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Modelling dairy grazing systems: an integrated approach

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TO NATALIA

Declaration

I hereby declare that this thesis has been composed by myself, and is the product of my own work.

Date: 19/12/97

Abstract

This thesis describes a management decision-support system for dairy grazing systems based on simulation and multiple criteria decision-making (MCDM) models.

Appropriate selection of holistic management strategies for livestock farming systems requires: 1) understanding of the behaviour of, and interrelations between, the different parts of the system, 2) knowledge of the basic objectives of the decision-maker managing such enterprise, and 3) understanding of the system as a whole in its agro-ecoregional context.

Increasing economic and environmental pressures on livestock production systems have created the need to re-evaluate current management practices and to study new alternatives to ensure their sustainability. As a consequence, the demand for decision-support systems based on mathematical models has increased in the past years. Validated simulation models provide cost-effective means to represent the dynamics of the system and its components, while MCDM models allow for appropriate selection of resource allocation strategies depending on the different objectives and management 'styles' of particular individuals. Integration of both mechanisms provides the necessary elements for efficient decision-support at farm or ecoregional level.

A decision-support system based on these techniques has been built to represent pastoral dairy production systems. The biological aspects (grass growth; grazing; digestion and metabolism; animal performance, and herd dynamics) are represented by simulation studies under a variety of management regimes. The outputs from the simulation runs (such as pasture utilisation, stocking rates, milk yields, fertilizer use, etc.) are used as data input to the MCDM models, and the latter have been used to select the management strategies which make the most efficient use of the farm's resources (i.e. land, animals, pastures).

Examples are given with reference to highland dairy farming in Costa Rica. Nevertheless, the model frameworks are generic and can be adapted to different farming systems or ruminant species. The effect of model formulation and sensitivity, different decision-maker objectives, and/or activity or constraint definitions on management strategy selection are analysed. Future areas of research to expand this work to other livestock farming systems and to integrate other related disciplines into this decision-support framework are also discussed.

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Introduction

This thesis describes a management decision-support system for dairy grazing systems based on simulation and multiple criteria decision-making (MCDM) models.

The logical outline of this work is as follows. Chapter 1 briefly describes the general problems faced in Latin American grazing systems, and discusses the need for integrated systems approaches, in order to develop general holistic decision-support methodological frameworks for designing sustainable management strategies at the farm level.

Chapter 2 concentrates on briefly describing highland dairy production systems in Costa Rica, which are taken as a case study for the development of the systems approaches mentioned in the previous chapter. The third chapter of this thesis is a review on kikuyu pastures, which is the main pasture species in the highlands of Costa Rica, as well as in other tropical and subtropical environments. This chapter has several objectives. First, obtaining some of the data required for parameterisation of the pasture model described in Chapter 5, and second, collating the existing information on pasture growth and animal performance for validating the models described in Chapters 5 and 6.

Knowledge of the biological basis of grazing systems and its components is required to design a whole grazing systems decision-support system. Chapter 4 is a critical review of the different approaches used to mathematically describe these components. It also provides insight into the basic requirements for the biological representation of some of these processes, although emphasis is also made on the trade-off between model design and modelling objectives.

Chapters 5 and 6 describe models of the key biological processes necessary for modelling grazing systems and analyse common 'what if' scenarios that may help to explain and determine different management strategies. Chapter 5 concentrates on modelling pasture growth and grazing processes, and factors affecting them; while Chapter 6 describes and validates a simple model for predicting potential intake, digestion and animal performance from ruminants.

A management decision-support system is not complete if mechanisms to select between alternative management strategies, according to the characteristics of individual farms and the objectives of the decision-maker, is available. Chapter 7 describes a method to design and select holistic management strategies for grazing systems by integrating the output of the simulation models previously described with a multiple-objective decision making (MCDM) model representing a whole dairy farm and its activities. It incorporates the biological aspects described in Chapters 5 and 6 with elements of herd management, land use and economic analysis, and farm/farmer characteristics. Concluding remarks about the methodology presented are discussed in Chapter 8. Required research and ways to integrate other important areas of expertise into this methodological framework are proposed in order to expand the uses of these decision support tools to other agro-ecological zones and production systems.

Chapter 1

Decision-support for Latin American grazing systems: integrated frameworks*

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* Adapted from:

Herrero, M., Fawcett, R.H. and Dent, J.B. (1996) Integrating simulation models to optimise nutrition and management for dairy farms. In: *Livestock Farming Systems: Research, Development, Socio-Economics and the Land Manager*. J.B. Dent et al. (editors). European Association for Animal Production Publication No. 79. Wageningen Pers. pp. 322-326. (Appendix 1)

Herrero, M., Fawcett, R.H., Perez, E. and Dent, J.B. (1997) The role of systems research in grazing management: applications to sustainable cattle production in Latin America. In: *Application of Systems Approaches at the Farm and Regional Levels*. P.S. Teng *et al.* (editors). Kluwer Academic Publishers, The Netherlands. pp. 129-136. (Appendix 1)

Chapter 1

Decision-support for Latin American grazing systems: integrated frameworks

1.1 Background

Grasslands are one of the major natural resources of Latin America. They comprise about 28% of the total land of the region and support approximately 25% of the world's cattle population (1.3 billion head) (FAO 1994). A large proportion of them are rangelands which support relatively low levels of animal production. Therefore, in the past 25 years, efforts to increase animal production have been directed towards technologies such as introduction of improved pastures, legumes and their associations (Lascano 1990). Substantial evidence of the benefits of these introductions in terms of animal performance is available (see Skerman et al. (1988) or Humphreys (1991) for reviews). However, a common issue is the delicate balance between animal production per unit of area and per animal required to ensure the persistence of these species on the long term (Lascano 1990), and their interactions with the other aspects of the farming system. Thus, a well known scenario starts with the degradation of the pasture, and the change to rangeland vegetation, which usually reduces farm output. Alternatively, it may encourage overgrazing and/or land clearing to maintain farm output. The final result is increases in soil erosion, a progressive depletion of the natural resource base and a social degradation of the rural communities. On the other hand, another common scenario is the increased use of foreign technologies and inputs, which increase the dependency on imported goods and promotes an underutilisation of the local resources. In these cases, since local currencies usually devaluate faster relative to the dollar, there is a high level of risk associated, and production costs tend to increase in the long run. The final result, is again, a socio-economic degradation of the rural communities and an unsustainable system.

Increasing economic and environmental pressures on livestock production systems have created the need to re-evaluate current management practices and to study new alternatives to ensure their sustainability. As a consequence, the demand for decision-support systems (DSS) based on mathematical models has increased in the past years. Models, if properly built and validated, are very cost-effective and rapid tools to test hypothesis and the effect of different management strategies on the behaviour of parts or whole livestock systems. Since they can analyse a wide variety of strategies, they tend to be a complement to experimental studies, where the cost and the time required make it impossible to study a wide range of management possibilities. However they need to be incorporated into a holistic framework for effective decision-support purposes (Dent et al. 1995).

Progress has been made in recent years modelling biological processes. In the case of crops and livestock the nature of the processes represented has led to the construction, at different levels of aggregation, of very similar models throughout the world. This overlapping has made model-building an expensive and time consuming activity because researchers often take on the enormous task of building new models rather than selecting and adapting the existing ones for their own purpose. Efforts have usually been directed towards representing individual units or processes within a defined system (i.e. the animal, the plant, growth, lactation). These types of models by themselves are useful but usually fail to provide the decision maker with solutions to managerial problems (Dent et al. 1994). As pastoral ruminant production systems are a dynamic multi-component activity, integration of these 'individual models' together with herd and socio-economic data and a mechanism to select viable management strategies according to predetermined objectives, such as multiple criteria decision models (MCDM), should provide a framework for a decision-support system.

This chapter briefly shows the importance of a systems approach in sustainable cattle production systems in Latin America and describes the general framework and some elements required in a decision-support system based on systems simulation and optimisation techniques to identify sustainable management strategies in pasture-based cattle production systems.

The primary hypotheses of this work is that a framework, such as the one mentioned above, can provide the backbone for the development of a comprehensive DSS for pastoral systems.

1.2 Sustainable cattle production systems: concepts and compromises.

The term sustainability has become fashionable in the past decade but it is a subjective concept. Many definitions have been formulated depending on the context of its use, but one of the most quoted ones is the proposed by the WCED (1987):

'...*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*'.

In a pastoral context, Figure 1.1 illustrates in the left hand column grazing management issues which although often conflicting, together, in compromise, lead to sustainability at the field level. Figure 1.1 also shows how sustainability measures at different levels within the farm, demand compromise management to achieve overall sustainability. It is evident that grazing management is one of the key determinants of sustainability for the whole farm in the long run.

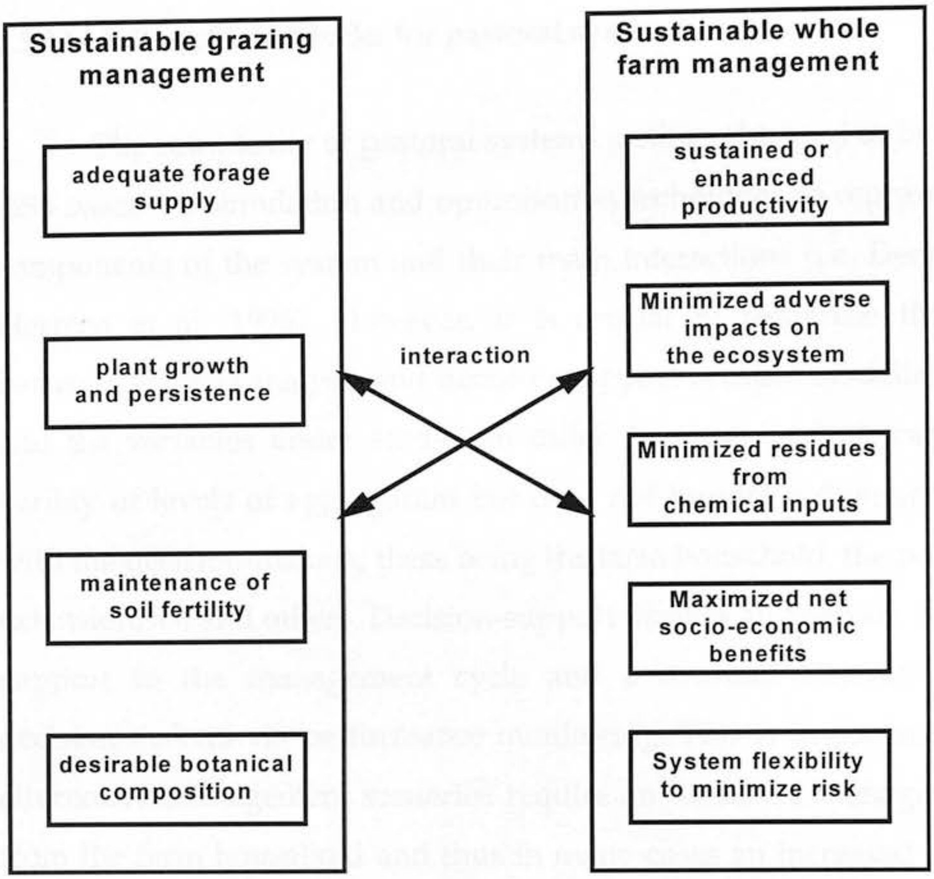

Figure 1.1. Attributes of sustainable grazing and sustainable farm management.

However, because all the requirements have to be met simultaneously, a series of compromises arise which cannot be studied unless the whole system and associated objectives are represented. For example, in biological terms, the provision of an adequate year-round forage supply of a desired botanical composition and quality is central to animal performance. However, to obtain this while at the same time maintaining soil fertility or the legume component, keeping a flexible system to minimise risks due to climate and markets and minimising residues from fertiliser and chemical inputs is a formidable task (Humphreys 1994). The problem is multiplied several fold if socio-economic and external aspects which are fundamental to the decision-making process are included (Dent et al. 1994).

1.3 Modelling frameworks for pastoral systems.

The complexity of pastoral systems justifies the need to build dynamic DSS based on simulation and optimisation techniques to represent different components of the system and their main interactions (i.e. Dent et al. 1994, Herrero et al. 1996). However, it is crucial to recognise the difference between systems analysis and decision-support because modelling objectives and the variables under study can differ. Systems analysis can occur at a variety of levels of aggregation but does not require a dynamic interaction with the decision-makers, these being the farm household, the policy-makers, extensionists, and others. Decision-support implies an analysis of the system, support to the management cycle and a constant interaction with the decision-makers via performance monitoring. This is important since some alternative management scenarios require an increased managerial capacity from the farm household and thus in many cases an increased participation and interaction between the farmer and extension/advisory personnel.

The variables driving the system should represent the variables handled by the decision-makers, according to the planned time horizons for the different goal achievements. The variables and the decision rules can be quantitative or qualitative depending on the information available (Röling 1994, Dent 1995). In quantitative systems, there is a trade-off between the level of aggregation, the accuracy required and the ease of validation and understanding. 'Hybrid' models based on a mechanistic platform but with empirical site-specific parameters obtained from local data may be the ideal for decision-support purposes. Figure 1.2 shows the general methodology for modelling pastoral production systems. It consists of:

A biological simulation system composed of 3 interactive simulation models which are a grasslands model representing the growth, structure and chemical composition of a sward under rotational grazing with responses to N fertiliser applications, temperature and light interception throughout the year. The function of this model is to determine the effects of different grassland management options on pasture dry matter (DM) production, chemical composition and sward structure. In a rotational grazing system, the typical examples of management practices that could be examined deal with the length of the regrowth period, the amount and timing of fertiliser applications, the effects of defoliation regime on subsequent sward growth and structure and their interactions. On a continuous grazing regime, the same aspects apply but stability and nutrient cycling also take major roles.

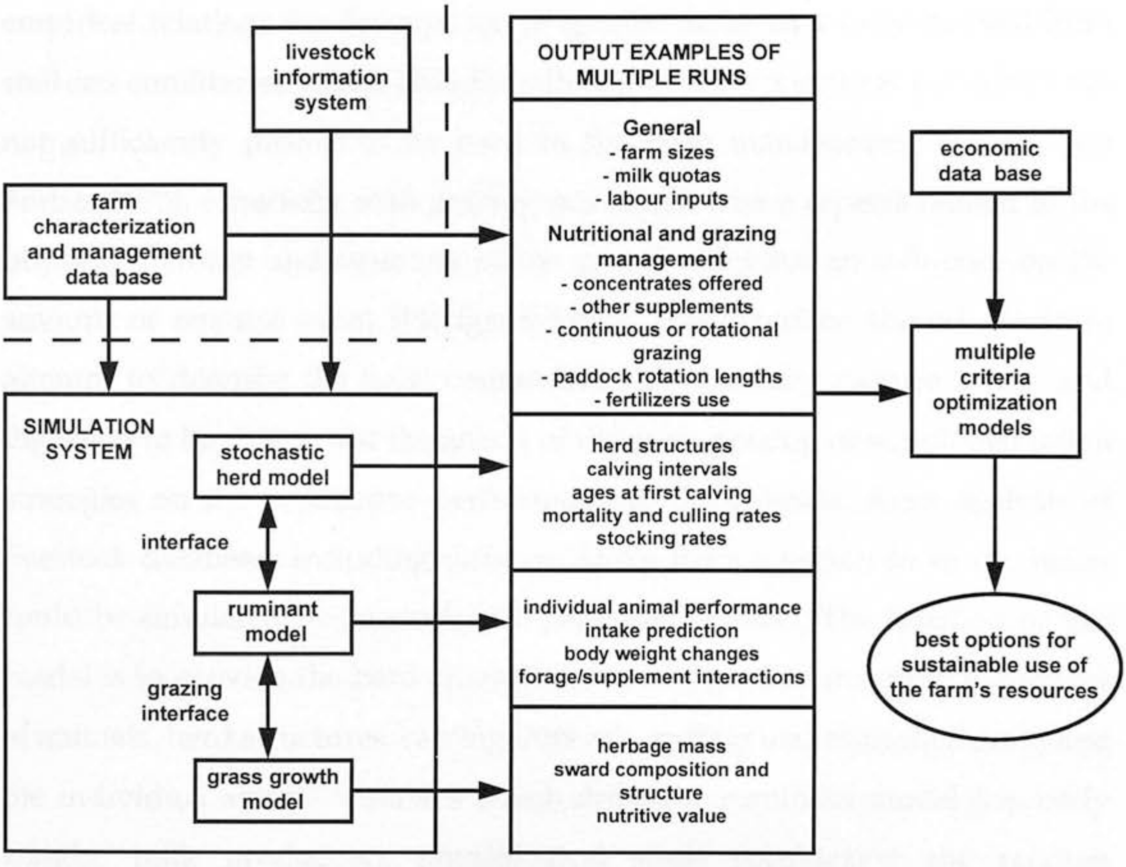

Figure 1.2. General modelling framework for grazing cattle production systems.

The grass growth model should be linked via an interface representing the grazing process and the effect of sward characteristics upon animal intake to a ruminant model which simulates potential intake, digestion kinetics, and nutrient supply, and calculates nutritional requirements according to the cow's physiological state, milk production, body weight and body weight changes. The representation of the interaction between plants and animals is one of the most critical developments for the system because the sensitivity and accuracy of the prediction of the productive responses to nutrients of grazing ruminants is largely determined by a good estimate of pasture intake. While recent systems of feeding standards (i.e. SCA 1990, Sniffen et al., 1992, AFRC 1993) have estimated the nutritional requirements of ruminants with some degree of accuracy, they have not dealt satisfactorily with intake prediction. Most of the proposed empirical relations are descriptions of specific datasets, mostly derived from stall-fed conditions, which broadly reflect practical conditions but which are not sufficiently precise to be used in the farm management context (see Forbes 1993), especially with grazing ruminants where aspects related to the physical quantity and structure of the sward also have an influence on the amount of pasture eaten (Hodgson 1985). This interface should therefore attempt to describe the basic components of voluntary pasture intake and digestion to be able to test the effects of different grazing or supplementation strategies on the productive performance of the animals. After analysis of livestock databases including different farms from a region in study, herds could be simulated by an stochastic population model. The function of this model is to provide the herd characteristics of a particular farm (i.e. number of animals, herd structures, calving intervals, culling and mortality rates) and the individual animal variables which drive the ruminant model (i.e. body weight, milk production, physiological state) considering the random variation existing in the real systems. Its importance lies in the representation of the effects of changes in management practices on herd production and economic performance (Sorensen et al. 1992, Jalvingh et al. 1994)

Data from farm surveys should provide additional inputs influencing the production responses from the biological models (i.e. concentrates allowance, fertilisers use, paddock rotation lengths) and the relevant farm and management characteristics (i.e. farm size, milk quotas, young stock rearing practices) that are linked to the herd model or that constrain the system.

Validation of the simulation system against real farm data is done with animal performance and grazing databases obtained from available farm monitoring services, farm records, literature or experiments. The important variables to validate are the outputs of each individual model, those variables with a high sensitivity to changes in management practices or those which largely determine the economic efficiency of the system. For example, herbage production, individual milk production or herd structures.

Finally, the validated outputs of alternative simulations are combined with economic data and are used as inputs in MCDMs. The whole farm simulation system is run under different scenarios associated with changes in grass production, grazing strategy, nutritional or herd management and land use options and the MCDMs examine the different simulation runs and identify the management strategies which produce the most viable compromise between the farm's resources according to the established objectives. Important attributes of MCDMs are that the farmers objectives can be represented and they can take into account all the activities of the farm (holistic). This allows for better targeted and more realistic decision-support since it is recognised that the farm is a multi-component activity in which a decision taken in one aspect (i.e. herd management) will have an influence in another part of the system (i.e. grazing management), and that finding an 'optimal' or a 'best solution' is relative, since it depends on the objectives of the decision-maker and the weights that he/she assigns to each one. In other words, what is 'optimal' for one farmer might not be for another one. This allows for 'tailor-made' decision-support in individual farms when required.

All these models should have two important attributes: they should be *generic* and have a *modular structure*. *Generic* in the sense that they should be able to be adapted to different species of pastures (e.g. *Cynodon spp.*, *Brachiaria spp.*, rangelands) or ruminants (i.e. cattle, sheep); and different agroecological zones (i.e. lowlands, highlands) or production systems (i.e. dairying, beef or dual purpose) with simple modifications, mostly in parameter values, while the processes represented (e.g. photosynthesis, digestion) remain the same. The *modular structure* should allow them to work independently but interactively between themselves. This has the advantage that, if required, each individual model could be incorporated into other DSSs, or could be used separately to study specific processes (i.e. pasture growth) without hampering the working ability of other parts of the system. These two characteristics are necessary to cope with the heterogeneity in Latin American ruminant production systems and to increase the portability of the DSS or its parts. The mechanistic nature of the models provides the flexibility required to deal with a variety of management scenarios while at the same time providing understanding about the system or process under study.

1.4 Livestock information systems: their role in decision-support systems.

A key element of any DSS involves monitoring of the actual performance of the system and the provision of analysed data for the decision-maker.

In the context of tropical cattle production systems, this concept was pioneered by the Herd Health Project of the School of Veterinary Medicine of the National University of Costa Rica (Pérez et al. 1989). The VAMPP (Veterinary Automated Management and Production control Program), originally developed by Utrecht University, The Netherlands (Noordhuizen 1984) was introduced and adapted to the local farming systems and information requirements. The main objective of its introduction was to provide information to the farmer according to his needs for his operational (day to day) farm management while at the same time creating livestock databases for research and teaching purposes. This function was developed as a farmer-oriented livestock information system (LIS). The system works by periodic monitoring of individual farms and the collection of production, reproduction and health data from individual animals. Databases are created and analysed and an immediate feedback to the farmer is given via action lists (cows to inseminate, to calve, to dry-off, etc.) to support his operational management. Other longer-term performance indexes are also provided (calving intervals, ages at first calving, replacement rates, etc.) (see Baaijen and Pérez, 1992).

