl l^{-1}	Water SO_4 mg SO_4 l^{-1}
PLT1	1.58	6.6	4500	4875
PLT2	0.10	21.6	5625	4625
PLT3	0.96	10.4	4875	4625
PLT4	1.69	9.1	9125	5000
PLT5	0.47	5.4	13375	5000
PLT6	1.19	0.0		3375
PLT7	0.23	5.5	5000	5750
PLT8	0.06	6.3	6250	6000
PLT9	0.04	1.8	3250	5750
PLT10	0.05	8.2	10500	6875
PLT11	0.04	0.0	10250	7125
PLT12	0.04	0.0	8250	6250
PLT13	0.49	0.0	9375	5875
PMT1	1.14	28.5	8750	5125
PMT2	0.84	5.3	3000	5375
PMT3	1.01	11.4	3125	5250
PMT4	0.08	13.2	250	5000
PMT5	0.01	21.4	3875	5500
PMT6	0.08	0.2		4875
PMT7	0.04	1.5	16500	6000
PMT8	0.06	2.3	10625	5250
PMT9	0.14	5.4	3500	8500
PMT10	0.05	0.0	4000	5500
PMT11	0.05	0.6	10000	9375
PMT12	0.03	0.0	4000	5375
PMT13	0.02	0.0	3875	6750
PRT1	0.15	2.0	7250	6000
PRT2	0.03	8.4	4625	5750
PRT3	2.30	10.7	5000	4500
PRT4	0.15	4.1	8125	5375
PRT5	0.02	9.4	3625	3750
PRT6	0.03	3.6	1000	5125
PRT7	0.03	2.7	3375	4500
PRT8	0.03	0.5	2625	5375
PRT9	0.04	0.0	3375	6125
PRT10	0.04	0.1	2375	5625
PRT11	0.06	0.0	875	6875
PRT12	0.07	3.6	875	6375
PRT13	0.04	4.8	1875	6375
BC1a	0.19	0.0	215000	3875
BC2a	0.07	0.0	190000	4500
BC3a	0.12	0.0	202500	3250
BC4a	0.27	0.0	187500	2750
BC5a	0.34	0.0	152500	3500
BC6a	0.22	0.0	187500	6875
BC7a	0.03	0.0	200000	4750
BC8a	0.13	0.0	155000	5500
BC9a	2.64	0.0	192500	5000
BC10a	0.08	0.0	145000	4375
BC11a	0.26	0.0	152500	5125
BC12a	0.37	0.0	175000	4625
BC13a	0.14	0.0	222500	4625
BC1b	0.43	0.0	145000	5625
BC2b	0.00	0.0	135000	3250
BC3b	0.00	0.0	117500	5375
BC4b	0.10	0.0	152500	4125
BC5b	0.00	0.0	137500	5750
BC6b	0.00	0.0	142500	5500
BC7b	0.01	0.0	140000	6125
BC8b	0.19	0.0	140000	6000
BC9b	0.00	0.0	50000	6125
BC10b	0.09	0.0	125000	6125
BC11b	0.03	0.0	117500	4375
BC12b	0.04	0.0	145000	3250
BC13b	0.12	0.0	112500	3875

continued overleaf

Sample number	Water react. P mg P l^{-1}	Water NO_3-N mg NO_3-N l^{-1}	Water Cl mg Cl l^{-1}	Water SO_4 mg SO_4 l^{-1}
TEX1a	0.00	0.0	25000	3700
TEX2a	0.00	0.0	352500	4000
TEX3a	0.00	0.0	53500	3400
TEX4a	0.09	0.0	78000	3600
TEX5a	0.00	0.0	87000	4700
TEX6a	0.19	0.0	330000	4200
TEX7a	0.14	0.0	84500	7300
TEX8a	0.00	0.0	83500	7300
TEX9a	0.00	0.0	54000	9500
TEX10a	0.37	0.0	79500	7200
TEX11a	0.09	0.0	60500	7100
TEX12a	0.13	0.0	47500	7100
TEX13a	0.20	0.0	67000	7400
TEX1b	0.00	0.0	43500	3800
TEX2b	0.14	0.0	42000	3800
TEX3b	0.00	0.0	44500	3600
TEX4b	0.00	0.0	45500	3600
TEX5b	0.00	0.0	59500	4400
TEX6b	0.36	0.0	64000	6500
TEX7b	0.00	0.0	90000	7200
TEX8b	0.00	0.0	70000	7100
TEX9b	0.08	0.0	66000	7400
TEX10b	0.10	0.0	60500	7300
TEX11b	0.05	0.0	66500	7000
TEX12b	0.23	0.0	57000	7300
TEX13b	0.72	0.0	56000	6900

Table 12.33 Water turbidity and suspended solid content, 1994 field sites

Sample number	S. solids mgl^{-1}	Turbidity FTU	Sample number	S. solids mgl^{-1}	Turbidity FTU	Sample number	S. solids mgl^{-1}	Turbidity FTU
PMT1	392	277	BC1	825	461	TEX1	825	-60
PMT2	255	227	BC2	825	461	TEX2	825	-50
PMT3	191	189	BC3	697	461	TEX3	364	-40
PMT4	445	308	BC4	825	461	TEX4	825	-30
PMT5	612	327	BC5	315	461	TEX5	540	-20
PMT6	825	461	BC6	587	461	TEX6	498	-10
PMT7	506	396	BC7	566	461	TEX7	728	0
PMT8	306	227	BC8	825	461	TEX8	825	10
PMT9	825	461	BC9	825	461	TEX9	341	20
PMT10	825	461	BC10	825	461	TEX10	494	30
PMT11	825	461	BC11	825	461	TEX11	620	40
PMT12	825	461	BC12	825	461	TEX12	584	50
PMT13	471	396	BC13	825	461	TEX13	374	60