In 1988, the system was introduced in 23 farms through a small pilot project and now periodical monitoring (every two weeks or once a month) is provided for more that 400 dairy, dual purpose and beef cattle farms in Costa Rica.

After the positive acceptance of the information system by the Costa Rican livestock farmers, links with other Latin American countries began in 1990 to establish similar systems. These were made through farmers organisations, cooperatives or Universities, and a regional network was created. Today, the livestock monitoring system is present in Nicaragua, Guatemala, Honduras, Panama, Colombia, Mexico, Venezuela and Bolivia.

The implementation of the LIS in the region has proved to be an efficient method for providing operational technical support to farmers while at the same time capturing information for research and teaching purposes (Baaijen and Pérez, 1992). The descentralised structure of the system can also collate data from individual farms to provide regional or group information to assist advisors, policy-makers and researchers if required.

1.5 Consolidation of a decision-support system: linking models and livestock information systems.

Linking together the modelling framework (planning and resource use allocation) and the LIS (operational management support and monitoring) creates a DSS and can be observed in Figure 1.3. The LIS supports operational decisions while the DSS creates the opportunity for strategic and tactical planning and target setting.

Once the DSS is sufficiently validated across a range of production systems, its role would be as a planning tool in conjunction with extension services to improve farm management and resource use.

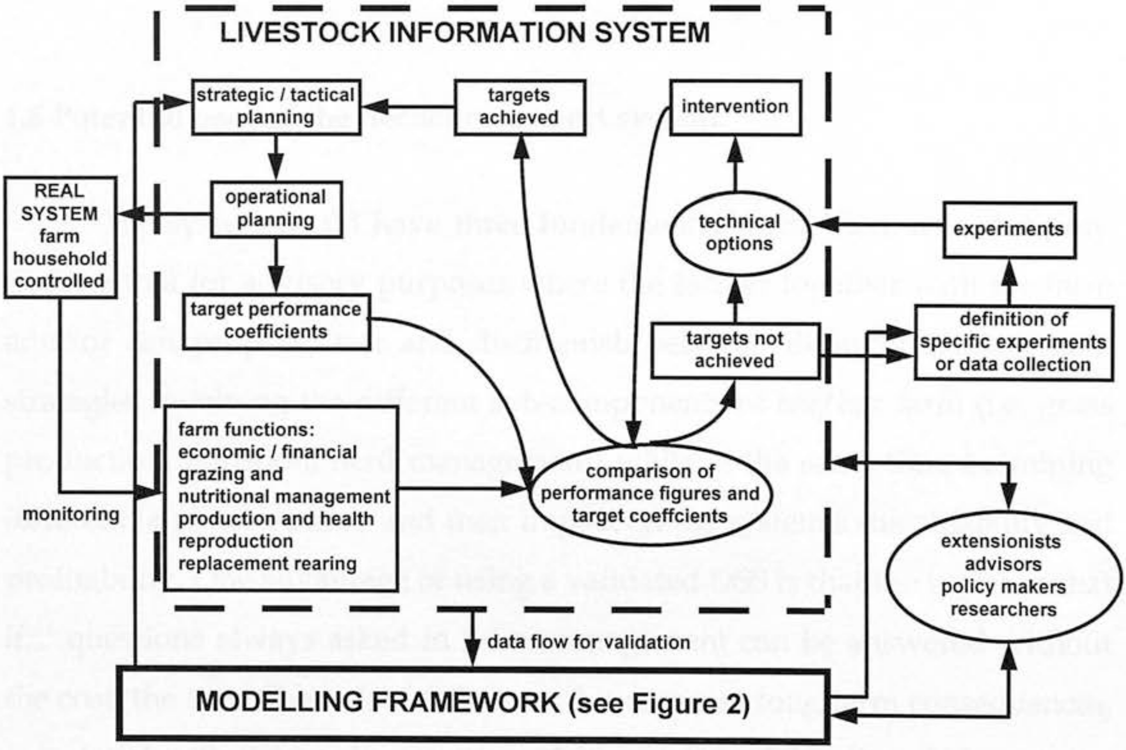

Figure 1.3. The decision-support system for pastoral enterprises.

For individual farms it will:

- provide alternative strategies dealing with technical and land use options.

- set target performance figures for the farm functions (i.e. grasslands utilisation, replacement rates) for the preferred selected strategy.
- monitor the current performance of each farm on a routine basis.
- do periodical analyses to check if the targets are being achieved.
- suggest ways to adjust the current system if targets are not being met.
- provide a basis for replanning if necessary.

At a more aggregated level it could be used as a policy-making and as a research/teaching tool. This use has the potential to create a link between the farmer, the extension agent, the policy-maker while at the same time creating livestock performance databases for research purposes. As the livestock information network is already working in several countries, a robust validation of the modelling framework would give the whole system the potential for regionalisation according to the farming systems and farm characteristics of the countries of the region.

1.6 Potential uses of the decision-support system.

The system could have three fundamental roles. First, as a decision-making tool for advisory purposes where the farmer together with the farm advisor can propose, test and distinguish between different management strategies involving the different sub-components of his/her farm (i.e. grass production, nutrition, herd management) while at the same time examining different land use options and their impact on the system's sustainability and profitability. One advantage of using a validated DSS is that the typical 'what if...' questions always asked in farm management can be answered without the cost, the time, the risk of failure, and sometimes long term consequences, associated with the implementation of an unsuccessful policy. Although the number of alternatives is theoretically infinite, only a small number can be validated, implemented and produce the best compromise between the resources available.

This decision support tool could also be used for strategic planning at the regional level. In situations where farm monitoring systems are operating, the main characteristics of the farms of a region are usually known. In such cases, the system could be expanded to represent different types of farms, and the impact of different policies on the region's use of land and resources could be tested or could be compared with other regions to provide a better specification of their problems and to prioritise their advisory and extension needs.

The system may also be integrated as a part of research activities to help in the understanding of biological and management processes and to identify factors influencing their responses. It could also help to find specific areas of research where the knowledge and information available is not sufficient to allow a formal or informal representation in the system. This could prioritise and increase the cost-effectiveness of research programmes.

A third role could be in teaching activities. Systems-oriented education is becoming increasingly important because it has been recognised that the managerial capacity of farm households is complex and does not respond only to a particular sub-component of the farming system. Therefore, students related to the agricultural or veterinary disciplines need to understand the different interactions of the system and the objectives of the farm household if at some point in their careers they are going to be involved serving the farming community. A DSS based on simulation and optimisation techniques is an ideal complement to field practice to provide a 'test-bed' for students to assist understanding of a particular system and to test their ideas.

Chapter 2

Dairy grazing systems in the highlands of Costa Rica: a case study

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Chapter 2

Dairy grazing systems in the highlands of Costa Rica: a case study

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2.1 General background

Costa Rica is a democratic tropical country (lat 9-11° N) located in Central America. It borders to the North with Nicaragua, to the South with Panama; and with the Atlantic and Pacific oceans to the East and West, respectively. It has an area of 50700 km^2 and a population of 3.5 million inhabitants (World Bank, 1997). It is considered one of the most economically stable Latin American countries, with high standards of health, social security and education (Table 2.1). Expenditure in these areas accounts for approximately 63% of the total government's budget (World Bank, 1997).

The lack of expenditure in defense (the country does not have armed forces) has contributed to the economic stability of Costa Rica, since it has promoted foreign and local investment, tourism and trade. The annual growth rate of the gross domestic product (GDP) during 1990-1995 was 5.1% (World Bank, 1997). The provision of services, mainly as ecotourism, together with an active conservation policy (13% of the land area is protected in more than 30 national parks and biological reserves)(Boza, 1988) has contributed substantially to the economic development of the country. During this period, the tourism sector grew at an annual rate of 9.5%, and has become one of the most important exports in recent years. Industrial development is also growing steadily (5.2% per year).

Table 2.1. Some development indicators for Costa Rica: 1990 - 1995.

Indicator		
Land resources		
Total area	51	thousand km^2
Forests	30.0	% of total area
Cropland	10.0	% of total area
Permanent pastures	46.0	% of total area
Others	16.0	% of total area
Population		
Total population	3.5	million inhabitants
Population growth rate	2.3	% per year
Rural population	50.0	% of total population
Labour force in agriculture	26.0	% of total labour force
GNP per capita growth	2.8	% per year
Health		
Access to sanitation	100.0	% of population
Access to safe drinking water	99.0	% of population
Infant mortality	1.3	% (per 100 livebirths)
Malnutrition in children under 5	2.0	%
Life expectancy	77	years
Education		
Children reaching primary school Grade 4	90.0	% of children
Enrollment in secondary education	50.0	% of suitable age group
Enrollment in tertiary education	30.0	% of suitable age group
Literacy rate	95.0	%

Adapted from FAOSTAT (1997) and World Bank (1997)

Nevertheless, Costa Rica is still largely dependent on agriculture. The agricultural sector is growing (3.6% per year)(FAOSTAT, 1997), and agricultural products contribute to about 40% of Costa Rica's exports. Half of the population still lives in rural areas, and 26% of the labour force is involved in agricultural activities (World Bank, 1997).

Livestock production is an important component of Costa Rican agriculture, and has grown significantly in the past years. During 1990-1995, it grew at a faster rate (5.1% per year)(CEPAL 1991, FAOSTAT 1997), than the total agricultural sector. The main reasons were increases in poultry and milk production (Simpson, 1994), with the latter growing at an annual rate of 4.3% per year (Pomareda, 1994).

In terms of land use, in 1995, cropland and permanent pastures accounted for 10 and 46%, respectively; of the total land area, while forests covered 30% of the country (World Bank, 1997; FAOSTAT, 1997). Figure 2.1 demonstrates the trends in land use in Costa Rica since 1970. While the cropland area has not changed since 1970, it is evident that the area of pastures increased consistently until the mid-1980's, at the expense of forest cover.

There has been substantial debate about the causes of deforestation in Costa Rica and the Central American region (Pomareda, 1992; Lutz et al. 1993; Simpson 1994; French, 1994, Kaimowitz, 1996). However, some common factors reviewed by Kaimowitz (1996) include:

- Strong markets for livestock products, specially before the mid-1980's.
- Government subsidies for livestock credit and road construction.
- Land clearing for cattle is still a common method for demonstrating possession of new lands.
- Environmental and pasture degradation.
- Slow technological change in livestock systems.
- The high timber prices, relative to the fluctuating beef prices also provided an incentive for forest clearing (Pomareda, 1992).

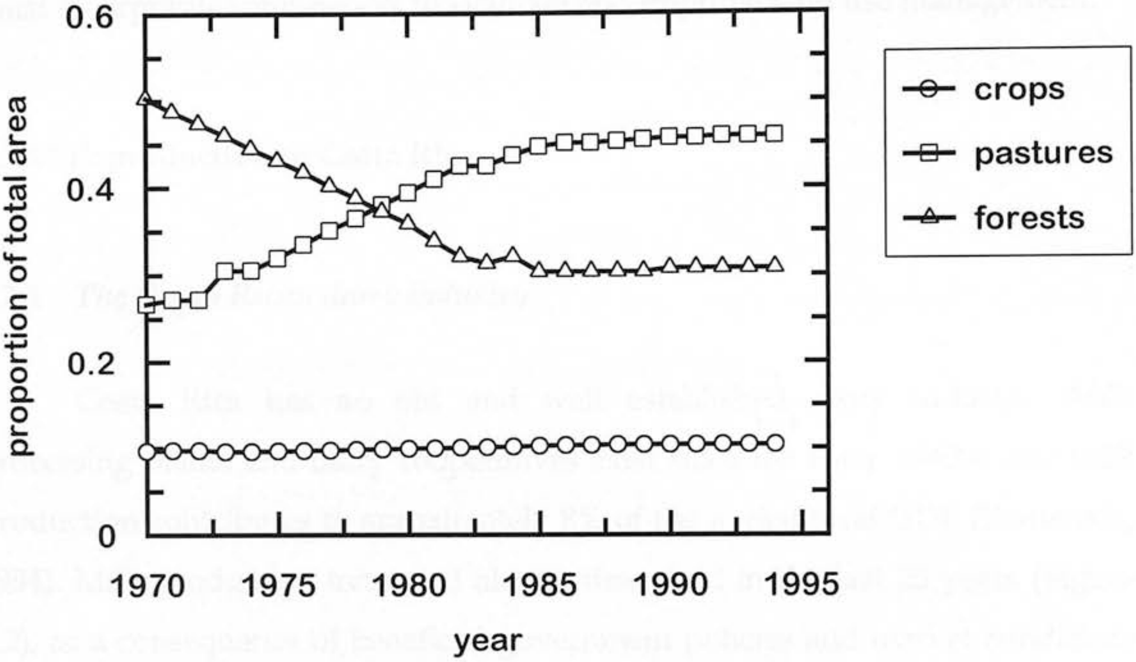

Figure 2.1. Land use in Costa Rica: 1970 - 1995 (Data from FAOSTAT, 1997)

It is clear that the deforestation dilemma is complex. However, there is general consensus that the driving force behind it has been population growth, mainly mediated via the required increases in the production of food and other commodities to meet its demands. In Costa Rica, the reductions in the rate of land clearing after the mid 1980's (see Figure 2.1) have been, among others, caused by a greater public education and awareness of the importance of conserving biodiversity, by the expansion of nationally protected areas (Kaimowitz, 1996), improved forestry laws, and by the effects of these factors on a considerable reduction in timber exports (Pomareda, 1992).

As stated in the previous chapter, it is also clear that if these sort of problems are to be resolved with the help of the scientific community, research efforts must be capable of evaluating and undestanding the consequences of a particular strategy on the behaviour of different parts of livestock systems, and must incorporate frameworks to evaluate and improve land use management.

2.2 Milk production in Costa Rica

2.2.1 *The Costa Rican dairy industry*

Costa Rica has an old and well established dairy industry. Milk processing plants and dairy cooperatives exist since the early 1940's, and milk production contributes to aproximately 8% of the agricultural GDP (Pomareda, 1994). Milk production increased almost three-fold in the last 25 years (Figure 2.2), as a consequence of beneficial government policies and market conditions (CATIE, 1990), mainly to decrease milk imports and increase local consumption.

From a development policy perspective, in the 1970's it was demonstrated that milk could be produced economically, specially in the humid tropics (Villegas, 1982), and a national dairy programme was started with the objective of making the country self sufficient in milk production. According to Camacho (1989) and Ruiz et al. (1994), as a means of promoting dairying, the government took several strategies: 1) High milk prices were offered to producers. For example, in 1983, the price of milk was \$0.38/lt, while it has decreased and stabilised at around \$0.30/lt since 1988 (Ruiz et al. 1994). 2) Credit was subsidised to small livestock farmers, of which 40% was allocated to dairying. 3) A widespread installation of small scale milk collection centres throughout the country, linked to an increased road and electrification network, promoted better markets. 4) New milk watersheds were established, particularly in the humid tropics, and 5) a captive market was created through high import tariff barriers and government regulated prices.

These strategies were very effective. Costa Rica reduced milk imports from 20 thousand tons to 5 thousand tons per year from 1974 to 1988 (Simpson, 1994). Today, the country is the only self-sufficient Central American country in milk production. It produces 26% of the total milk volume of the region (Nuñez and Galetto, 1993), and since 1992 has exported its net surpluses (2 - 10% of the total production) to the rest of Central America and the Caribbean (Pomareda, 1994; Ruiz et al., 1994). This region imports 15% (300 thousand litres) of its milk requirements to satisfy the local demand (Nuñez and Galetto, 1993).

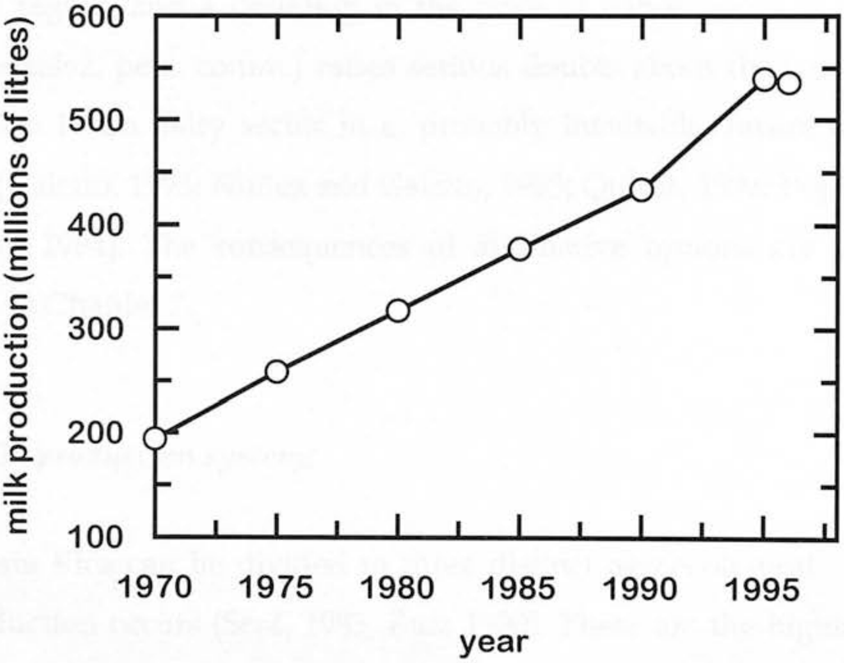

Figure 2.2. Evolution of milk production in Costa Rica: 1970 - 1996 (Data from FAOSTAT, 1997).

Milk production reached approximaltely 540 million litres in 1995 (FAOSTAT, 1997). Of this milk volume, only 50% is pasteurised and processed in dairy plants (CATIE, 1990), and 85% of this milk is processed in farmers cooperatives (CATIE, 1990). The rest is sold as crude milk directly to the public by farmers or intermediaries. This milk self-sufficiency position in Costa Rica, is believed to have played a substantial role in the reduction of malnutrition of children under 5 (CATIE, 1990). Current milk consumption per capita is approximately 150 lts/yr, compared to 75 lts/yr for the whole of the Central American region (Nuñez and Galetto, 1993; Ruiz et al., 1994).

From an international perspective, the beneficial strategies of the 1970's and 80's have been under scrutiny, since they might not be viable under the current globalisation trends. For example, although the price of milk has decreased to $0.30/lt, it is still 37% higher than the international price. This, together with a 111% tariff barrier for imported milk from outside of the Central American region, and a doubling in the price of concentrates in the last five years (Gonzalez, pers. comm.) raises serious doubts about the competitiveness of the Costa Rican dairy sector in a, probably inevitable, future open market situation (Galetto, 1993; Nuñez and Galetto, 1993; Quirós, 1994; Pomareda, 1994, Ruiz et al. 1994). The consequences of alternative options are studied and discussed in Chapter 7.

2.2.2 *Milk production systems*

Costa Rica can be divided in three distinct agroecological zones where milk production occurs (Seré, 1983, Ruiz 1990). These are the highlands (about 30% of the country), the humid lowlands and the wet/dry lowlands. Table 2.2 summarises the main environmental characteristics of these regions.

The climatic differences between these regions define the type of resources available for milk production, and hence the type of production system. Two main milk production systems can be identified: specialised dairying, in the highlands and humid lowlands; and dual-purpose systems accross the lowlands (Ruiz, 1990).

Table 2.2. Climatic conditions of the milk producing regions of Costa Rica[*]

Parameter	Highlands	Humid lowlands	Wet/dry lowlands
Altitude (m.o.s.l)	1200 - 3000	0 - 1200	0 – 1000
Rainfall (mm/yr)	2000 - 4000	2000 - 5000	1000 - 2000
Dry season (months)	2 - 4	2	5 - 6
Temperature (°C)	10 - 20	20 - 30	25 - 35
Relative humidity (%)	75+	90+	60+

Adapted from Seré (1983), Holmann (1990) and Ruiz (1990)

Specialised dairying contributes to about 70% of the total milk volume, while the rest is produced in dual-purpose systems (Ruiz, 1990). About 50% of the milk produced in specialised dairy systems is produced in the highlands and the rest in the humid lowlands (CATIE, 1990). Since dual purpose systems also exist in the humid lowlands, this region produces about 50% of the total milk volume of the country, followed by 35% from the highlands. The rest (15%) is produced in the dry lowlands were beef production, instead of milk, is the predominant livestock production system. Figure 2.3 summarises the distribution of milk production in Costa Rica by region and production system.

Dual-purpose systems have been extensively described elsewhere (Sere, 1983; Ruiz, 1990, Ruiz et al, 1994). However, they are mainly characterised by the production of milk and beef from the same herd, usually by using *Bos indicus* X *Bos taurus* crosses (i.e. Brahman X Brown Swiss), or in extensive systems, by using the best milk producing beef cows. Cows are milked once daily and produce total lactation yields between 900 - 2000 kg milk. Calves are raised artificially or naturally, and are weaned at around 6 - 8 months with

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[*] More precise ecoregional definitions can be obtained in Holdridge (1987), but these are beyond the scope and objectives of this chapter.

bodyweights between 120 - 200 kg. Nutrition is based on pastures (*Cynodon spp., Brachiaria spp., Panicum spp., Hyparrhenia rufa, Ischaemum ciliare* and other natural grasses), low levels of supplementation and use of local feed resources (i.e. molasses, rice polishings, crop residues).

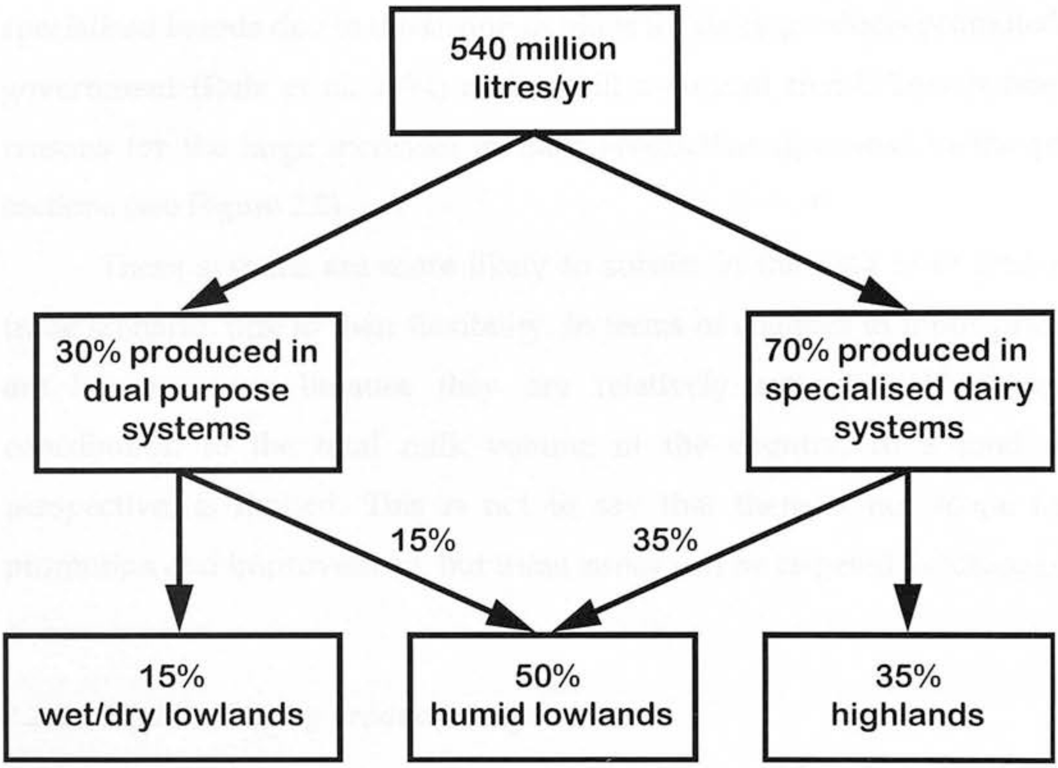

Figure 2.3. Distribution of milk production in Costa Rica by production system and region Adapted from CATIE (1990), Ruiz (1990) and Pomareda (1994).

This type of system is very flexible. Cows produce milk, which is sold to cooperatives, or more often directly to the consumer as raw milk or cheese. The heifers are used as replacements for the cows, while the weaned male calves are used for beef production. They can either be sold or raised on the farm depending on land available and/or market conditions. Due to the use of crossbreds, the system can also be directed to single activities (i.e. milk or beef) depending on market conditions. In Costa Rica, the use of dual purpose systems increased in the 1970's-80's due to a contraction of the beef industry (Camacho, 1989). Beef farmers started to become milk producers as well. In the humid lowlands, specialised milk production has been largely derived from dual-purpose systems, by increasing the crossbreeding towards the milk producing specialised breeds due to the strong markets for dairy products promoted by the government (Ruiz et al. 1994) and is still a current trend. This is one of the reasons for the large increases in milk production discussed in the previous sections (see Figure 2.2).

These systems are more likely to subsist in the long term under a free trade scenario, due to their flexibility. In terms of changes in input prices, they are less sensitive because they are relatively extensive. However, their contribution to the total milk volume of the country, in a food security perspective, is limited. This is not to say that there is not scope for their promotion and improvement, but these issues will be targeted in future studies.

2.2.3 *Highland dairy production systems*

The present study aims to design decision-support methodologies using specialised dairy production systems as an example. Dairy systems in the Poás region were chosen due to several reasons. The School of Veterinary Medicine of the National University has had a pilot project since 1988 comprising 23 dairy farms of the region, therefore the logistics and technical support were already in place. These farms were the first used, and the test-bed, for the development of the VAMPP livestock information system, therefore a substantial amount of data existed prior to the beginning of the study. The author of this work had previous knowledge of the region, since he was a member of the project and the technical advisor for the farms under study.

There are also other reasons justifying the work on specialised dairy systems in Costa Rica. According to Ruiz et al. (1994) these farmers would be the most affected in a free trade scenario, since they don't have the flexibility offered by dual-purpose systems to change to other activities. They also have a substantial amount of investment on infraestructure, and are usually the farmers involved in the cooperatives, which means that they are the 'true dairy farmers' willing to invest in mechanisms to promote, process and market their products. It is their chosen way of life, and usually have a tradition of dairy farming of at least one or two generations. From a food security perspective these peri-urban systems are also extremely important, since they produce 70% of the total milk volume of the country, and since they use relatively high inputs, cost-reduction strategies are more difficult to design. In terms of land use, they consist of smaller farms, therefore there is a limitation to production volumes, which would probably determine the possibilities to continue farming depending on the long term price and input policies and land use options (Holmann et al. 1992).

2.2.3.1 Characteristics of the farms in the Poás region

The Poás region is located in the highlands of the provinces of Heredia and Alajuela between the Poás and Barva volcanos at an altitude of 1800 to 2000 m.o.s.l. It is an area of high rainfall (3000 - 3500 mm/yr) with annual minimum and maximum temperatures of 13.1 - 21.3°C. The rainy season extends from May to December and the dry season from January to April with occasional rains. (Baayen and Pérez, 1990). The zone has relatively irregular topography and volcanic soils of low pH (<5.5) that present a strong phosphorus fixation (andisols)(Bertsch, 1986).

Milk production systems in the region have been described previously by Baayen and Pérez (1990)(42 farms) and van der Grinten et al. (1992)(23 farms). These systems are based on Holstein-Friesian cattle, which is the predominant breed (74% of the farms), while the remaining are Jersey cattle. Farm sizes vary from 17 - 560 ha, with an average of 137 ha, of which approximately 79 ha are covered by pastures. Average herd sizes are 141 animals (range 29 - 401 animals), of which 63 are lactating cows (range 13 - 200 cows). These farm sizes are larger than what is generally observed in other specialised highland dairy systems of Costa Rica. According to Camacho (1989) up to 80% of the dairy farms in Costa Rica have sizes between 10 and 50 ha. Therefore, a farm with these characteristics from the Poás region will be used for the development of this work.

Resources and management practices are similar accross the dairy farms in highlands. The main pasture species is common kikuyu grass (*Pennisetum clandestinum*), which is rotationally grazed. Paddock rest periods vary from 22 - 42 days, but the most common management system is 1-day grazing followed by a 30 day rest period. Fertiliser use is very variable. It ranges from 0 - 530 kg N/ha/yr, with average use of around 200 kg/ha/yr. The use of legumes, mainly *Trifolium repens* is restricted, and may comprise up to 10% of the forage available (see Chapter 3 for comments). Common stocking rates for lactating cows are usually around 2.0 cows/ha (van der Grinten et al. 1992).

Milk production for Holsteins and Jerseys is 5695 ± 1247 and 3681 ± 1088 kg/305 d lactation, respectively. Cows are milk twice daily and are supplemented with grain concentrates in all the farms. The level of grain supplementation varies from 1.3 - 10.3 kg/d/cow, while average concentrate use is 6.1 kg/cow/d. Agro-industrial by-products and other supplements are also used in some farms. For example, molasses, wet brewers grains and banana peelings are fed in 53, 26, and 11% of the farms respectively (van der Grinten et al., 1991). Farmers are looking for alternative strategies to manage their resources. They want to make better use of the grassland resources, which are currently under-utilised (van der Grinten et al. 1992; Herrero et al., unpublished) in order to try and reduce supplementation. For example, van der Grinten et al (1992) found an oversupplementation with protein, which is an expensive nutrient, of more than 100% in several farms of the region.

In terms of youngstock management, female calves are reared artificially with approximately 3 kg of milk/day, chopped forages (mainly *Pennisetum spp.*) and a pelletized starter fed *ad libitum* until 4 months of age when they are weaned. Male calves are slaughtered at birth. After weaning, female calves graze rotationally and receive approximately 2 kg of concentrates until they are 12 - 18 months old. A big variation in young stock nutrition exists between farms (Solano, 1993). Age at first calving ranges from 23 - 47 months (31 months on average)(van der Grinten, 1992).

Reproductive performance of the farms in the region is relatively good. The average calving interval is 395 ± 23 d. This is probably related to the fact that routine veterinary assistance is provided in more than 80% of the farms. All farms use artificial insemination. Record keeping is practiced in 86% of the farms, while 90% of them have some sort of formal identification system for the animals (Baayen and Pérez, 1990). However, problems with abortions have started to increase and it is believed to be due to an outbreak of *Neospora caninum* (Pérez, pers. comm.).

These systems are considered to be productive. However, they are susceptible to labour and concentrate price changes as these are imported goods which represent almost 55 - 65% of the variable costs of the dairy enterprise (CATIE 1990, Pomareda 1994), and are increasing. For example, the real prices of concentrates have doubled in the last 5 years, mainly due to marked increases in the international price of grains such as maize (González, pers. comm.), which is the most important grain for the manufacture of concentrates in Costa Rica. For a country like Costa Rica, whose livestock feedingstuffs imports represent around 60% of all agricultural imports and whose currency constantly devaluates in relation to the dollar, this means that the cost of farm inputs always increases, therefore decreasing the economic efficiency of the system. Due to the beneficial policies of the 1970's, these farmers were never under any economic or productive pressure, and always relied on the use of grains which were subsidised. This, together with the benign environmental conditions, explains why a strong grassland management tradition does not exist among Costa Rican dairy farmers. It is until now, when globalisation is eminent, that they feel that changes in the management strategies of their systems are required in order to sustain their systems and their livelihoods. It is believed that the present work can help to devise such strategies.

Chapter 3

Kikuyu grass (*Pennisetum clandestinum*): a review*

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* Adapted from:
Herrero, M., Fawcett, R.H., Russell, G. and Dent, J.B. (1998) The agronomy, physiology and use for animal production of kikuyu grass (*Pennisetum clandestinum*): a review. Tropical Grasslands (*accepted for publication*).(Appendix 1)

Chapter 3

Kikuyu grass (*Pennisetum clandestinum*): a review.

3.1 Introduction

Since highland dairy production systems in Costa Rica are based on kikuyu grass (*Pennisetum clandestinum*) pastures, it was necessary to review the available literature on this species before starting the modelling efforts, and for subsequent validation of the models.

Kikuyu grass (*Pennisetum clandestinum*) is a stoloniferous and rhizomatous C4 tropical pasture species originally from the Kenyan highlands. It has become one of the most important pasture species in subtropical regions of countries like Australia (Minson *et al.* 1993), New Zealand (Percival 1978; Piggot 1985) and South Africa (Marais *et al.* 1987), where it provides a substantial amount of the summer and autumn feed in some livestock production systems. In the tropics, its distribution is confined to highland areas of Africa, Central and South America and Asia, where it is also highly regarded for animal production.

Mears (1970) reviewed the available literature on kikuyu grass and concluded that this species had several desirable attributes as a tropical pasture, but that it had received little attention from research workers. Since then, a vast amount of information has been produced regarding its agronomic characteristics, nutritional value, management and animal production potential.

This review provides an update of research on kikuyu pastures since the Mears review was published. It attempts to integrate concepts from the different disciplines, rather than to analyse each area separately, in order to provide some insight into their interactions and to more validly explain some of the results in the literature. Such an approach may help to understand and develop suitable management guidelines to improve grazing systems for this grass species.

Readers requiring detailed information on the botanical description, geographical distribution and diseases of kikuyu grass are referred to Mears (1970).

3.2 Genetic variability

From 3 ecotypes (Molo, Kabete and Rongai) in Kenya, which rarely produce seed, 4 free-seeding cultivars (Whittet, Breakwell, Noonan and Crofts) have been bred and released in Australia. Six lines have been identified in New Zealand. Cultivars or lines vary in morphology and differ in dry matter (DM) production because of varying tolerance of cooler conditions.

Mears (1970) stated that 3 ecotypes had been recognised in the Kenyan highlands. These were Molo, Kabete and Rongai and they differed in leaf morphology and flowering behaviour. However, he stated that these differences were difficult to recognise in existing pastures and that in Australia, common kikuyu was a mixture of them. Before 1970, kikuyu pastures were established vegetatively, as male sterility is normally a heterozygous condition in common kikuyu (Piggot and Morgan 1986). A mixture of male sterile but female fertile and fertile bisexual plants was produced resulting in very low or rarely observed seed production.

Breeding of kikuyu therefore began, and is most advanced, in Australia, where 4 cultivars have been released since 1970. These are Whittet (Wilson 1975) released in 1970, Breakwell (Wilson 1975) released in 1972, and Crofts (Anon. 1983a) and Noonan (Anon 1983b). In contrast to common kikuyu, these cultivars produce only (i.e. Whittet and Noonan), or mostly

(Crofts and Breakwell), bisexual plants and can produce large quantities of seed.

Whittet and Breakwell varieties were introduced primarily for their ability to produce seed (Wilson 1975; Quinlan *et al.* 1975) which made the establishment of kikuyu swards easier. Noonan was selected primarily for its resistance to kikuyu yellows - a serious fungal disease - (Anon. 1983b), and Crofts for its adaptation to cooler regions (Anon. 1983a; Pearson *et al.* 1985).

There are also morphological differences between the cultivars. Whittet kikuyu is taller, has longer internodes, wider leaves and thicker stems than common or Breakwell kikuyu (Wilson 1975). It forms a more open sward and is therefore considered more suitable for associations with legumes (Wilson 1975; Rumball and Lambert 1985). Breakwell is similar in morphology to common kikuyu. It has a prostrate growth habit, shorter internodes and tillers profusely. Crofts is the tallest cultivar but has narrower leaves and thinner stolons than Whittet (Anon. 1983a). These differences are most apparent at cooler temperatures (Anon. 1983a). When immature, Noonan kikuyu cannot be distinguished easily from Whittet, but Noonan plants seem to have shorter leaves and stolons at more advanced stages of growth.

In New Zealand, 6 lines have been identified, of which some are male sterile and others are fertile (Piggot and Morgan 1985). Piggot and Morgan (1985) found with plants grown in pots, that total DM yield was relatively similar in all 6 lines, however there were differences in the proportions of leaf and stem produced. Piggot and Morgan (1985) and Piggot (1991) concluded that these New Zealand lines did not outyield the Australian cultivars nor the high altitude Kenyan accessions they tested (Molo and Njoro). The morphological differences between the Australian cultivars and the New Zealand and Kenyan lines evident in these studies were less obvious under field conditions, since pot experiments with individual plants do not reflect the processes of canopy development and senescence in established swards. As the leaf area index (LAI) of artificial swards is less than in the field, light usually penetrates to the lower leaves thus reducing leaf senescence. As a consequence, the leaf to stem ratio in these pot experiments overestimates the value in field swards. For example, Piggot (1991) reported leaf:stem ratios of 3.0:1-3.3:1 for Whittet kikuyu and the other Australian cultivars. This contrasts with the results of 1.4:1 and 1.8:1 obtained by Hacker and Evans (1992) and Köster *et al.* (1992) respectively, in established swards. For common kikuyu, Mears and Humphreys (1974b) found that, under field conditions during the summer/autumn period, leaf:stem ratios were close to 1.1:1, and Piggot (1991), in his second trial, reported mean values close to 1.5:1 for the lines, which are selections from common kikuyu.

Differences between cultivars or lines in total DM production seem to depend on their ability to grow at cooler temperatures (Pearson *et al.* 1985; Rumball and Lambert 1985). The cold-tolerant varieties produce more dry matter, reflecting their ability to extend the growing season during late autumn and early spring in these subtropical regions. Although cultivars and lines vary in leaf size, stolon yield, flowering behaviour and vigour, the effect of these differences on dry matter production and sward composition is slight in comparison with the effect of grazing management and environmental factors such as temperature and rainfall (Rumball and Lambert 1985). N utilisation does not seem to vary between cultivars (Pearson *et al.* 1985). Nevertheless, trials to separate the genotype effects on morphology and yield under grazing have not been designed.

It has been suggested that all cultivars have similar *in vitro* DM digestibility and mineral concentrations (Anon. 1983a). However, the differences in nutritive value between cultivars and lines has rarely been studied systematically. Rethman and de Witt (1988) found no differences in crude protein content (CP) between Whittet and a local line, although Quinlan *et al.* (1975) suggested that Whittet had an above average CP. The interpretation of the results is complicated by possible differences in the unstated proportion of leaf and stem in the material analysed (see section on nutritive value).

3.3 Seed production

Experimental production of seed from kikuyu grass has reached 700 kg/ha (Wilson and Rumble 1975), but under commercial conditions, reported seed yields range from 118-500 kg/ha (Wilson 1970; Wilson *et al.* 1975; Quinlan *et al.* 1975). Kikuyu grass seed usually has a germination rate of 75-90% (Wilson 1970; Quinlan *et al.* 1975; Gardener *et al.* 1993a). Gardener *et al.* (1993a) reported that the specific gravity of kikuyu seeds was 1.27g/cm^3 and found seed dimensions of 2.4, 1.5 and 1.1 mm for length, width and depth respectively. Average seed weights of 2.3-2.6 mg (380-434 thousand seeds/kg) have been found (Pearson and Ison 1987; Piggot 1991), and Pearson and Ison (1987) reported typical sowing rates are 1-6 kg/ha .

Management of kikuyu grass for seed production requires short mowing or grazing (Wilson and Rumble 1975) to stimulate the production of secondary tillers, which flower prolifically and form seeds (Wilson *et al.* 1975). For a detailed methodology, see Wilson *et al.* (1975).

If ingested, kikuyu grass seeds survive ruminant digestion to some extent (Gardener *et al.* 1993a, 1993b), and are spread by cattle (Wilson and Hennessy 1977; Gardener *et al.* 1993a, 1993b) and sheep (Rethman 1989) via faeces. About 50% of the consumed viable seeds still germinate after digestion, and this seems to be of ecological importance for the species survival and dispersal during wet periods (Rethman 1989, Gardener *et al.* 1993a). Rethman (1989) also found that the success of establishment of seedlings via sheep faeces was lower than that of seedlings in cattle dung pats due to their lower moisture content.

3.4 Factors affecting growth rate and dry matter yields

3.4.1 *Soil nutrients and fertilisation*

Nitrogen (N) fertilisers. The response of kikuyu grass to N fertilisers is well documented. Annual DM yields on well watered soils have ranged from 4.0 t/ha with modest N applications (<100kg/ha N) (Cross 1979b) to 30-32 t/ha at rates above 850 kg/ha N (Colman 1966; Whitney 1974b; Colman and O'Neill 1978). However, annual DM yields for current N fertilisation practices (< 500 kg/ha N) have ranged from 4.5-17.3 t/ha depending on soil and environmental factors (Whitney 1974a, 1974b; Whitney and Tamimi 1974; Forde *et al.* 1976b; Taylor *et al.* 1976b; Cross 1979a; Tainton *et al.* 1982; Davies and Hunt 1983; Castillo *et al.* 1983; Brockett and Gray 1984; Cook and Mulder 1984a; Lowe and Bowdler 1984; Consentino *et al.* 1985; Rethman and de Witt 1988; Rumball 1991). Without N fertilisers, yields are substantially lower and confirm Mears' (1970) conclusion that kikuyu needs high soil fertility to be productive. However, it is difficult to make comparisons even between experiments carried out in similar regions because experimental procedures have not been standardised. For example, cutting height varies between experiments from 3 cm (Colman and O'Neill 1978) to 10 cm (Cook and Mulder 1984a). This is important due to the differences in herbage accumulation and density across the sward's vertical strata. The lower horizons are usually denser and contain most of the dry matter, thus underestimating the total DM yields more than proportionally at higher cutting heights. Murtagh *et al.* (1980a) found differences of up to 71% in total DM yield when cutting kikuyu swards at heights of 8 or 12 cm above the ground, although leaf yield was unaffected.

The efficiency of response of a crop to applied N fertiliser is largely dependent on the soil organic matter (OM) concentration, which determines the potential of soils to supply N and the slope of the response (Russell 1973), and by temperature (see below). From the analysis of a series of experiments, Mears (1970) concluded that the mean efficiency of response of kikuyu grass to N fertiliser ranged from 13-27 kg DM/kg N. Similar results have been obtained by Kemp (1975), Colman and O'Neill (1978) and Cook and Mulder (1984a) in Australia, Soto *et al.* (1980) in Colombia, Consentino *et al.* (1985) in Brazil and Tainton *et al.* (1982) in South Africa. Higher average responses (> 40 kg DM/kg N) have been reported by Whitney (1974b), Cross (1979a) and Anon. (1987) and can be explained by 2 reasons. First, the higher responses in Whitney's (1974b) trial in Hawaii were probably caused by temperatures nearer the optimum for growth which resulted in a higher potential growth rate in the absence of nutrient limitations. This is in agreement with Mears and Humphreys (1974a), Colman and O'Neill (1978) and Murtagh and Moore (1987) in subtropical Australia, who observed seasonal differences in the efficiency of response to N fertiliser, with responses being higher during the summer-autumn period, where temperatures are higher. The results reported by Cross (1979a) and Anon. (1987) cannot be explained by this factor, since the South African temperature regimes where kikuyu grows are lower. Possibly these higher responses were caused by lower soil OM concentrations, which were enhanced when N was applied. As a general criticism, it is surprising that none of the trials investigating yield responses to N fertiliser stated the basal soil N status and their potential for N mineralisation. Miles (1991) has shown that differences in the magnitude of the growth response to applied N can be due to this factor.

Kikuyu grass grows well on soils with pH levels above 4.8 (Awad *et al.* 1976). High applications of ammonium sulphate or nitrate may reduce soil pH by reducing the concentration of exchangeable bases with the result that soluble aluminium (Al) and/or manganese (Mn) concentrations can increase to toxic levels (Teitzel *et al.* 1991). This phenomenon can explain the reduced efficiency of N sometimes seen at moderate-high levels of N fertiliser applications (Awad and Edwards 1977). Although few critical reports exist on the effects of lime on kikuyu DM yields, liming is common practice to balance the acidifying effects of high N fertilisation (Awad and Edwards 1977; Miles *et al.* 1985; Miles 1991). Awad and Edwards (1977) found substantial increases in DM yields (around 30%) when pastures received 3.7 t lime at N applications of 672 kg/ha/yr. Nutrient uptake depends on rooting density and pH; therefore interactions between N fertilisation, lime and phosphorus uptake are sometimes observed (Miles *et al.* 1985). The mineral composition of kikuyu grass can also be affected by these interactions (Awad *et al.* 1979; Miles 1991) (see section on minerals).

Even when soil pH and other nutrients are adequate, it is common for the response to applied N to decline with increasing application rate, and this has important implications when optimal use of N fertilisers is sought. Whitney and Tamimi (1974), Cross (1979a) and Anon. (1987) found reduced growth responses at applications higher than 360 kg/ha/yr N, which agree with the results obtained by Mears and Humphreys (1974a) above 334 kg/ha/yr N, and Miles (1991) at around 400 kg/ha/yr N. These results might explain the low efficiency of response obtained by Kemp (1976) at higher N levels, and suggest that the efficiency of growth response of kikuyu grass to applied N decreases at around 350-400 kg/ha/yr N, depending on environmental (i.e. temperature, rainfall) or management factors (i.e. soil N supply, previous grazing). This would imply that there is a physiological limit to the utilisation of N by the grass crop which is dependent on its concentration in the plants' tissues and their potential growth rate. However, this does not imply that these are the optimum levels of N fertilisation for kikuyu pastures. The optimum levels will depend, not only on the growth responses of the pasture, but on the interactions with defoliation pressure, animal performance and the economic, environmental and productive objectives of the farming enterprise.

Differences between sources of N. Differences in yield response to N fertiliser type have been reported. Gartner (1966), in Australia, found that urea produced lower DM yields at rates of 225 and 450 kg/ha/yr N than ammonium sulphate, ammonium nitrate or sodium nitrate. His results were confirmed by Whitney and Tamimi (1974) in Hawaii, who applied N at 112-336 kg/ha/yr. Responses with urea were 29-90% of those with ammonium sulphate. Volatilisation of ammonia, especially at high application rates, is a well known problem with urea and this was probably the cause of reduced responses. Murtagh (1975) and Cross (1979a) found similar results comparing urea with ammonium nitrate and limestone ammonium nitrate, respectively. However, Castillo *et al.* (1983) found no differences in DM yields when they repeated the Whitney and Tamimi (1974) trial in Costa Rica at rates between 125-500 kg/ha/yr N. The different results between studies could be due to the cutting intervals, the amount of fertiliser used per dressing or environmental conditions (in particular soil moisture status after application). Whitney and Tamimi (1974) applied the N in 4 dressings/yr, while Castillo *et al.* (1983) applied the same amount in 12 dressings/yr. In Whitney and Tamimi's (1974) experiment, the increased amount of fertiliser per dressing could have led to a higher rate of volatilisation. Minson *et al.* (1993) concluded that research required on N fertilisers should aim to improve their economics by reducing volatilisation and oxidation losses. They stated that modelling studies and new techniques to assess N transfer between the different N pools could be used as tools to develop management strategies that reduce N losses. Urease inhibitors could be used to reduce volatilisation losses (Russell 1973), but their cost might not justify a wide on-farm use.

South African results (Hefer and Tainton 1990) suggest that a liquid source of N (urea ammonium nitrate, UAN) could be cheaper but that its effective use would depend on using it with low N concentrations to prevent leaf scorching. More recently, Hefer *et al.* (1992) found that applications of up to 69 kg/ha N as UAN (8% N) combined with 5% ammonium thiosulphate as a urease inhibitor would not damage the leaves of kikuyu. However, this level of N application is too low to maintain highly productive kikuyu pastures.

Sward structure. The effect of N fertiliser on the proportion of leaf and stem of kikuyu DM yield has been studied by Minson (1973) and Mears and Humphreys (1974a). These authors found that the proportion of stolons in the DM increased slightly with higher N applications. For example, Mears and Humphreys (1974a) report proportions of stolon in DM yield of 49% without N applied, to 54% for N applications of 672 kg/ha/yr. These were possibly due to increases in leaf senescence at higher N levels caused by faster development of the canopy which decreased the light interception of the lower leaves. Management decisions such as frequency, pressure or height of defoliation and their interactions with N fertilisation play a more important role in determining the sward's structure.

Gibberelic acid promotes an elongation of the stems (Lester *et al.* 1972). Although sward height increases (Whitney 1974a) and higher stem DM yields are obtained, these are associated with lower grazing intakes (Whitney 1976) due to the lower quality of the stem material.

Phosphorus (P) fertilisers. Mears (1970) concluded that little work had been done on the phosphorus requirements of kikuyu grass and the picture has hardly changed since then. In pot experiments, Wilson and Sandland (1976) found increased DM yields when applying 125-1072 kg/ha superphosphate at N fertiliser levels of 17.8-480 kg/ha/yr. Under normal conditions, the additive response of P fertilisers to increased kikuyu DM yields is small when N is applied (Cross 1979a; Annessens 1989; Miles 1991) but greater responses have been observed at higher N fertiliser levels (Cook and Mulder 1984b).

As with other plants, high responses to P fertilisers may be observed in situations where soil P is extremely deficient (Mears 1970). As soil P is relatively immobile, root length and distribution play an important role in its absorption (Wilson and Sandland 1976). Most of the kikuyu grass roots are in the top 70 cm of the soil (Quinlan *et al.* 1975) and its root mass can be as high as its above-ground DM (Mears and Humphreys 1974a). This would explain high P absorption rates when soils are P deficient and P fertilisers are applied.

Beneficial but marginal effects of P fertilisation on kikuyu DM yields are also observed on acid soils due to the removal of Al toxicity (Awad and Edwards 1977). Although P is more readily available at soil pH 5.5-7.5 (Buckman and Brady 1969), evidence appears equivocal in the studies where lime and P have been applied together. Awad and Edwards (1977) found no increases in kikuyu DM yields when applying both fertilisers. However, they concluded that, in their trial, P *per se* was not limiting growth of kikuyu, thus explaining the lack of response to additional P. Miles *et al.* (1985) attributed the increases in DM yield to an increased P uptake when lime was applied. Although they did not relate the results to soil pH or Al toxicity, the increases in soil pH observed in their study would have resulted in a higher availability of P. Nevertheless, P nutrition of kikuyu pastures and its interaction with lime and N should be the subject of further studies.

Potassium (K) and sodium (Na) fertilisers. Relationships involving Na and K cannot be separated as their roles are closely linked. A good explanation of the interactions between the 2 minerals is given by Smith *et al.* (1980) who postulated that kikuyu grass is a natrophobe plant species. This means that kikuyu does not require Na as a nutrient and that there is some biochemical or physical barrier to the movement of Na into the transpiration stream. Leaves therefore have a low Na:K ratio. This would provide a physiological explanation for the low Na concentrations in kikuyu grass and would explain why Russell (1976) found that kikuyu was tolerant of high soil salt concentrations.

Yield responses to K applications have been observed only when N supply is non-limiting (Cross 1979a; Miles 1991). This may partly be because the trials have taken place on K-rich clay soils or more likely because of the efficient recycling of this mineral through livestock urine and faeces (Cross 1979a). Recent evidence from pot experiments suggests that increases in soil K have positive effects on plant size and tillering rate and may also reduce the rate of senescence of older leaves (Pinkerton and Randall 1993), but the major effect of K fertilisers on kikuyu grass is to change its mineral composition (Miles 1991; Pinkerton and Randall 1993). Luxury uptake of K can occur at high rates of K application (see section on mineral composition).

Other nutrients. Apart from the observations cited by Mears (1970), few responses to other nutrients have been reported, although it is rarely clear whether this is because the plant requirement is low or because the soil can provide an adequate supply. Lipsett (1975) found no response in DM yields to additional molybdenum (Mo) but stated that the soil might have had an adequate Mo status. Provided that N, P and K are supplied in adequate amounts and the soil pH is maintained above the critical level to prevent Al or Mn toxicities and to maintain high concentrations of exchangeable bases, it is unlikely that DM yields will be depressed by low soil micronutrient concentrations in the regions where kikuyu grows. Micronutrients, especially Mo, together with the macrominerals P and sulphur (S), are more important when kikuyu is associated with legumes (Fulkerson *et al.* 1993).

3.4.2 *Responses to light*

Despite the fact that photosynthesis is one of the major physiological processes controlling DM yields of higher plants, very little work has been carried out on the response of photosynthesis to environmental factors in kikuyu grass (G. J. Murtagh, personal communication).

Lester *et al.* (1972) estimated apparent photosynthesis of whole micro-swards but their results are difficult to interpret as LAI was not reported. Weng (1988) estimated single leaf photosynthesis but unfortunately at only one qunatum flux density (1500 μmol/m^2/s photosynthetically active radiation, PAR) which is below the point of light saturation.

When modelling canopy photosynthesis, the factors affecting LAI (rates of leaf appearance and extension and specific leaf area, (SLA)) and N utilisation play a more important role than photosynthetic rates at the single leaf level. Latitudinal effects such as seasonal temperature fluctuations play a major role.

Irradiance affects the SLA of grasses and legumes (Ludlow and Wilson 1971). In their study, light levels up to full sunlight decreased the SLA of *Panicum maximum* and *Macroptilium atropurpureum* and low light levels increased it. The average SLA of kikuyu leaves has been found to around 24 m^2/kg. (Murtagh 1988a).

Leaf photosynthesis is commonly found to increase with leaf N concentration. Bolton and Brown (1980), for example, showed this relationship for *Panicum maximum*. Weng (1988) similarly found that high soluble N concentrations in kikuyu grass leaves were associated with higher photosynthetic rates and Ludlow *et al.* (1988) showed that the N concentration in kikuyu grass was positively correlated with its chlorophyll content. Their results are related to the high proportion of plant N (> 30%) present as photosynthetic enzymes, and might explain the observations of Henzell and Oxenham (1973) and Murtagh (1988a), that for optimal growth, the first fully expanded leaf of kikuyu should contain at least 3.5% N. The low growth responses at 365 kg N/ha and high irradiances found by Ericksen and Whitney's (1981) could be explained by this threshold not being reached.

The responses to light is one of the fundamental subjects that requires more attention if the physiology of kikuyu grass growth is to be better understood and if mechanistic variables driven by environmental variables are going to be built.

3.4.3 Temperature

Temperature is another key determinant of kikuyu grass productivity. It causes the seasonal growth cycle in the subtropics (Lambert *et al.* 1977; Goold 1979; Murtagh and Moore 1987; Piggot 1988; Rumball 1991; Minson *et al.* 1993), influences the responses to N fertilisation (Whitney 1974a; Murtagh 1975; Colman and O'Neill 1978; Cook and Mulder 1984a; Pearson *et al.* 1985) and has marked effects on its physiology.

The optimum 24-hour mean temperature in the field depend, both, on the shape of the response and on the diurnal temperature cycle. Working in growth chambers, Ivory and Whiteman (1978a) reported optimum day and night temperatures for maximum total plant growth of 29.4 and 25.6 °C, respectively. Murtagh *et al.* (1987) obtained maximum growth in the field at average temperatures of 25 °C.

Ivory and Whiteman (1978a) also suggested that differences existed in the temperatures maximising the growth rate of different plant parts. The optimal temperature for tillering rate was lower (mean 23.4 °C) than for total plant growth, and tillering was less responsive to temperature (except at extreme temperatures). Although leaf size increased with increasing day temperature up to 34.1 °C, it was relatively insensitive to low temperatures which might be explained by its origins (Kenyan highlands), and would confirm its adaptation to the subtropics and cooler regions of the tropics. They also found that kikuyu growth ceased at around 8 °C (Ivory and Whiteman 1978b) and this was confirmed by Colman and O'Neill (1978) in a field experiment. Murtagh *et al.* (1987) also found that internode thickening and extension of the primary stolons increased up to 30°C.

Leaf appearance rate is markedly affected by temperature and can be one of the most important factors explaining seasonal DM yield at different latitudes. Murtagh (1987) reported leaf appearance rates of 5.5, 3.8, 1.8 and 1.4 days at 15, 20, 25 and 30 °C, respectively. Mannetje (1975) found that increasing temperature increased the leaf content of kikuyu grass swards. His results could be explained by an increased leaf appearance rate. These responses to temperature have a marked effect when scaling single-leaf gross photosynthesis up to the whole canopy.

Ludlow and Wilson (1971) and Johnson and Thornley (1984) suggested that the temperature effects on single-leaf light-response curves are mediated through changes in the *PMax* and that there is a linear relationship between the two variables. Respiration rates are also affected by temperature (Murtagh *et al.* 1987). In their miniature sward experiments, specific maintenance respiration rates increased from 11 mg/g/d at 15 °C to 37 mg/g/d at 30 °C.

Kikuyu has a good overwintering ability (Quinlan *et al.* 1975). It can withstand mild frosts (Mears 1970) and, in countries like South Africa, it is used as foggage (frosted herbage) (Zacharias *et al.* 1991). Ito *et al.* (1985) have related this overwintering ability to the accumulation of non-structural carbohydrates (NSC). During late summer and autumn, canopy net photosynthesis exceeds the demand for assimilate for structural tissues and high NSC concentrations accumulate in consequence. These NSCs are used as an energy reserve and to lower the freezing point to survive the winter temperatures but are depleted by the time spring arrives. As temperature and daylength increase in spring, cell division and expansion speed up, more photosynthate is produced and the grass re-establishes its growing pattern.

3.4.4 *Soil water and irrigation*

Yield responses to irrigation and nutrients by plants depend on the initial soil water status before application (Russell 1973). Mears (1970) concluded that kikuyu withstands dry periods especially if nutrients are not limiting and that without N fertilisation, increasing the frequency of irrigation hardly increased DM yields. Kemp (1975) confirmed these results and concluded that during short dry periods the additional yield from N applications was greater than the extra yield from irrigation alone. The high fertiliser rates used in Forde *et al.'s* (1976b) or the moderate N applications in Lowe and Bowdler's (1984) studies support these conclusions, as they could not find a significant yield difference between irrigated and unirrigated plots. However, the experimental design of these studies, which were carried out to solve site-specific problems, only allowed for short periods, if any, of mild water stress, and therefore did not compromise greatly the DM yield potential of the pastures. The initial soil water status of the unirrigated plots together with the low rainfall might have been enough to permit normal growth during most of the experimental periods. Murtagh (1975) suggested that an abrupt change from dry to wet conditions would enhance the response to N fertiliser relative to response of continuously wet plots, because of the high mineralisation rates of organic N when dry soils are watered (Russell 1973). Therefore, another explanation for the lack of response to additional irrigation could be that in the dryland plots of Forde *et al.* (1976b) and the low-frequency irrigation plots in Lowe and Bowdler's (1984) experiments, the sporadic rainfall caused high rates of soil N mineralisation, thus masking the effects of mild water stress.

Murtagh (1988b) demonstrated a relationship between soil water potential, evaporative demand and growth rate. At a peak growth rate of 234 kg DM/ha/d and an evapotranspiration rate of 2 mm/d, water stress began to reduce growth rate when the soil water potential was less than - 134 kPa, while at an evaporative demand of 5 mm/d, growth rate was only 39% of the peak growth rate and growth ceased at a soil water potential of -101 kPa.

Critical studies designed to understand the physiological response and the limits of kikuyu grass growth to water stress have not been performed, and are needed to plan optimal irrigation schemes. These experiments should attempt to find the lowest soil water deficit required before water stress limits growth rate, rather than to test the effect of additional water on DM yield.

3.4.5 *Effect of defoliation intervals*

Cutting trials (Whitney 1974b; Kemp 1976; Soto *et al.* 1980; Rethman and de Witt 1988) have demonstrated that increasing the cutting interval increases annual DM production and decreases N content of kikuyu grass over a wide range of N fertiliser application rates. The physiological explanation for the increased production is an increased LAI and therefore a higher light interception from the sward as it matures.

Interactions between N fertilisation level and cutting interval are usually found in these trials. An improved N utilisation at older stages of growth has been suggested (Soto *et al.* 1980), especially at higher N rates. These results are consistent with the positive relationship between chlorophyll and N levels found by Whitney (1974b) and Ludlow *et al.* (1988). The improved N utilisation might also be masked by supracritical N concentrations (Murtagh 1990a) which would buffer the effect of a N deficiency. The lower N concentration in kikuyu as it matures is partly explained by the translocation of surplus N from the aerial parts of the plant to the roots to counteract the low soil N concentrations at longer periods of growth.

From a grazing management point of view, the balance between growth, especially of leaves, senescence, and sward composition is very important as their relative proportions will markedly influence the sward's nutritional value and utilisation (Stobbs 1975). Unfortunately, none of the trials mentioned above reports the sward composition at different stages of growth. As LAI increases, less light reaches the lower horizons of the sward, the lower leaves die (Murtagh 1987) and consequently more senescent material accumulates. The final effect is an increase of stolon relative to leaf yields, a reduction in nutritive value; and either an underutilisation of the pasture, or a reduction in animal performance.

Physiological concepts should be given more consideration in cutting trials or grazing studies to find the appropriate management strategies that produce the required sward composition, cutting intervals or paddock rest periods.

3.5 Associations of kikuyu with other grasses and legumes

Subtropical regions. In the subtropics, where marked seasonal variations in temperature and moisture define the growth habits of plant species, it is a common practice to use kikuyu in association with temperate grasses and legumes to balance the feed availability throughout the year for ruminants (Betteridge 1979; Goold 1979; Davies and Hunt 1983; Piggot and Morgan 1984; Hill 1985; Betteridge and Haynes 1986; Piggot 1988; Harris and Bartholomew 1991) or to devote an area of the farm for the production of temperate species (Murtagh and Moore 1987).

Kikuyu has peak growth rates in summer and autumn (Murtagh and Moore 1987), where temperatures are favourable for its growth. It is usually associated in winter-spring with temperate grasses such as: *Lolium* spp. (Lambert *et al.* 1979; Betteridge 1979; Murtagh and Moore 1987; Harris and Bartholomew 1991), which are the predominant temperate species; *Oryza sativa* (Minson *et al.* 1993); *Poa* spp. (Goold 1979; Piggot 1991); *Festuca arundinacea* (Hill *et al.* 1985); *Bromus* spp. (Hill 1985; Hill *et al.* 1985; Betteridge and Haynes 1986); and/or with legumes, the most common being clovers (*Trifolium* spp.) (Davison 1985; Fulkerson *et al.* 1993) and *Lupinus* spp. (Royal and Hughes 1976). Fulkerson and Slack (1993) suggested that the legume, *Lotus penduculatus*, was a promising association. However, more recently, Fulkerson and Slack (1994) found that kikuyu associations with white clover produced higher DM yields (21% higher), their seasonal pattern of growth complemented kikuyu better, and the swards had a higher nutritive value than those with *Lotus* spp. They also found that a severe defoliation down to 5 cm, coupled with a flexible defoliation interval depending on the season (longer regrowth periods in winter and shorter ones in late spring), maintained a balanced association between clover and kikuyu. However, whether associations with *Lotus* spp. are more suitable in other climatic regimes where kikuyu grows is still not known. Tropical legumes such as *Desmodium* spp. (Jeffery 1971b; Brands and Cook 1976; Woomer *et al.* 1990) and *Glycine* spp. (Colman *et al.* 1966; Jeffery 1971b; Quinlan *et al.* 1975) could be used in association with kikuyu for summer feeding.

The high growth rates of kikuyu during summer and autumn and its aggressive nature (Russell and Kleinschmidt 1984; Rumball 1991), often result in the need to renovate the temperate species in mixed swards in order to obtain enough food for the winter-spring period. The preferred methods of re-introduction are oversowing (Betteridge 1985; Harris and Bartholomew 1991; Fulkerson *et al.* 1993) or direct drilling (Hill 1985; Minson *et al.* 1993), which are usually carried out in autumn (Fulkerson *et al.* 1993).

Pre-sowing management usually consists of slashing (Minson *et al.* 1993), hard grazing or mowing the kikuyu pastures to reduce their competitiveness for light and to allow more temperate species seed to reach the ground (Piggot and Morgan 1984; Betteridge and Haynes 1986). Glyphosate ('Roundup')(Hill 1985; Piggot 1991; Fulkerson and Slack 1993) and paraquat (Hill 1985; Betteridge and Haynes 1986) are also used to control over-dominance of kikuyu prior to temperate species renovation. Since these activities are carried out at a time of the year when the NSC reserves in the stem bases and stolons are high, they do not compromise the ability of kikuyu to regrow when conditions are favourable.

Seeding rates for *Lolium* spp. range from 15-50 kg/ha (Davies and Hunt 1983; Betteridge and Haynes 1986; Harris and Bartholomew 1991; Fulkerson *et al.* 1993), whereas *Trifolium* spp. are sown at rates 3-20 kg seed/ha, depending on the timing of the forage required and whether they are to be grown in associations with kikuyu pastures or alone as a winter-spring feed (see Fulkerson *et al.* 1993). Mixed pastures have a higher nutritional value in the winter and spring, but a delicate balance exists to match feed availability throughout the year (Lambert *et al.* 1979; Rumball and Boyd 1980). Bloat control is necessary when legumes represent a high proportion of the pastures on offer (Battese and Fulkerson 1994) in winter-spring.

It is widely recommended that kikuyu associations with *Trifolium* spp. be fertilised with superphosphate at 100-250 kg/ha plus 100 kg/ha muriate of potash (Colman *et al.* 1966; Fulkerson *et al.* 1993). Lime should be applied if the pH is below 5.5 (Battese and Fulkerson 1994).

Philpotts (1981) noted that poor nodulation of glycine (*Neonotonia wightii*) and forage lupins may occur in krasnozem soils where kikuyu grows, and suggested that rhizobia were suppressed by extracts of kikuyu roots. The subject needs further research as soil type is not the only possible cause for reduced nodulation. Chou *et al.* (1987; 1989) studied allelopathic interactions in a pasture-forest system in Taiwan, and found that an aqueous leachate of kikuyu promoted the growth of 2 weed species. On the other hand, Woomer *et al.* (1990) suggested that the mat formed in kikuyu pastures was responsible for the reduced abundance of rhizobia associated with *Trifolium repens* but not of rhizobia associated with *Desmodium intortum*.

Tropical highland regions. In tropical highland regions, seasonal temperature cycles are not as marked as in the subtropics, and moisture availability largely determines the growth pattern of kikuyu grass. Under these conditions, associations, mainly with *Trifolium* spp., are sometimes found (Mears 1970) but are very difficult to manage due to the mild temperatures, which promote high growth rates of N-fertilised kikuyu grass under the favourable moisture conditions. Stocking rates are seldomly adjusted to counteract these high growth rates, with the result that a dense mat of stolons is usually formed which inhibits light penetration and prevents the legume from establishing properly (Mears 1970; Fulkerson *et al.* 1993). Therefore, the legume component is usually lost or makes only a small contribution to the sward's yield in long established kikuyu pastures in the tropics (van der Grinten *et al.* 1992).

Very little information has been published regarding management of kikuyu-legume associations in tropical regions. More research is required in these areas to reduce N fertiliser and supplementation costs. Legume species with different morphological characteristics which enable them to tolerate better the aggressive growth habits of kikuyu grass should be tested (Woomer *et al.* 1990).

3.6 Nutritional value of kikuyu grass

3.6.1 *Crude protein (CP)*

Crude protein (N X 6.25) concentrations ranging from 74 to 282 g/kg DM have been reported in fresh kikuyu grass (Figure 3.1) and from 120 to 164 g/kg DM in kikuyu silage (de Figuereido *et al.* 1989; de Figuereido 1991).

CP concentration increases with increasing N fertilisation (Minson 1973; Whitney 1974b; Castillo *et al.* 1983; Pearson *et al.* 1985; Rumball 1991), and decreases at very high day-night temperature regimes (32/24 °C) (Mannetje 1975). In the subtropics, CP initially increases during the summer

(Pearson *et al.* 1985) probably because of the fertilisation regime, but as the growing season advances, there is a diluting effect on CP concentration caused in part by the high growth rates (Murtagh 1975; Minson 1990), and partly by changes in the structural composition of the sward. Laredo and

Table 3.1. Nutritive value of kikuyu grass.

Chemical fraction	Mean (g/kg DM)	Range (g/kg DM)	References
Crude protein (CP)	164	74-282	Gomide *et al.* (1969a); Jeffery (1971a); Minson (1973); Joyce (1974); Whitney (1974b); Kaiser (1975); Mannetje (1975); Royal and Hughes (1976); van Ryssen *et al.* (1976); Reid *et al.* (1979); Fernando and Jayaratne (1980); Soto *et al.* (1980); Laredo and Mendoza (1982); Tainton *et al.* (1982); Laredo *et al.* (1983; 1990); Ramirez *et al.* (1983); Pearson *et al.* (1985); Sanchez *et al.* (1986); Dugmore *et al.* (1986; 1991); Dugmore and Du Toit (1988); Hughes *et al.* (1988); Meissner and Paulsmeier (1988); Rethman and de Witt (1988); Marais (1990a); Marais *et al.* (1990); Rukantabula and Kusekwa (1990); Rumball (1991); Singh and Narang (1991); Evans and Hacker (1992a); Hamilton *et al.* (1992); Köster *et al.* (1992); Singh *et al.* (1992); van der Grinten *et al.* (1992); Punia and Leibholz (1994); Herrero *et al.* (1996)
Crude fibre (CF)	258	167-314	Gomide *et al.* (1969a); van Ryssen *et al.* (1976); Campabadal and Sanchez (1986); Dugmore *et al.* (1986; 1991); Anon. (1987); Bredon *et al.* (1987); Dugmore and du Toit (1988); Rukantabula and Kusekwa (1990)
Neutral detergent fibre (NDF)	654	474-827	Moir *et al.* (1977); Reid *et al.* (1979); Laredo and Mendoza (1982); Rukantabula and Kusekwa (1990); Davison *et al.* (1991); Singh and Narang (1991); Köster *et al.* (1992); Singh *et al.* (1992); Herrero *et al.* (1996)
Acid detergent fibre (ADF)	333	246-402	Joyce (1974); Whitney (1974b); Reid *et al.* (1979); Laredo and Mendoza (1982); Ramirez *et al.* (1983); Dugmore *et al.* (1986); Laredo *et al.* (1990); Rukantabula and Kusekwa (1990); Singh and Narang (1991); Köster *et al.* (1992); Singh *et al.* (1992); Punia and Leibholz (1994)

::: continued

Chemical fraction	Mean (g/kg DM)	Range (g/kg DM)	References
Lignin	54	24-88	Bailey and Hunt (1973); Whitney (1974b); Reid *et al.* (1979); Laredo and Mendoza (1982); Dugmore *et al.* (1986); Marais (1990b); Rukantabula and Kusekwa (1990); Singh and Narang (1991); Singh *et al.* (1992); Punia and Leibholz (1994)
Non-structural carbohydrates (NSC)	70	34-156	Joyce (1974); Forde *et al.* (1976a); Taylor *et al.* (1976a); Betteridge (1979); Fernando and Jayaratne (1980); Marais *et al.* (1990); Kaiser *et al.* (1993); de Figuereido and Marais (1994)
Dry matter *In vivo* digestibility[1]	561	473-686	Jeffery (1971a); Minson (1972; 1973); Joyce (1974); Ishizaki *et al.* (1976); Soto *et al.* (1980); Rees and Little (1980); Marais *et al.* (1990); Schiere *et al.* (1990); Rumball (1991); Punia and Leibholz (1994)
Dry matter *In vitro* digestibility[1]	643	500-834	Mannetje (1975); Royal and Hughes (1976); van Ryssen *et al.* (1976); Laredo and Mendoza (1982); Castillo *et al.* (1983); Ramirez *et al.* (1983); dos Santos Abrahao (1983); Hughes *et al.* (1988); Pastrana *et al.* (1990); Evans and Hacker (1992b); Hamilton *et al.* (1992)
Gross energy (MJ/kg DM)	18.5	16.9-20.4	Campbell *et al.* (1969); Betteridge (1979); Soto *et al.* (1980); Bredon *et al.* (1987); Marais *et al.* (1990)

1 Papers where organic matter digestibility and intake had been calculated have been transformed to dry matter to maintain uniformity.

Minson (1973) found that leaves had a higher CP than stolons (126 vs 110 g/kg DM). Similar results have been obtained by Mannetje (1975) and Marais (1990a; 1990b). Forde *et al.* (1976a) also reported differences between leaf lamina and sheath, with the former having a higher CP concentration (214 vs 175 g/kg DM). Dead material has a low CP concentration (< 80 g/kg DM). Thus the higher the proportion of leaves relative to stolons and dead material, the higher the crude protein concentration of kikuyu grass.

A particular feature of kikuyu when compared with other tropical grasses is that it can maintain a relatively high CP level (> 100 g/kg DM) when mature (Mears 1970). This is at least partly due to the essentially vegetative status of the sward. Reid *et al.* (1979), in Uganda, found a CP concentration of 113 g/kg DM in kikuyu after 12 weeks regrowth. Soto *et al.* (1980) confirmed this finding in Colombia with a crude protein concentration of 131 g/kg DM after 11 weeks regrowth. Even after a 6-month dry season in Tanzania, Rukantabula and Kusekwa (1990) report CP levels of 74.4 g/kg DM, which is close to the level at which dietary protein starts to limit intake and therefore animal performance (Milford and Minson 1965; Minson 1981). Lower concentrations are sometimes observed in the subtropics during the winter (Jeffery 1971a; Zacharias *et al.* 1991) and this is often related to lower leaf:stem ratios due to lower leaf appearance and extension rates (Buxton and Fales 1994). As stated by Mears (1970), it is unlikely that animals will experience protein deficiency in kikuyu grazing systems.

Recent Australian studies (Reeves *et al.* 1994), have concentrated on finding defoliation intervals which produce the best compromise between forage availability and quality using morphological indicators. Preliminary results suggest that during early summer, the N concentration in leaves declines after 26 days of regrowth. This would be explained by the increasing temperature regimes in this season and an increased utilisation of leaf N to produce more structural tissue. More studies of this type are needed to find optimal defoliation intervals for particular production purposes and climatic regimes.

Current feeding systems (i.e.SCA 1990, AFRC, 1993) assess the protein needs of ruminants in terms of requirements for microbial protein synthesis, rumen undegradable (UDP) and rumen degradable protein (RDP). The synthesis of microbial protein in the rumen is largely dependent on the amount of energy and RDP available to the animal (SCA 1990).

Hart and Leibholz (1990) compared kikuyu grass samples containing CP and acid detergent fibre (ADF) concentrations of 130 and 294 g/kg DM, respectively, with others containing 62 g/kg DM CP and 381 g/kg DM ADF. They discovered that the true ruminal protein degradability of the samples was similar at 0.80 and 0.79, respectively. Mean rumen retention times (MRT) were 39.8 and 36.7 h for the two samples. Microbial N flow to the omasum was 25 and 14 g/kg DOM. In another set of studies, Punia *et al.* (1984) and Punia and Leibholz (1994) found that microbial N flow to the omasum increased with increasing level of intake. Punia and Leibholz (1994) found microbial N yields of 34, 24.1, and 20.7 g/d for kikuyu hay intake levels of 60.7, 50, and 39 g/kg metabolic weight ($BW^{0.75}$). These microbial N yields represent 13-16 g/kg DOM which are low when compared with published values (ARC 1984). Low rumen ammonia concentrations or low rates of carbohydrate fermentation might have affected microbial production in their studies. Protozoal N accounted for 26.1-29% of the microbial N and protozoal numbers in rumen liquor and omasum were $1.09X10^{-5}$/ml and $0.51X10^{-5}$/ml, respectively.

Pheloung and Brady (1979) found that the solubility of CP from kikuyu grass leaves containing 181 g/kg DM CP was 26%. Similar results (24%) were obtained by Ali and Stobbs (1980). They also suggested that CP solubility was unaffected by stage of growth and that stem protein was considerably more soluble (66%) than leaf protein. The findings of Marais *et al.* (1987) and Marais (1990a; 1990b) support this conclusion. In their studies the stem fraction contained a high level of non-protein organic N (NPON) which is highly soluble and very low protein N, while the leaves contained very high protein N and low NPON. Fernando and Jayaratne (1980) reported mean values ranging from 24.5 to 30.2% for composite plant samples, probably reflecting a high proportion of leaf material.

Pheloung and Brady (1979) found that 13% of the soluble protein in kikuyu grass leaves was in the form of fraction 1 protein, which is the major soluble protein of the chloroplast and which has been implicated in the occurrence of bloat. However, Pienaar *et al.* (1993a; 1993b) attributed observations of high *in vitro* foaming capacity of kikuyu samples to saponins.

Accepting the importance of microbial protein in determining the protein supply of ruminants, substantially more work is needed on the kinetic properties of kikuyu grass protein.

3.6.2 Fibre fractions

Mears (1970) did not include the fibre composition in his review, but this aspect has been the subject of considerable research in recent years. The importance of the fibre fractions lies in their association with digestibility, rumen fill and intake (Minson 1982, 1990; van Soest 1982).

Crude fibre (CF). When expressed as CF, levels range from 167-314 g/kg DM (Table 3.1), but this measurement has largely been superseded by neutral detergent fibre (NDF), acid detergent fibre (ADF) and lignin analyses which give a better description of the fibre composition (see van Soest 1982).

Neutral detergent fibre (NDF). Reported levels of NDF (cell wall) in composite samples range from 474-827 g/kg DM (Figure 3.1), but differences exist between plant parts due in part to anatomical reasons (see Wilson 1991; 1994), leaves having a lower NDF concentration than stems (Laredo and Minson 1973; Moir *et al.* 1979; Marais *et al.* 1992). Laredo and Minson (1973) found mean NDF concentrations of 680 and 706 g/kg DM in leaves and stems, while Moir *et al.* (1979) and Marais *et al.* (1992) found higher differences (532 vs 687 and 476 vs 578 g/kg DM, respectively). These higher differences were possibily caused by a more mature stolon fraction (Minson 1990). Similarly, Bailey and Hunt (1973) reported lower hemicellulose levels in leaf blades than in sheaths.

In terms of its rumen degradability, Köster *et al.* (1992) working on fistulated sheep with samples of oesophageal extrusa containing 628 g NDF/kg DM and 251 g CP/kg DM found that 73.9% of the NDF disappeared from the rumen after 48 h at a rate of 2.97% per h. In another experiment, Singh *et al.* (1992) found that the degradation of kikuyu NDF in the rumen of steers exhibited an initial lag phase of 4.34 h. Their samples (135.1 g CP and 713 g NDF/kg DM) had a degradation rate of 4.19% per hr. Herrero *et al.* (1995), using gas production measurements as a proxy for NDF loss, found seasonal differences in the rate of degradation of NDF but not on its extent. Their samples, collected under tropical highland conditions, had a significantly lower NDF degradation rate during the mild dry season than during the wet season (3.68% vs 4.68%, respectively). The lower degradation rate found by Köster *et al.* (1992) in comparison with the previous studies was possibly caused by the short incubation times used (maximum 48 h), therefore failing to define the asymptote of the degradation curve and the lag phase.

Acid detergent fibre (ADF). ADF levels in composite samples are about half of the NDF concetrations and range from 246-402 g/kg DM (Table 3.1). As was the case with NDF, Laredo and Minson (1973) found that leaves also have a lower ADF concentration than stems (323 vs 360 g/kg DM, respectively).

Singh *et al.* (1992) found that ADF degradation in the rumen also exhibited a lag phase of 7.09 h and had a rate of disappearance of 3.81% per h for a sample of kikuyu containing 402 g ADF and 135 g CP/kg DM.

Lignin. Lignin levels in composite samples of kikuyu grass range from 24-88 g/kg DM (Table 3.1), with levels in leaves lower than in stolons (Laredo and Minson 1973; Marais *et al.* 1992).

Several factors affect the concentration of these fibre components in kikuyu. Firstly, the proportion of cell wall in kikuyu leaves has been found to increase with temperature (Wilson *et al.* 1976; Moir *et al.* 1977). This is partly a reflection of the higher growth rates at increased temperatures. Secondly, Laredo and Mendoza (1982) found higher concentrations of all fibre components during the dry season in Colombia, suggesting that low moisture also plays an important role. It has long been recognised that grasses grown in dry conditions exhibit altered anatomical features such as an increase in sclerenchymatous tissues (e.g. Grace and Russell 1977). Thirdly, Reid *et al.* (1979) found that the fibre components increase as kikuyu matures, but as with protein, the rate of change is slow, thus maintaining low fibre concentrations. In their study, 4- and 12-week kikuyu regrowths contained 584 and 688 g NDF/kg DM while lignin increased from 35 to 53 g/kg DM. However, the stolon fraction matures faster that the leaf fraction (Minson 1990; Wilson 1994).

3.6.3 Non- structural carbohydrates

Non-structural (soluble) carbohydrates (NSCs) are an important energy source for rumen microbes to ensure a proper utilisation of protein (Preston and Leng 1987).

Several authors have published NSC levels of composite kikuyu samples ranging from 21.7-156 g/kg DM (Table 3.1). The large variation between samples is typical of the measurement of NSC. As NSCs are the product of photosynthesis, which is temperature and irradiance dependent (see section on responses to light), marked fluctuations in their levels occur throughout the day (Marais and Figenschou 1990) and between seasons (Ito *et al.* 1985). Marais and Figenschou (1990) observed variations of almost 38% in NSC concentrations during a single day, levels typically peaking during the afternoon when the grass had been exposed to sunlight for several hours.

The stems of graminaceous plants act as storage organs (Milthorpe and Davidson 1966). Marais and Figenschou (1990) confirmed this finding in kikuyu and noted that stems accumulated higher concentrations of NSC's than leaves. However, in the study of Taylor *et al.* (1976a), leaves contained slightly higher NSC levels than stems (92 vs 82 g/kg DM). NSC concentrations are reduced by high temperatures (Marais and Figenschou 1990) and this is a possible cause for the differences between authors. Perhaps in Taylor *et al.*'s (1976a) experiment, the temperature regimes were higher, therefore the NSCs stored in the stems would have been used as an energy source for increased respiration at high temperatures (see section on temperature). In Marais and Figenschou (1990) study, leaves and stems of plants grown at day/night temperatures of 19/9 °C and 31/16 °C contained 79 and 83, and 65 and 71 g NSC/kg DM. Sheaths typically contain less NSCs than leaves (Forde *et al.* 1976a). In kikuyu silages, de Figuereido and Marais (1994) found NSC concentrations of 23 g/kg DM after 120 days of fermentation.

The NSC of kikuyu grass consist mostly of sucrose although differences between leaves and stems are associated with increases in the fructose concentrations of the latter (Marais and Figenschou 1990). Starch contents are very low (< 10 g/kg DM) (Taylor *et al.* 1976a).

The NSC levels reported by most authors are low when compared with values for other species and therefore confirm Betteridge's (1979) observations that kikuyu pastures have a low soluble:structural carbohydrate ratio. However, it has not been possible to separate the effects of species and climate. These observations require further study as low NSC levels, coupled with low rates of degradation of structural carbohydrate, could be the cause of the low N retention and animal performance (see section on animal performance). Rumen microbes would not have had the required energy source to utilise the high N levels in kikuyu grass, much of which would have been lost as ammonia. Therefore, the often reported high N concentration would be irrelevant if it could not be properly utilised. This also suggests that the balance between the chemical fractions coupled with a knowledge of their kinetic properties should be more important in nutritional studies than looking for high or low concentrations of specific nutritional components.

3.6.4 Digestibility

Digestibility of the dry matter (DMD) and the chemical fractions is one of the subjects most studied in kikuyu grass due to their direct relation to the metabolisable energy concentration and forage intake (Minson 1982). Results obtained by several authors are presented in Table 3.1. When estimated *in vitro,* digestible DM values range from 500-834 g/kg DM. Ishizaki *et al.* (1976) and Hacker and Minson (1981) found that *in vitro* measurements overestimated DMD in kikuyu grass when compared with *in vivo* trials. *In vivo* estimations in sheep ranged from 473 to 686 g/kg DM. *In vitro* digestible DM of kikuyu silages has been found to be between 350-450 g/kgDM (de Figuereido *et al.* 1990; de Figuereido 1991).

In terms of plant parts, digestibility of stolons is similar to or slightly higher than that of the leaf fractions (Laredo and Minson 1973, 1975; Mannetje 1975). Hacker and Minson (1981) summarised the results of 21 *in vivo* digestibility trials with sheep and found that DMD of leaves and stems was 510 and 520 g/kg DM, respectively. Contrasting results were found by Taylor *et al.* (1976a) and Reid and Stevenson (1983), who found that leaves were between 7.5-8% more digestible than the stolons. Differences between these studies are possibly due to the age of the regrowth. Minson (1990) suggested that, at an immature stage, there are no differences in DMD between leaves and stems, but as the plant matures, the stem becomes less digestible. Wilson (1994) concluded that this was caused by an increased proportion of thick-walled cells and a more rapid lignification of the stem of tropical pastures when compared to leaves. Differences have also been found between leaves and sheaths (Forde *et al.* 1976a) with the latter being more digestible (661 vs 705 g/kg DM). Hacker and Minson (1981) suggested that leaves of grasses at the top of the canopy were more digestible than leaves at lower strata. In kikuyu this has been confirmed by Reid and Stevenson (1983) who found that the upper, younger leaves were slightly more digestible *in vitro* than side leaves (739 vs 713 g/kg DM).

High temperature decreases the DMD of kikuyu grass (Mannetje 1975; Wilson *et al.* 1976; Wilson 1994) and these effects are mediated through changes in the fibre composition (Wilson *et al.* 1976; Moir *et al.* 1977; Wilson 1994). Stage of growth similarly affects digestibility due to changes in the proportions of leaves, sheaths, stems and senescent material and their respective changes in digestibility. Minson (1990) estimated that DMD of kikuyu decreased at a rate of 0.2%/d with a range of 0.18-0.22%/d. N fertiliser rate appears to have no effect on DMD of kikuyu (Minson 1973).

Differences also exist between the digestibility of the different chemical fractions (Minson 1982). The digestibility of CP has been found to vary between 48.6-65.8% (Jeffery 1971a; Soto *et al.* 1980). NDF digestibility ranges from 44.9-69.0% (Moir *et al.* 1977; Soto *et al.* 1980) whereas ADF digestibility has been found to be 28.8-48.7% (Soto *et al.* 1980). The ranges in the fibre fractions depend mostly on the degree of lignification as the plant matures (Minson 1982; Wilson 1994).

Reported gross energy in kikuyu ranges from 16.9 to 20.45 MJ/kg DM (Campbell *et al.* 1969; Betteridge 1979; Soto *et al.* 1980; Bredon *et al.* 1987; Marais *et al.* 1990) but, for practical purposes, the well established value of 18.4 MJ/kg DM can be used. The DMD and the digestibility of gross energy in grasses are highly related (Minson 1981) and Minson and Milford (1966) and Jeffery (1971b) found it to be 2-4% lower than that of the DM. Metabolisable energy (ME) concentrations can be estimated as 0.81 X digestible energy (Minson 1981).

3.6.5 *In vitro gas production*

In vitro gas production measurements are gaining popularity as methods to characterise the nutritive value of forages due to their relationship with ME concentrations (Menke and Steingass 1988), and intake and digestibility (Khazaal *et al.* 1993, Kibon and Ørskov 1993). They can also provide kinetic parameters for digestion modelling studies (Pell and Schofield 1993, Jessop and Herrero 1996), and if gas production from fermentation of soluble carbohydrates is taken into consideration, the corrected gas volumes can be used to predict NDF disappearance (Herrero and Jessop 1996).

Herrero *et al.* (1995) estimated seasonal ME concentrations in kikuyu grass from gas production and obtained values ranging from 6.52 MJ/kg DM during the dry season to 7.52 MJ/kg DM during the wet season. The gas production dynamics of a range of kikuyu grass samples are presented in Table 3.2 (Herrero *et al.* 1996).

3.6.6 *Mineral composition*

Macro-minerals. Results from several authors are summarised in Table 3.3. A comparison of the mean macro-mineral concentrations of kikuyu grass against recently published mineral concentrations required in feeding stuffs for ruminants and horses suggests that:

- If the total Ca concentrations in kikuyu are compared with required dietary Ca concentrations, it seems that these are adequate for dairy and beef cattle, lambs and ewes (Minson 1990; SCA 1990). The only exceptions are very young animals with high growth rates (i.e. 200 kg beef cattle gaining > 1.0 kg/d; lambs gaining > 0.3 kg/d) and ewes producing 2-3 kg/milk/d.

- The total Ca concentrations in kikuyu grass seem to sustain maximum milk production levels for Jersey and Friesian cows of 14 and 20 kg/d, respectively. However, it is unlikely that cows eating kikuyu grass as their sole diet will produce such milk yields (see below). Growing horses or pregnant and lactating mares need to be supplemented with a Ca source as their Ca requirements would not be met (McDowell 1992) from kikuyu grass pastures as their sole diet. In subtropical regions, kikuyu pastures can be Ca deficient during winter and spring (Fulkerson *et al.* 1993).

Table 3.2. Seasonal *in vitro* gas production dynamics of kikuyu grass in the Poás highlands, Costa Rica.

	wet season (ml/200 mg DM)			dry season (ml/200 mg DM)		
time (h)	mean	s.d.	range	mean	s.d.	range
3	4.2	0.89	2.5-5.8	3.8	0.70	3.0-5.0
6	7.3	1.59	3.9-10.5	6.7	1.34	4.7-9.2
12	17.0	2.91	10.7-22.5	15.3	2.55	11.5-19.2
24	29.4	3.01	22.2-35.0	27.1	3.02	22.7-31.7
36	35.1	2.65	29.2-39.7	32.7	4.17	26.5-39.7
48	39.6	2.63	33.2-45.0	37.8	4.49	31.2-46.0
72	43.3	2.73	37.5-49.2	42.4	4.50	39.1-50.7
96	44.8	2.96	39.6-51.1	44.9	4.44	38.5-52.9
rate of gas production (%/h)	4.68	0.056	3.46-6.70	3.68	0.040	2.91-4.00

Adapted from Herrero *et al.* (1996)

Two factors make difficult a more detailed analysis of the sufficiency of the Ca concentrations in kikuyu grass. First, the true Ca requirements of ruminants and the adequacy of dietary Ca concentrations are difficult to quantify, since ruminants can use bone Ca to reduce the effects of a deficiency and dietary Ca availability is partly dependent on the level of production (Minson 1990). Second, the availability of dietary Ca can be reduced if it is bound as insoluble Ca oxalate crystals (Minson 1990), and a high proportion of Ca in kikuyu can be present in this form and may not be available to livestock (Blaney *et al.* 1981; Marais 1990a). Therefore, the real contribution of the Ca concentrations in kikuyu grass towards the Ca requirements of grazing livestock is considered marginal and still requires more research. It is considered that supplementation of this mineral should be given to livestock on kikuyu pastures to obtain the desired levels of production (Kayser 1975; Fulkerson *et al.* 1993). For example, Kaiser (1975) found increased growth rates of beef cattle grazing kikuyu when they were supplemented with a Ca source.

- The P concentrations of kikuyu grass are usually adequate to maintain high levels of animal production from ruminants and horses (SCA 1990). However, low P concentrations in kikuyu can be found in periods of rapid growth or in soils with low available P (Minson 1990).
- The concentrations of Mg, S and Cl are sufficient to maintain high levels of animal production from beef and dairy cattle, sheep and horses (Minson 1990; McDowell 1992).
- Kikuyu grass is low in Na (Sherrell 1978; Pastrana *et al.* 1990; Miles 1991), and beef and dairy cattle, sheep and horses grazing kikuyu need to be supplemented with a Na source. It can contain very high concentrations of K (Miles 1991; Pinkerton and Randall 1993), but under practical situations, this should only present problems for animal production if levels exceed 3.0% (McDowell 1992). As is the case with temperate pastures, excessive K uptake decreases the Ca, Mg, and Na concentrations in kikuyu and may be responsible for grass tetany (Awad *et al.* 1979; Miles 1991). Marais *et al.* (1987) suggested that the high K concentrations coupled with high rates of N fertilisation also promote high nitrate accumulation in kikuyu grass.

Table 3.3. Mean macro-mineral composition of kikuyu grass.

Macro-mineral	Mean (g/kg DM)	Range (g/kg DM)	References
Calcium (Ca)	3.5	1.5-8.4	Gomide *et al.* (1969b); Joyce (1974); Kaiser (1975); Awad *et al.* (1979); Betteridge (1979); Reid *et al.* (1979); Fernando and Jayaratne (1980); Tainton *et al.* (1982); Laredo *et al.* (1983; 1990); Pearson *et al.* (1985); Campabadal and Sanchez (1986); Sanchez *et al.* (1986); Anon. (1987); Bredon *et al.* (1987); Hughes *et al.* (1988); Marais (1990a); Pastrana *et al.* (1990); Davison *et al.* (1991); Evans and Hacker (1992a)
Phosphorus (P)	3.3	1.5-5.6	Gomide *et al.* (1969b); Joyce (1974); Kaiser (1975); Betteridge (1979); Reid *et al.* (1979); Fernando and Jayaratne (1980); Rees and Little (1980); Tainton *et al.* (1982); Laredo *et al.* (1983; 1990); Cook and Mulder (1984b); Pearson *et al.* (1985); Campabadal and Sanchez (1986); Sanchez *et al.* (1986); Anon. (1987); Bredon *et al.* (1987); Hughes *et al.* (1988); Pastrana *et al.* (1990); Davison *et al.* (1991); Rumball (1991); Evans and Hacker (1992a)
Magnesium (Mg)	2.3	1.0-4.1	Gomide *et al.* (1969b); Joyce (1974); Kaiser (1975); Betteridge (1979); Reid *et al.* (1979); Tainton *et al.* (1982); Laredo *et al.* (1983; 1990); Pearson *et al.* (1985); Sanchez *et al.* (1986); Hughes *et al.* (1988); Pastrana *et al.* (1990); Davison *et al.* (1991); Evans and Hacker (1992a)
Sodium (Na)	0.5	0.2-0.9	Kaiser (1975); Sherrell (1978); Betteridge (1979); Reid *et al.* (1979); Laredo *et al.* (1983); Pastrana *et al.* (1990); Evans and Hacker (1992a); Pinkerton and Randall (1993)
Potassium (K)	26.4	12.7-45.0	Gomide *et al.* (1969b); Joyce (1974); Kaiser (1975); Awad *et al.* (1979); Betteridge (1979); Reid *et al.* (1979); Fernando and Jayaratne (1980); Tainton *et al.* (1982); Laredo *et al.* (1983); Pearson *et al.* (1985); Sanchez *et al.* (1986); Bredon *et al.* (1987); Marais (1990b); Pastrana *et al.* (1990); Davison *et al.* (1991); Evans and Hacker (1992a)
Sulphur (S)	19	1.2-2.8	Rees and Little (1980); Laredo *et al.* (1983); Evans and Hacker (1992a)
Chlorine (Cl)	31.0	-	Russell (1976)

N fertilisation affects the mineral composition of kikuyu grass (Awad *et al.* 1976; Pearson *et al.* 1985). Pearson *et al.* (1985) found that increasing the rate of applied N decreased P concentrations and increased the Ca and Mg concentrations. Awad *et al.* (1976) found that K levels were also increased at high N applications but Mg and Mn concentrations decreased. The variation in results between studies may be related to soil pH differences as Awad *et al.* (1976) were working with acid soils. Awad and Edwards (1977) found that when lime was applied to suppress the acidifying effects of N fertilisation, herbage Ca, Mo and P increased while Mn decreased.

Micro-minerals. Micro-mineral concentrations in kikuyu grass (Table 3.4) indicate adequate concentrations of Mn, Cu, Co and Fe to meet ruminant and horse requirements (SCA 1990; McDowell 1992). Zn concentrations are within the range proposed by Minson (1990) and SCA (1990) for cattle and sheep but are slightly low for lactating dairy cattle and horses (McDowell 1992).

The micronutrient concentrations in kikuyu grass can vary over the growing season due to differences in uptake by roots as a consequence of soil and weather conditions. In Colombia, Pastrana *et al.* (1990) found that the concentrations of Cu, Co, Fe, Mn, Mo, Se, and Zn in kikuyu during the wet season were sufficient to meet the requirements of sheep but levels of Cu and Mo were deficient during the dry season.

Table 3.4. Mean micro-mineral composition of kikuyu grass.

Micro-mineral	Mean (mg/kgDM)	Range (mg/kg DM)	References
Manganese (Mn)	166.00	35-450	Gomide *et al.* (1969b); Awad *et al.* (1979); Reid *et al.* (1979); Laredo *et al.* (1983); Sanchez *et al.* (1986); Pastrana *et al.* (1990)
Copper (Cu)	10.40	5.32-13.1	Gomide *et al.* (1969b); Kaiser (1975); Reid *et al.* (1979); Laredo *et al.* (1983); Sanchez *et al.* (1986); Pastrana *et al.* (1990)
Cobalt (Co)	0.14	0.12-0.16	Pastrana *et al.* (1990)
Iron (Fe)	211.50	57-306	Gomide *et al.* (1969b); Laredo *et al.* (1983); Sanchez *et al.* (1986); Pastrana *et al.* (1990)
Zinc (Zn)	35.15	22.9-46.4	Gomide *et al.* (1969b); Reid *et al.* (1979); Laredo *et al.* (1983); Sanchez *et al.* (1986); Pastrana *et al.* (1990)
Molybdenum (Mo)	0.44	0.16-1.20	Awad and Edwards (1977); Reid *et al.* (1979); Pastrana *et al.* (1990)
Selenium (Se)	0.17	0.14-0.20	Pastrana *et al.* (1990)

3.7 Pasture intake

Kikuyu grass intake has been estimated by several authors. For comparative purposes, results are presented as g/kg $BW^{0.75}$. Organic matter intakes range from 35-57 g/kg$BW^{0.75}$ for sheep (Betteridge 1979; Meissner and Paulsmeier 1988; Köster *et al.* 1992; Pienaar *et al.* 1993b). When results have been expressed as dry matter intake (DMI), figures for sheep range from 39.8-60.5 g/kg$BW^{0.75}$ (Jeffery 1971b; Minson 1972, 1973; Rees and Little 1980; Soto *et al.* 1980) implying that 6-12% of DM is in inorganic form. DMI for growing cattle ranges from 65.3-97.7 g/kg$BW^{0.75}$ (Rees and Little 1980; Pattinson *et al.* 1981; Ramirez *et al.* 1983; Dugmore and du Toit 1988; Schiere *et al.* 1990). Estimates of intake of lactating cattle ranged from 87.5-128 g/kgBW$^{0.75}$ (Colman and Holder 1968; Hamilton *et al.* 1992; Henning 1993).

Several factors related to the chemical composition of kikuyu grass have been associated with DMI and are responsible for the ranges observed in the literature. Soto *et al.* (1980) suggested that high DMD and low fibre constituents resulted in increased DMI, although Dugmore and du Toit (1988) could not find any relation between digestibility and intake. Laredo and Minson (1973) found that cattle consumed substantially more leaf than stem with the leaf having a slightly lower digestibility. They found a positive association between leaf DMD and intake but not between stem DMD and intake and attributed these results not to the DMD *per se* but to the shorter rumen retention time of the leaf fraction (20.5 vs 38.5 h) which was caused by the larger particulate surface area available for rumen degradation. They also found that the lower grinding energy of the leaf fraction contributed to higher intakes and this can be correlated to the physical breakdown of large to small particles during rumination. The higher particle size breakdown rate of the leaf fraction probably caused a higher rate of passage of leaf small particles from the rumen, thus explaining the lower mean retention time and the higher intakes. These results can also be related to the work of Moir *et al.* (1977), who found that the higher resistance to digestion and a higher rumen retention time of the stem fraction resulted in reduced *in vitro* gas production. Recent evidence suggests that *in vitro* fermentation characteristics are highly related to the degradation characteristics of forages and that both are good predictors of DMI (Ørskov *et al.* 1988; Khazaal *et al.* 1993; Kibon and Ørskov 1993). The relationships with degradability would therefore explain to a greater extent the earlier observations of Laredo and Minson (1973) and Moir *et al.* (1977).

Very little information exists on the DM degradability of kikuyu grass, but Singh *et al.* (1992) (see section on nutritive value) estimated the 3 parameters for the Ørskov and McDonald (1979) degradation (d) equation (d= a+b(1-e^{-ct}), where: the rapidly soluble fraction (a) was 1.63%, the insoluble but degradable fraction (b) was 61.12%, the degradation rate constant (c) was 4.1%/h and t was time.

The low DM content of kikuyu grass in some seasons (< 100 g/kg fresh grass) has also been implicated on several occasions in reductions in voluntary feed intake (Cross 1979b; Kenney *et al.* 1984; Piggot 1991; Köster *et al.* 1992) and this is probably associated to a high water holding capacity of the NDF fraction of kikuyu grass. This subject needs to be investigated.

Alkanes are a relatively new technique for the estimation of intake and diet composition in herbivores (Mayes et al. 1986, Dove and Mayes 1996). Table 3.5 presents the highest alkane concentrations found in leaves and stems of kikuyu grass. High concentrations of C31 and C33 have been reported in temperate (Dove and Mayes 1996) and tropical forages (Laredo et al. 1991). However, kikuyu grass also contains unusually high concentrations of C35 alkanes. Leaves have higher alkane concentrations than stems, which is useful for the estimation of these botanical fractions in the diet selected by ruminants (Dove and Mayes 1996).

Table 3.5. Main alkanes in leaves and stems of kikuyu grass.

	Alkane concentrations (mg/kg DM)			
	leaves		**stems**	
Alkane	**mean**	**range**	**mean**	**range**
C31	150	129-171	45	23-56
C33	212	187-246	92	48-117
C35	125	105-150	60	30-72

Herrero, Jessop and Mayes (unpublished).

3.8 Diet selection and grazing behaviour.

In situations where herbage allowance is high, ruminants will preferentially select the leaf component of the sward (Stobbs 1973a, 1974, 1975; Chacon and Stobbs 1976a, 1976b; Murtagh *et al.* 1980b; Minson 1981). This has justified the observation of several researchers (Stobbs 1975; Chacon and Stobbs 1976a, 1977; Murtagh *et al.* 1980b; Cowan *et al.* 1986, 1993; Hughes *et al.* 1988) that leaf yield is a better estimator of potential animal performance than total DM. This is particularly important in tropical grasses such as kikuyu as the leaf component does not always comprise the highest proportion of the total DM in the sward (Stobbs 1973b). Where stolons comprise a large part of the herbage present, animals prefer to decrease their intake rate rather than to eat the stoloniferous material (Minson 1981; Dugmore *et al.* 1991; Fulkerson and Slack 1993). The data of Pattinson *et al.* (1981) suggest a sharp decrease in intake after the first day of grazing. Although they did not measure the quantity of leaf available, their results suggest that animals tended to decrease pasture consumption as the proportion of leaf DM diminished. Kikuyu grass can form a mat of stolons when lightly grazed and this causes a reduction in the quality of the sward and an increase in sward height. Pre-grazing sward heights range from 10-35 cm (Bransby 1980, 1981; dos Santos Abrahao 1983; Henning 1993; J.B. Hacker, personal communication), for rest periods of 3-5 weeks. Mears (1970) reported that, under some conditions, kikuyu grass may form a loose sward up to 46 cm high. It is often stated that kikuyu pastures should be kept short to maintain dense, leafy pastures (Quinlan *et al.* 1975; Bransby 1981), or when associated with legumes to permit proper legume establishment (Mears 1970). Reeves *et al.* (1993; 1994) in New South Wales, Australia; found that hard grazing or mulching to 5 cm with regrowth periods of 4-5 weeks kept the sward in a leafy state with a high nutritional value. Whether the same management regimes apply to other climatic conditions is still not known and should be investigated.

From the grazing behaviour viewpoint, pasture intake can be described as a function of grazing time, biting rate and bite size (Allden and Whittaker 1970; Stobbs 1973a, 1973b; Hodgson 1985). There is very little information on the grazing behaviour of ruminants on kikuyu pastures, but the observations of Stobbs (1973a; 1974) and Chacon and Stobbs (1976a) suggest that the maximum biting rate of cows grazing tropical pastures is around 36,000 bites per day. As the proportion of leaf in the sward decreases, grazing animals tend to decrease their bite size and increase their biting rate (Chacon and Stobbs 1976a), which would suggest a higher selection for leaf as the sward is progressively defoliated.

Stobbs (1973a) and Chacon and Stobbs (1976a) found that bite size greatly determines intake and so is one of the most important components of grazing behaviour. Chacon and Stobbs (1977) found that, at a high leaf DM allowance (2.2 t/ha), bite size of Jersey cows grazing 5-week old kikuyu regrowth was 237 g OM/bite. Using data from Stobbs (1973a), a 400 kg Jersey cow grazing for 10 h and eating 80g OM/kg BW$^{0.75}$ would have had a biting rate of 28,320 bites/d which is consistent with the maximum biting rate previously mentioned. Bulk density of the pasture is positively correlated with bite size (Chacon and Stobbs 1976a; Black and Kenney 1984) and kikuyu swards usually have a high bulk density (Quinlan *et al.* 1975; Chacon and Stobbs 1977; Hacker and Evans 1992) if kept short.

Another way in which ruminants modify their grazing behaviour to maintain intake as sward structure changes is altering grazing time. The maximum grazing time for cattle in tropical swards is between 9-12 h/day (Stobbs 1974; Chacon and Stobbs 1976a). Animals increase the time spent grazing when leaf DM allowance decreases to counteract the smaller bite size and to try to maintain intake (Chacon and Stobbs 1976a). Henning (1993) found that lactating dairy cows grazing swards of 2, 4 or 8 weeks of regrowth grazed for 8.1, 6.3 and 5.7 h/day, respectively. Intake was similar for all treatments (128g DM/kg $BW^{0.75}$). This suggests that the lower leaf availability of the shortest regrowth period (2 weeks) forced the animals to eat for longer periods and possibly to take more bites per day, while at the higher herbage allowance (8 weeks), swards were probably denser and bite size greater, therefore decreasing biting rate and grazing time. A lower nutritional value may have also played a role in limiting intake of the latter group.

It has been well recognised that grazing animals will select plant parts of higher nutritional value, and that, in the case of kikuyu grass, these are leaves (see section on nutritive value). However, recent evidence (Dugmore *et al.* 1991; Milne 1991) suggests that there are exceptions to this rule and that material of a lower quality may be preferred on some occasions. Dugmore *et al.* (1991) found that steers selected kikuyu plant material of a lower CP concentration when the swards had CP concentrations above 150 g/kg DM. They suggested that the animals 'sought' an optimum CP concentration in their diet, which in their studies was around 140 g/kg DM. Their observations are possibly related to the fact that, when CP concentrations are high (>180 g/kg DM), kikuyu accumulates high levels of NPON which are soluble (Dugmore and du Toit 1988; Marais 1990a, 1990b). Under these conditions, the low non-structural carbohydrate concentrations or the low degradation rates of the structural fraction of kikuyu grass prevent the rumen microflora from utilising the highly soluble N levels and an ammonia overflow occurs. This results in enhanced N excretion and a decrease in the N content of the grazed diet to counteract and regulate the excessive ammonia levels by the steers. Other evidence suggests that ruminants can manipulate the quality of their diet to obtain a balance between dietary components and meet their requirements for specific nutrients. Kyriazakis and Oldham (1993), in an interesting choice-feeding experiment, found that pen-fed sheep could select a diet that met their CP requirements when given access to 2 feeds with CP concentrations below and above their requirements. They found that sheep regulated the consumption of the different feeds to maintain a CP intake close to their requirements and that, to a certain extent, they could avoid an excess of protein intake. They also suggested that sheep might discriminate against feeds with excess urea which would agree with the findings of Dugmore *et al.* (1991) with steers grazing kikuyu with high concentrations of soluble N.

Diet selection and grazing behaviour are 2 fundamental areas that need further research in order to understand better the interactions between the physical and chemical composition of kikuyu grass swards, intake and animal performance.

3.9 Animal performance on kikuyu pastures

3.9.1 *Dairy cattle*

Daily milk production from unsupplemented dairy cows grazing kikuyu grass (Table 3.6) ranged from 7.7-16 kg for Hostein-Friesian cattle (Cross 1979b; Olney *et al.* 1982; Laredo *et al.* 1983; Olney and Albertsen 1984; Hamilton *et al.* 1992; Henning 1993; Reeves *et al.* 1993; Fulkerson, personal communication) and 7.2-11.2 kg for Jersey and Guernsey cows (Stobbs 1972; 1973b; Colman and Kaiser 1974; Murtagh *et al.* 1980a). Dos Santos Abrahao (1983) found average milk production levels of 12.4 kg/d for Flamenga cows in Brazil, and Hughes *et al.* (1988) found maximum productions of 10.8 kg/cow/d from a mixed group of Holstein and Guernsey cows. Cross (1979b) and Hamilton *et al.* (1992) report milk production levels of 15.7 and 14.7 kg/d, respectively, for Friesian cows in early lactation. Similar milk production levels can be achieved from Friesian cows in mid lactation grazing well managed kikuyu swards (Reeves *et al.* 1994). These results agree

Table 3.6. Milk production from dairy cows grazing kikuyu grass.

Reference	N fert. (kg/ha/yr)	Breed^1	S. rate (cows/ha)	Milk kg/d	Butterfat (%)	Protein (%)
Stobbs (1972)	400	J	-	7.9	4.70	3.27
Colman and Kaiser (1974)	336	J+G	2.47	7.9	4.42	-
	336	J+G	3.29	7.6	4.23	-
	336	J+G	4.94	7.2	4.31	-
Cross (1979b)	-	F	3.00	15.7	-	
Murtagh *et al.* (1980a)	590	J+G	RGL^2	9.5	-	-
	590	J+G	RGL^2	8.6	-	-
Olney *et al.* (1982)	500	F	7.5	11.8	-	-
	200	F	5.0	13.2	-	-
dos Santos Abrahao (1983)	-	Flamenga	2.00	12.4	-	-
Laredo *et al.* (1983)	-	F	2.50	7.7	-	-
Olney and Albertsen (1984)	200	F	5.00	9.1	3.95	-
	200	F	7.00	6.0	4.16	-
Hughes *et al.* (1988)	100	F+G	L^3	4.5-8.0	4.20-4.40	2.97-3.11
	100	F+G	H^3	8.2-9.3	4.25-4.50	3.20-3.29
Hamilton *et al.* (1992)	-	F	GL^4	14.7	3.62	2.79
Henning (1993)	300	F	R2^5	8.7	-	-
	300	F	R4^5	10.1	-	-
	300	F	R8^5	8.3	-	-

1 F = Friesian; J = Jersey; G = Guernsey. 2 Residual green leaf (RGL) of 380 and 290 kg/ha, respectively; mean milk production over 3 years.
3 L and H = green leaf availabilities of 800 and 1200 kg/ha, respectively.
4 Green leaf availability of 2.4 t/ha; cows in 1st stage of lactation.
5 R2, 4, 8 = cows grazing 2, 4 and 8-week-old regrowths, respectively.

with the observations of Stobbs (1971) and Weston (1982), that maximum milk production levels that can be obtained from improved tropical pastures such as kikuyu are around 15 kg/d (±4500 kg/lactation). Butterfat (Stobbs 1972; Colman and Kaiser 1974; Olney and Albertsen 1984; Hughes *et al.* 1988; Hamilton *et al.* 1992) and protein (Stobbs 1972; Hughes *et al.* 1988; Hamilton *et al.* 1992) levels in milk produced on kikuyu have ranged from 3.62-4.70% and 2.79-3.29%, respectively.

As with other tropical grasses, the main factors controlling milk production when kikuyu grass is the only component of the diet are stocking rate (Colman and Kaiser 1974; Olney *et al.* 1982; Olney and Albertsen 1984), pasture availability and nutritive value (Murtagh *et al.* 1980a; Hughes *et al.* 1988; Henning 1993) and their interactions (see Humphreys 1991 for a detailed review).

Colman and Kaiser (1974), working on swards fertilised with 336 kg N/ha, found a reduction in milk yields from 7.9 to 7.2 kg/cow/d when the stocking rate of Jersey and Guernsey cows was increased from 2.47 to 4.94 animals/ha. In a study with Friesian cows on swards fertilised with 200 kg N/ha, increasing stocking rate from 5 to 7 cows/ha decreased milk production/cow from 9.1 to 6 kg/day (Olney and Albertsen 1984). Obviously these experiments cannot be compared directly, but the lower stocking rates, the higher fertiliser rate and the smaller breeds used in Colman and Kaiser's (1974) study, suggest that pasture availability per animal was high even at the high stocking rate and therefore milk production per cow was only slightly reduced while milk and butterfat production/ha increased dramatically. In Olney and Albertsen's (1984) experiment the chosen stocking rates (5 and 7 cows/ha) were very high and as a consequence milk production per cow at the high stocking rate decreased to a level where milk production per ha also diminished and supplementation seemed beneficial. These results were possibly exacerbated by the use of continuous grazing which created differences in pasture availability (3.6 vs. 2.5 t/ha, respectively) between the groups kept at 5 or 7 cows per ha (Olney and Albertsen 1984). Further evidence of the effect of kikuyu grass availability on milk production is found in the trial of Hughes *et al.* (1988). They found that cows grazing swards with a higher dry leaf availability (1200 vs 800 kg/ha) produced more milk (9.60 vs 8.01 kg/cow/d) and lost less liveweight (-0.2 vs. -0.75 kg/cow/d) than cows on the lower leaf availability.

Henning (1993) also found that cows grazing 4-week old regrowth produced more milk (10.1 vs. 8.7 kg/cow/d) than cows grazing 2-week old regrowth, which was presumably caused by the higher leaf availability at the older stage of growth. However, he found reduced milk production when the age of the regrowth was 8 weeks, possibly through reduction in the nutritive value of the grass as it matured.

Supplementation of dairy cattle grazing kikuyu grass is common practice. Milk production from cows grazing kikuyu grass and supplemented with concentrates or grain supplements at levels up to 8.3 kg/d ranges from 8.9 to 22.5 kg/cow/d (Colman and Kaiser 1974; Moir *et al.* 1977; Olney and Albertsen 1984; Campabadal and Sanchez 1986; Davison *et al.* 1991; Hamilton *et al.* 1992; van der Grinten *et al.* 1992; Reeves *et al.* 1993, 1994). The existing information suggests that, when concentrates or grain supplements are offered, the increase in milk production ranges from 0.4 to 1.3 kg milk/kg supplement offered (Colman and Kaiser 1974; Olney and Albertsen 1984; Hamilton *et al.* 1992; Reeves *et al.* 1994). The degree of response is dependent on pasture availability; at high availability the effect of supplements is lower and a higher substitution rate is observed, while their effect is maximised as pasture allowance decreases (see Humphreys 1991 for a review). Olney and Albertsen (1984) fed 4 kg/d barley to cows grazing swards at stocking rates of 5 or 7 cows/ha and increased milk production by 0.6 and 1.1 kg/kg supplement offered, respectively. They cautioned that supplementation was economically justifiable only at the higher stocking rate where pasture availability was low. Colman and Kaiser (1974) found responses of 0.6 kg milk/kg supplement when feeding 2.7 kg crushed oats to cows stocked at 4.94 animals/ha.

Reeves *et al.* (1994) also found that the degree of response was dependent on the type of supplement fed. In their studies, feeding barley as a carbohydrate source (4.8 kg/cow) and canola meal as rumen protected protein (1.2 kg/cow) produced milk yields of 21.5 kg/cow/d with an efficiency of response to supplementation of 0.9 kg milk/kg concentrate. The responses obtained were lower when feeding the energy supplement alone and decreased as supplement intake increased (0.8, 0.45 and 0.38 kg milk/kg barley at feeding levels of 3, 6 and 9 kg barley/cow). This shows the importance of a good balance of nutrients for high production. Unfortunately, it does not reflect the interactions between forage and supplement intake and their utilisation for productive purposes. When forage supplements have been offered, the increase in milk production has been low (< 0.35 kg milk/kg supplement) (Royal and Hughes 1976; Hughes *et al.* 1988).

3.9.2 *Beef cattle*

Since Mears' (1970) review, a considerable amount of information has been published regarding liveweight gains of cattle grazing kikuyu pastures (Table 3.7).

Authors differ in the definition of pasture available to grazing cattle. However, the evidence suggests that, at high herbage allowances, liveweight gains of cattle can range from 0.6-1.0 kg/animal/d (Cowan *et al.* 1976; Bransby 1981, 1990; Tainton *et al.* 1982; Campbell *et al.* 1987). Cowan *et al.* (1976) and Tainton *et al.* (1982) suggest that these liveweight gains can be obtained in periods of active pasture growth (i.e. summer and autumn in the subtropics) where more grass is available to the animals.

Table 3.7. Reported mean liveweight gains (LWG) of cattle grazing kikuyu grass.

Reference	N fertiliser (kg/ha/yr)	Breed[1]	Stocking rate (animals/ha)	LWG (kg/d)
Evans and Hacker (1973)[2]	478	H	4.0	0.42
Mears and Humphreys (1974b)[2]	0	A	2.2	0.42
	0	A	3.3	0.38
	0	A	4.9	0.25
	134	A	3.3	0.40
	134	A	4.9	0.32
	134	A	7.4	0.18
	336	A	4.9	0.52
	336	A	7.4	0.38
	336	A	11.1	0.26
Kaiser (1975)	228	H	9.9	0.43
Cowan *et al.* (1976)	165	Dairy breeds	2.5-4.2	0.44-0.54
Tainton *et al.* (1982)	150	Mixed	7.12	0.80
	300	Mixed	8.53	0.68
	450	Mixed	10	0.61
Sanchez *et al.* (1983)	-	F	-	0.52
Campbell *et al.* (1987)	-	H	-	0.64
Evans and Hacker (1992a)[2,3]	478	H	5.0	0.37
Evans and Hacker (1992b)[2,4]	478	H	4.0	0.41
	478	H	5.0	0.39

[1] H = Hereford; A = Aberdeen Angus; Mixed = Brahman, Brahman crosses, Simmentaler, British breeds; F = Friesian.[2] Initial weights of 180-190 kg/animal.
[3] Leader-follower system; rotational grazing. Growth rates were similar for both so they are presented as a mean. [4] Continuously stocked pastures.

Bransby (1981; 1990) and Karnezos *et al.* (1988) found similar gains when using sward height, as measured by a disc meter, as an indicator of herbage availability. At sward heights of 12-14 cm, their steers gained weight at rates above 0.6 kg/animal/d while liveweight gain decreased linearly with height as the sward was defoliated. However, in trials where results have been expressed without considering seasonal growth differences, mean liveweight gains throughout the year vary between 0.35-0.55 kg/animal/d

(Evans and Hacker 1973, 1992a, 1992b; Kaiser 1975; Cowan *et al.* 1976; Sanchez *et al.* 1983). In New Zealand, Piggot (1991) reported average liveweight gains of 0.5 kg/animal/d for summer grazing pastures including 30-55% kikuyu grass.

Studies investigating the effect of stocking rate and its interaction with herbage availability and liveweight gain of cattle grazing kikuyu pastures, have shown a negative linear relationship between stocking rate and liveweight gain per animal, with the magnitude of the slope of the regression being dependent on pasture availability (Mears and Humphreys 1974b; Tainton *et al.* 1982; Bransby 1984; Evans and Hacker 1992a, 1992b). Mears and Humphreys (1974b) found that stocking rates giving maximum liveweight gain/ha caused reductions of almost 25% in liveweight gain/animal, which agrees with the decrease of 21% reported by Evans and Hacker (1992b). Evans and Hacker (1992b) also suggested that the productivity of stoloniferous grasses such as kikuyu was less affected than tussock-forming grasses (i.e. setarias) by high stocking rates, as the decrease in liveweight gain/animal per unit of increased stocking rate was less.

In terms of carcass composition, Mears and Humphreys (1974b) found that increasing the stocking rate decreased dressing percentage, eye muscle area and the depth of subcutaneous fat, irrespective of N application rate. However, in their study, only the animals kept at low stocking pressures (2.2, 3.3, 4.9 and 7.4 steers/ha for the paddocks receiving 0, 134, 336 and 672 kgN/ha, respectively) achieved an acceptable degree of finish for the market. In the study of Tainton *et al.* (1982), the lower N fertiliser rate (150 kg N/ha) and lower stocking rate (7.12 steers/ha) produced a higher proportion of high quality carcasses as a reflection of the higher liveweight gain/animal of that group (0.8 vs. 0.64 kg/d).

Kaiser (1975) found a 16% increase in carcass weights when calves grazing kikuyu grass were supplemented with a mineral mixture. He postulated that the response to the mineral supplement may have been due to the alleviation of Ca deficiency which could have been caused by high proportions of this mineral bound to oxalates, and therefore, unavailable to the animals.

3.9.3 Sheep

Information on sheep production from kikuyu pastures is available only from subtropical regions. Early observations made by Joyce (1974) in a stall-feeding experiment suggested that performance of sheep from kikuyu pastures was disappointing due to inadequate voluntary intake of digestible energy. The wethers lost weight, and although wool growth was not affected, it was significantly lower than that for animals on a grass/barley meal diet. Similar observations have been made in South Africa by Meissner and Paulsmeier (1988) and Barnes and Dempsey (1993), who found liveweight losses when sheep grazed kikuyu during the winter. These responses are usually associated with a decrease in the seasonal quantity and quality of kikuyu grass. However, Meissner and Paulsmeier (1988) also reported average liveweight gains of 132 g/d from stall-fed 45kg Dohne Merino wethers, while Hennesy and Williamson (1976) reported gains of 117 g/d when pelleted kikuyu leaf was given to penned 25 kg Dorset Horn X Border Leicester X Merino ewes. Similar liveweight gains (112 g/d and 150g/d, respectively) from Cheviot/Romney animals at grazing have been observed by Rumball and Boyd (1980) and Betteridge (1979) in mixed kikuyu-ryegrass-clover pastures after weaning and at 18 months of age, respectively. Betteridge (1979) suggested that as the proportion of kikuyu increased in mixed pastures, the performance of the animals tended to decrease due to a lower intake of readily fermentable carbohydrate. This is consistent with the results of van Ryssen *et al.* (1976), who found beneficial effects of molasses or maize meal supplementation on the growth and carcass composition of lambs grazing kikuyu grass.

Rumball (1985) concluded that a high stocking rate and controlled grazing were essential for efficient management of sheep production systems based on mixed pastures including kikuyu grass. He also postulated that grazing pressure should be doubled during the autumn to suppress the competitiveness of kikuyu grass compared with the temperate species. Rumball and Boyd (1980) and Piggot (1991) also suggested that later lambing or split spring-autumn lambing improved production in this type of system. The benefits of kikuyu grass in these systems are mediated via the increased stocking rates that can be maintained (Piggot 1991).

3.10 Toxic factors

Research on toxic factors in kikuyu grass has concentrated on 3 main areas. Since the early observations of Cordes *et al.* (1969), Busch *et al.* (1969), Martinovich and Smith (1973) and Smith and Martinovich (1973) in New Zealand on the death of cattle grazing kikuyu grass due to acute ruminal indigestion and alkalosis, similar observations have been reported in Australia (Gabbedy *et al.* 1974; Wong *et al.* 1987) and South Africa (Bryson and Newsholme 1978; van Heerden *et al.* 1978; Bryson 1982; Newsholme *et al.* 1983). The condition has also affected sheep (Martinovich and Smith 1972; Peet *et al.* 1990) and goats (Peet *et al.* 1990) but to a lesser extent. Even though the clinical signs in most studies have been similar, the cause of what is called 'kikuyu poisoning' is still inconclusive. Several factors appear to predispose livestock to the disease. For example, kikuyu poisoning has been observed after rains following periods of hot, dry weather in animals grazing lush kikuyu grass. Recent infestation of kikuyu paddocks with army worm (*Pseudaletia separata* in New Zealand; *Spodoptera exempta* in South Africa; and *Mythimna convecta* in Australia) is commonly associated with the disease. This raises the possibility that the condition is not caused by toxic factors in kikuyu grass *per se* but by a product secreted by the army worms.

Myrothecium sp. fungi (Martinovich *et al.* 1972) have also been implicated, but the results are equivocal.

Kikuyu grass is known to accumulate high levels of soluble oxalates (Blaney *et al.* 1981; Elphinstone 1981; Williams 1987; Marais 1990a; Williams *et al.* 1991). High levels (>0.3%) of soluble oxalates have caused *Osteodystrophia fibrosa* (bighead disease) in horses consuming kikuyu grass (Blaney *et al.* 1981; Elphinstone 1981). Marais (1990a) found that kikuyu samples contained equal proportions of soluble and insoluble oxalates. He also found that kikuyu leaves contained higher levels (0.79% and 0.54%, respectively) of soluble and insoluble oxalates than stems (0.02% and 0.37%, respectively) and postulated that, in some instances, the formation of calcium oxalate might reduce the bio-availability of Ca for ruminants grazing kikuyu (see section on Mineral composition). Ruminants seem to be more tolerant of oxalate poisoning than non-ruminants, as rumen bacteria can adapt to high concentrations of soluble oxalates and convert them into carbon dioxide.

Kikuyu grass may also accumulate toxic levels of nitrates under some circumstances (Marais 1980, Marais 1990a, 1990b; Williams 1987; Marais *et al.* 1987, 1988, 1990; Williams *et al.* 1991) and these are usually associated with CP concentrations higher than 180 g/kg DM (Marais 1990a, 1990b). High N fertilisation (Williams *et al.* 1991) and high K uptake rates (Marais *et al.* 1987) seem to increase the nitrate content of kikuyu grass. Stems accumulate higher concentrations of nitrates than leaves (Marais *et al.* 1987; Marais 1990a, 1990b) largely because they are substrate storage organs. This is an important observation, since it suggests that a reduction in the nitrate levels of kikuyu grass could be obtained by changes in management practices: i.e. by removal of the aftermath of stolons. The effect of high nitrate levels on ruminant digestion is not a direct one. Marais *et al.* (1988) found that accumulation of high nitrite levels during the conversion of nitrate to ammonia caused a reduction in the digestibility of kikuyu grass and a reduction in rumen microbial populations. The high proportion of soluble N in high nitrate kikuyu grass may also be responsible for the low N retention sometimes observed in grazing ruminants (Marais *et al.* 1990). This factor is known to cause energy-protein imbalances as shown by elevated rumen ammonia levels (Marais *et al.* 1990). Under these circumstances, the energy required for the extensive recycling and subsequent excretion of N in urine may play a part in the often reported low animal performance from this grass species. The subject needs further investigation.

The potential of kikuyu pastures to produce cerebrocortical necrosis in ruminants has also been studied (Meyer 1989), but their role was discounted, as very low thiaminase activities and thiamine concentrations were found in the samples analysed. Tannin contents of kikuyu grass have been found to be low (Reid *et al.* 1979).

Chapter 4

Components of models of grazing systems*

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* Adapted from:
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Chapter 4

Components of models of grazing systems

4.1 Introduction

Grazing systems are one of the main agroecological systems for food production in the world. These systems comprise about half of the world's land area (Stuth and Stafford-Smith, 1993), and increased interest exists in improving their management and ensuring sustainability. As discussed in Chapter 1, there is concern to prevent degradation of the resource base, and its consequent environmental, social and economic effects.

A common approach in studying grazing systems has been by way of mathematical modelling (Stuth and Stafford-Smith, 1993). Unfortunately, many scientists have looked at specific and detailed phenomena within a part of the system without taking into account interactions and effects at the whole system level (Demment et al., 1995). Only recently, have more integrated approaches, linking concepts from different disciplines across a variety of levels of knowledge, been implemented. The integration of various levels exposes enormous complexity within a grazing system. The degree of detail in these levels depends on the purpose for which the model is meant to be used, the users, the level of accuracy required and the planning horizon (i.e. operational, strategic or tactical).

The present chapter attempts to review the approaches and the components required to model grazing systems for decision support purposes.

4.2 Modelling the forage resource

4.2.1 *Modelling primary production*

A wide range of approaches to model the forage resource are found in the literature. These vary widely in degree of complexity, number of species represented, variable and parameter definitions, and simulated output.

Some of the simplest representations are based on the functional form of plant growth curves (see Thornley and Johnson, 1990; for a review). For example, Brougham, (1956); Morley, (1968); Noy-Meir, (1975, 1976, 1978), Christian et al., (1978) and Woodward et al., (1993, 1995) used logistic growth curves to represent pasture growth in their models:

$$\frac{dW}{dt} = mW(1 - \frac{W}{Wmax}) \qquad (1)$$

where m = the maximum relative growth rate, W = initial plant biomass, Wmax = the asymptote plant biomass and t = time. This description assumes that growth is proportional to plant biomass, rate of growth is proportional to the amount of substrate, and substrate is finite (Thornley and Johnson, 1990). Equation (1) is easy to parameterise when smooth experimental data of the dynamics of plant growth is available. The appropriateness of the parameters will depend on the quality of the experimental data and will only reflect the particular conditions in which the plants were growing for that particular data set. Nevertheless, the shape of the curve can be explained physiologically. Exponential growth occurs due to increased irradiance captured by increases in leaf area index (LAI) during early stages of development, while growth progressively decreases to a plateau as respiration losses, due to senescence, equal photosynthesis. It has the advantage that it is a simple curve with biologically meaningful parameters which can represent changes in the growing environment by modification of m and Wmax. However, it is limited, in that it does not represent the physiological mechanisms (e.g. photosynthesis, LAI development, N uptake) underlying sward growth and is therefore not flexible enough to represent effects of management interventions. Such models also fail to describe biomass in different botanical fractions (leaves/stems/dead material) or species compositions (grass/legume mixtures or rangelands) and their vertical distribution within the sward, which are important elements in predicting diet selection and/or species succession caused by disturbances (e.g. grazing, fire) in grasslands. The fact that only one sward component is represented (i.e. total herbage dry matter (DM)) implies that diet selection can only be studied by superimposing selectivity coefficients on total DM (Christian et al., 1978).

These limitations have lead to the construction of several more detailed grassland models for single pasture species (Johnson and Thornley, 1983, 1985; Thornley and Veberne, 1989; Smith et al., 1985; Lopez-Tirado and Jones, 1991a,b; Doyle et al., 1989; Sheehy et al., 1996; Guerrero et al., 1984; Charles-Edwards et al., 1987; Rodriguez et al., 1990; Murtagh, 1988; Veberne, 1992; van Keulen et al., 1981; Seligman et al., 1992) or multi-species (Gilbert, 1975; Innis, 1978; Parsons et al., 1991; Hanson et al., 1988, 1994; Coughenour, 1984; Coughenour et al., 1984; Hunt et al., 1991; Hacker et al., 1991; Blackburn and Kothmann, 1989; Deitling et al., 1979; Lauenroth et al., 1993; Richardson et al., 1991; Moore et al., 1997). The former come mostly from the agricultural sciences, while some of the latter also have a strong ecological background (e.g. Innis 1978, Coughenour 1984; Hanson et al. 1988, 1994).

The majority of these models represent plant growth as a function of one or more environmental, soil and/or management variables. The simplest analyses use only one environmental driving variable (e.g. rainfall, irradiance) to determine sward growth rates. Charles-Edwards et al. (1987), used Monteith's (1972) factorial approach to determine growth rate of a sward, with ample supply of nutrients and water, based on daily irradiance intercepted by the pasture, the efficiency of light utilisation by the plant to produce new material and a partitioning coefficient for above-ground material. Shiyomi et al. (1986) used a similar approach to study energy flows in grasslands in Japan. Guerrero et al. (1984) and Hacker et al. (1991) determined plant growth as a function of rainfall. Due to the large effects on growth caused by severe water-stress in the regions of their studies, they were able to use simple soil water balance budgets as primary predictors of herbage production. In even more complex models (e.g. Hanson et al., 1988, 1994), the basic components of water balance submodels include rainfall, evapotranspiration, transpiration, runoff and infiltration, and these are modelled using well recognised principles (van Keulen and Wolf, 1986; Thornley and Johnson, 1990). Moisture indices are derived from these variables to scale the growth rates of forage.

On the other hand, several models estimate biomass production as functions of a number of environmental variables. This usually results in models representing carbon (C) and nitrogen (N) fluxes in grassland ecosystems. The level of detail and empirical representations varies widely between models, although this is usually due to the original objectives of the model or their implicit site-specificity.

Inputs to the carbon cycle are usually represented by photosynthesis, and one of the most common methods is to integrate single leaf photosynthesis over the canopy LAI using Beer's Law (Monsi and Saeki, 1953) as the light attenuation factor through the depth of the canopy (Johnson and Thornley, 1983, 1985; Thornley and Veberne, 1989; Hanson et al., 1988, 1994; Sheehy et al., 1996). Single leaf photosynthesis is commonly represented by rectangular (Innis, 1978; Johnson and Thornley, 1983; Doyle et al., 1989) or non-rectangular hyperbolas (Johnson and Thornley, 1985, Thornley and Veberne, 1989). Other authors (Coughenour, 1984; Hunt et al.,

1991) also include CO_2 concentrations and stomatal, internal and leaf boundary layer resistances to account for water use and CO_2 effects on photosynthesis. Temperature and leaf N content (Thornley and Veberne, 1989; Hanson et al., 1994) are used to scale the photosynthetic capacity of the sward. Outputs from the carbon pool are represented by fractions used for new growth, senescence, respiration and grazing. Recycling of nutrients from senescent tissues also contribute to the C cycle.

The approaches to represent the N cycle of the grazing system are also diverse, but the basic factors are demonstrated in a simple model by Scholefield et al. (1991) (Figure 4.1).

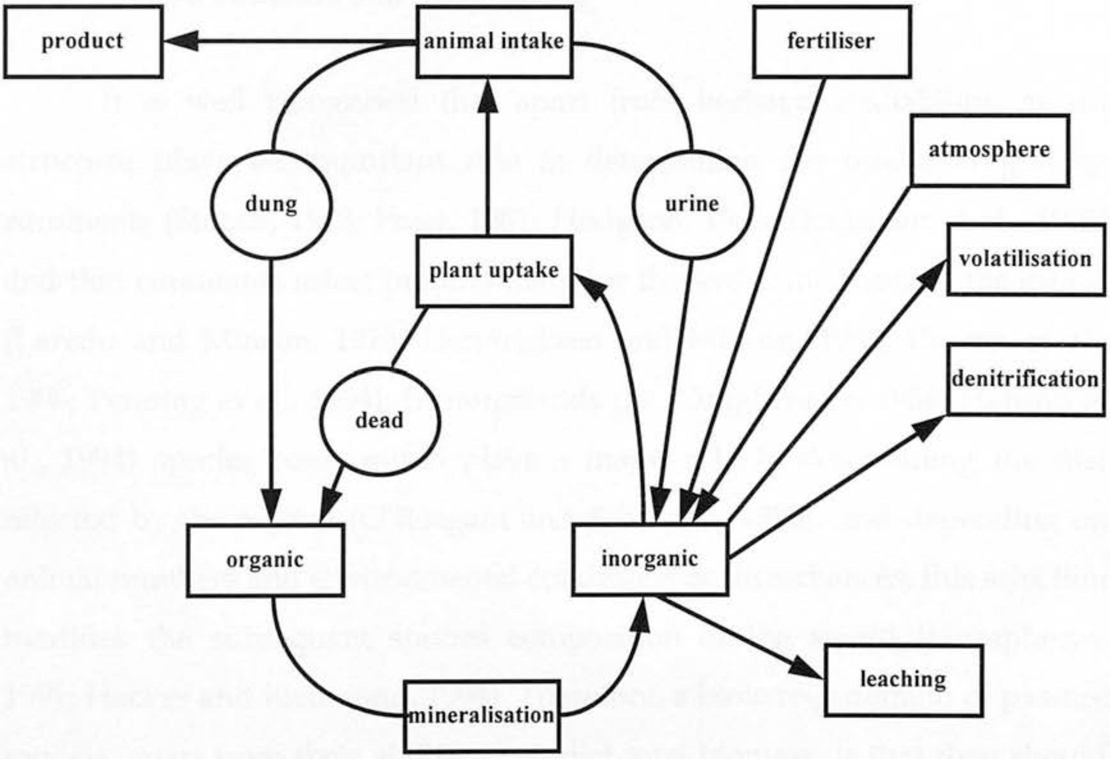

Figure 4.1. Basic N cycle in pasture ecosystems (From Scholefield et al. 1991)

Although Scholefield's et al. (1991) model is empirical, the same processes can receive a mechanistic treatment, but the complexity of the model and its subsequent validation are increased several-fold (e.g. Veberne, 1992).

Thornley and Veberne (1989) argue that data to validate soil-plant mechanistic models are scarce or incomplete and that experiments are difficult to design, and therefore a subjective assessment on the behaviour of the model is sometimes made. While the C cycle is relatively easy to validate due to a wide availability of field methods, there is still a considerable amount of progress to be made in designing soil submodels that are easy to parameterise at field level.

4.2.2 *Sward structure and composition*

It is well recognised that apart from herbage availability, sward structure plays an important role in determining the intake of grazing ruminants (Stobbs, 1973; Freer, 1981; Hodgson, 1985; Demment et al., 1995) and that ruminants select preferentially for the leaf component of the sward (Laredo and Minson, 1973; Hendricksen and Minson, 1980; Cowan et al., 1986; Penning et al., 1994). In rangelands (i.e. Coughenour, 1984; Hanson et al., 1994) species composition plays a major role in determining the diet selected by the animal (O'Reagain and Schwartz, 1995), and depending on animal numbers and environmental conditions or disturbances, this selection modifies the subsequent species composition of the sward (Humphreys, 1991; Hacker and Richmond, 1994). Therefore, a basic requirement of pasture models, apart from their ability to predict total biomass, is that they should be capable of differentiating between plant parts, and their density across the sward's vertical strata and/or species composition in the case of multi-species systems. Table 4.1 shows some of the main differences in the representation of sward morphology and composition between models. It can be observed from the table, that several models do not differentiate between plant parts.

Table 4.1. Differences in the representation of sward composition in some models.

Model	No. species[a]	total biomass	plant parts[b]	phenology or age of plant parts	species comp.
Noy-Meir (1975, 1976, 1978)	1	√	-	-	-
Johnson and Thornley (1983, 1985)	1	√	l/s/d	√	-
Parsons et al. (1991)	2	√	l/s/d	√	√
Charles-Edwards et al. (1987)	1	√	-	-	-
Hunt et al. (1991)	1	√	-	-	-
Hanson et al. (1988, 1994)	3+	√	g/d/p	√	√
Christian et al. (1978)	1	√	g/d	√	-
Coughenour et al.(1984)	3+	√	b/sh/s/f	√	√
Lauenroth et al. (1993)	3+	√	l/s/d	√	√
Lopez-Tirado and Jones (1991)	1	√	g/d	-	-
Guerrero et al. (1984)	1	√	-	-	-
Rodriguez et al. (1990)	1	√	l/s/d	√	-
Woodward et al. (1993, 1995)	1	√	-	-	-
Doyle et al. (1989)	2	√	l/s/d	√	-
Smith et al. (1985)	1	√	g/d	√	-
Hacker et al. (1991)	3+	√	-	-	√
Seligman et al. (1992)	1	√	l/s/d	√	-

[a] 1=single species, 2=grass/legume, 3=rangelands.
[b] l=leaves, s=stems, d=dead, p=propagules, g=green, sh=sheaths, f=flowers.

The most common fractionation of morphological composition is between leaf, stem and dead material and this is usually linked to age characteristics of the sward. This fractionation occurs partly because the models rely on photosynthesis and require an estimate of LAI for pasture growth calculations. This is a convenient attribute, since removal of LAI by grazing can link, in a physiological sense, the effect of grazing on total resource capture, pasture growth and subsequent sward composition (Johnson and Parsons, 1985; Parsons et al., 1994).

The models of Johnson and Thornley (1983, 1985) and Thornley and Veberne (1989), did not represent the vertical distribution and bulk density (bd) within the sward, but they do have a convenient structure to model them. These models divide the leaf and stem structural mass into 4 distinct age categories, from new material down to senescent. The move from one category to the next is determined by the rates of appearance of these components, therefore making it possible to distribute them, separately, across the height of the sward according to the pasture species modelled.

Separation between green and dead material in other models is mainly for the purpose of determining the sward's nutritive value. For example, to be able to represent diet quality, some models (Christian et al., 1978; Guerrero et al., 1984; Smith et al., 1985) subdivide the biomass empirically into 3 or 4 compartments representing new, mature, senescent and/or dead material, without describing them morphologically, and assign quality characteristics (i.e. digestibility, cell wall) within these categories. However, the definition of physiological states without a morphological description present three problems. First, they are difficult to handle in diet selection studies, where identification of the different components of the diet selected by ruminants is usually done by botanical fractions (Hendricksen and Minson, 1980; Humphreys, 1991), therefore reflecting morphological differences in the sward (Arnold, 1981; Hodgson, 1985). Physiological state of the sward does not represent its morphological structure. Second, it is difficult to accommodate different diet selection patterns of different animal species. For example, sheep are able to select more leaf than cattle (Arnold, 1981; Forbes and Hodgson, 1985; Penning et al., 1994) and these differences cannot be predicted if the sward is only divided into physiological state compartments. Third, even at a similar chemical composition, botanical fractions have different physical structures (Wilson, 1994), which affect the rates of breakdown from large to smaller particles of forage in the rumen (Kennedy and Murphy, 1988; Wilson and Kennedy, 1996) and therefore affect passage rates and pasture intake. This concept is difficult to model when sward physiological states are used because the botanical composition of each compartment (e.g. new material) is not known. From the diet selection viewpoint, in rangeland models the discrimination between species becomes more important (Baker et al., 1992) than within species, and most rangeland models only discriminate between, rather than within, species to represent sward biomass.

4.3 Grazing processes and diet selection

4.3.1 *Intake and grazing processes*

Intake prediction is one of the most important elements in grazing systems models because the prediction of animal responses to nutrients (Blaxter, 1989; see Forbes and France, 1993 for reviews) are largely dependent on it. In addition, pasture intake influences the regrowth of the sward (Brougham, 1956; Vickery, 1981; Parsons et al., 1988), the efficiency of fertiliser use (Humphreys, 1991), supplementation strategies (Allden, 1981; Ørskov, 1994; Rook et al., 1994), nutrient cycling (Simpson and Stobbs, 1981; Scholefield et al., 1991), land use practices via the area required to maintain stock (Olney and Kirk, 1989) and the spatial distribution of pasture species in rangeland landscapes (Senft et al., 1987; Demment et al., 1995; O'Reagain and Schwartz, 1995).

A number of methods of simulating intake and grazing processes have been reported, but 3 distinct approaches can be observed:

1. *prediction of intake from systems of energy requirements.*
2. *establishment of relations between herbage mass and intake.*
3. *prediction of intake from grazing behaviour measurements.*

The flexibility of studying different nutritional and management strategies, and their effects on the whole system, will largely depend on the method chosen to represent intake.

4.3.1.1 Intake as a function of energy requirements

This method assumes that estimates of pasture intake can be derived from the energy requirements of the animal and the energy content of the pasture consumed. This last parameter has been usually derived from *in vivo* or *in vitro* digestibility estimates. The energy value of the forage as well as the animal's requirements have been expressed most commonly as digestible (DE), metabolisable (ME) or net energy (NE) (McDonald et al., 1995).

Two approaches are commonly used. The first one is to estimate intake from the 'inverse' of the nutrient requirements, and the second one to use regression equations, which are often included in requirements systems. These methods of intake estimation have been widely used in livestock models (Sanders and Cartwright, 1979; Konandreas and Anderson, 1982; Guerrero et al., 1984; Gartner and Hallan, 1984; Olney and Kirk, 1989). However, although it is accepted that nutrient requirements represent one of the most important driving forces of eating, these systems *per se* (apart from SCA, 1990 and; NRC, 1996), fail to take into account constraints on intake imposed by herbage availability and sward structure (Hodgson, 1985). This has already been discussed by Whelan et al. (1984). However, the following points should also be considered:

1. Classic work by Conrad et al., (1964) demonstrated that intake was proportional to energy requirements when the digestibility of the diet was higher than 67%. Below this threshold, intake was constrained by physical limitations of the reticulo-rumen. Therefore, for low digestibilities, when the 'reverse' calculation of intake from requirements is applied, intake is usually overestimated because animals are not physically able to eat sufficient

quantities of forage. More recently, Forbes (1993) suggested that, for cows, this digestibility threshold may be higher depending on the level of production. In view of these problems, several models have incorporated static physical fill limitation constraints on intake (Forbes, 1977; Kahn and Spedding, 1984; Mertens, 1987; Finlayson et al., 1995).

2. Constraints on forage intake may arise from both physical and metabolic causes. Whilst it might be appropriate to relate metabolic constraints to metabolic weight, this would not be so for physical constraints since it has been shown that rumen volume scales with weight (Illius and Gordon, 1991) rather than metabolic weight. These different scalings explain why depending on the type of intake constraint taking place, digestibility per se is sometimes not a good predictor of intake (Laredo and Minson, 1973; Poppi et al., 1981; Kibon and Ørskov, 1993), and also explains why, when physical fill limitations occur, factors that also scale with body weight (i.e. passage rates) become very important. In the trial of Laredo and Minson (1973), sheep consumed more leaf than stem with both plant fractions having the same digestibility, suggesting that other factors, such as the physical structure of plant parts, which influence particle breakdown and passage rates (Poppi et al., 1981, Kennedy and Murphy, 1988; McLeod et al., 1990) play an important role in the control of feed intake; and also suggest that dynamic models of digestion which consider the competition between digestion and passage may yield better estimations of potential intake.

4.3.1.2 Empirical relations between herbage mass and intake

A variety of models have simulated the effect of herbage availability on intake using empirical relations (Freer et al., 1970; Noy-Meir, 1975, 1976; Arnold et al., 1977; Vera et al., 1977; Edelsten and Newton, 1975, 1977; Christian et al., 1978; Sibbald et al., 1979; White et al. 1983; McCall, 1984; Johnson and Parsons, 1985; Thornley and Veberne, 1989; Rodriguez et al., 1990; Blackburn and Kothmann, 1991; Richardson et al., 1991; Seman et al., 1991; Finlayson et al., 1995). These models use three basic steps for the calculation of intake at grazing:

1) The potential intake of the animal is estimated. Potential intake is usually defined as the intake of herbage without the constraints imposed by herbage availability, as a function of animal and plant characteristics. It is usually an input (Johnson and Parsons, 1985; Thornley and Veberne, 1989), or calculated in another submodel, from the knowledge of body weight, the energy requirements of the animal, and the digestibility or metabolisability of the diet (Arnold et al., 1977; Christian et al., 1978; Richardson et al., 1991) and physical fill limitations (Kahn and Spedding, 1984; Doyle et al., 1989; Finlayson et al., 1995).

2) The constraints on intake imposed by herbage availability are calculated. This is usually done by estimating 'scaling factors' with empirical functions, and leads to a term often called 'relative intake'. Table 4.2 summarises the functions used in different models to scale intake on the basis of different measures of herbage availability.

Common features of these scaling factors are their general shape, often expressed as Michaelis-Menten equations (Noy-Meir, 1975, 1976; Johnson and Parsons, 1985; Blackburn and Kothmann, 1991), and exponential or quadratic functions (see Table 4.2). However, large discrepancies occur between authors in the slopes of these functions (Figure 4.2), which are caused by the animal and sward characteristics for which the equations were derived. Nevertheless, marked decreases in intake appear to occur if less than 1000-1500 kg/ha DM are available.

Herbage availability is described in different ways by different authors. The most common relationship between intake and herbage availability is derived from herbage mass per unit of area, while others derive functions on the basis of herbage available per animal (Zemmelink, 1980; Loewer et al., 1987) or both (McCall, 1984). An exception is the function of Johnson and Parsons (1985), which uses LAI to estimate relative intake.

Table 4.2. Functions to estimate the effect of herbage availability on dry matter intake of grazing ruminants.

Source	**Function to estimate relative intake (RI)**
Freer et al. (1970) Arnold et al. (1977)	$RI = 1\text{-}\exp(-0.001*DM)$
Noy-Meir (1975, 1976) Blackburn and Kothmann (1991) Woodward et al. (1993, 1995)	$RI = [imax*(DM/(DM+X))]/imax$
Vera et al. (1977)	$RI = 1\text{-}\exp(-0.002503*DM)$
Edelsten and Newton(1975, 1977)	$RI = 1\text{-}\exp(-2.4*10^{-7}*DM^2)$
Christian et al. (1978)	$RI = 1\text{-}\exp(-0.000008*DM^2)$
Sibbald et al. (1979)	$RI = DM/(DM+250)$
White et al. (1983) Bowman et al. (1989)	$RI = 1\text{-}\exp(-0.000002*DM^2)$
Zemmelink (1980) Konandreas and Anderson (1982) Doyle et al. (1989)	$RI = [imax*(1\text{-}\exp(-DMH/imax)^{1.23})^{(1/1.23)}]/imax$
Johnson and Parsons (1985) Thornley and Veberne (1989) Parsons et al. (1991) Richardson et al. (1991)	$RI = [imax*(LAI/K)^Q/(1+(LAI/K)^Q)]/imax$ where $RI = imax/2$ for $LAI = K$ $K = 1$ and $Q = 3$ for sheep grazing ryegrass
Loewer et al. (1987) Rodriguez et al. (1990)	$RI = 2*FA/B\text{-}FA^2/B^2$ where $B = 750$
Seman et al. (1991)	$RI = 1\text{-}((1\text{-}0.1)/(HI\text{-}LOW)^2)*(HI\text{-}SH)^2$ where $HI = 20$ and $LOW = 5$
McCall (1984) Finlayson et al. (1995)	$RI = \theta*\exp[-1.016*\exp(-1.038*A)]$ where $A = (DM/imax)*(area/animals)$ $\theta = 1\text{-}1.42*\exp(-0.00198*DM)$

imax = potential intake (kg/animal/d), DM = pasture dry matter (kg/ha), X= Michaelis constant for consumption (g/m^2); LAI = leaf area index (m^2 leaf/m^2 soil), K = half maximal response of LAI, Q = constant, DMH = available dry matter/animal (kg/animal/d), FA = forage available/kg bodyweight (g DM/kg BW), B = threshold level of forage availability (g DM/kg BW), HI = height above which additional increases in sward height do not affect intake (cm), LOW = height below which forage is unavailable for grazing (cm), SH = total sward height (cm) area = grazing area (ha), animals = number of animals.

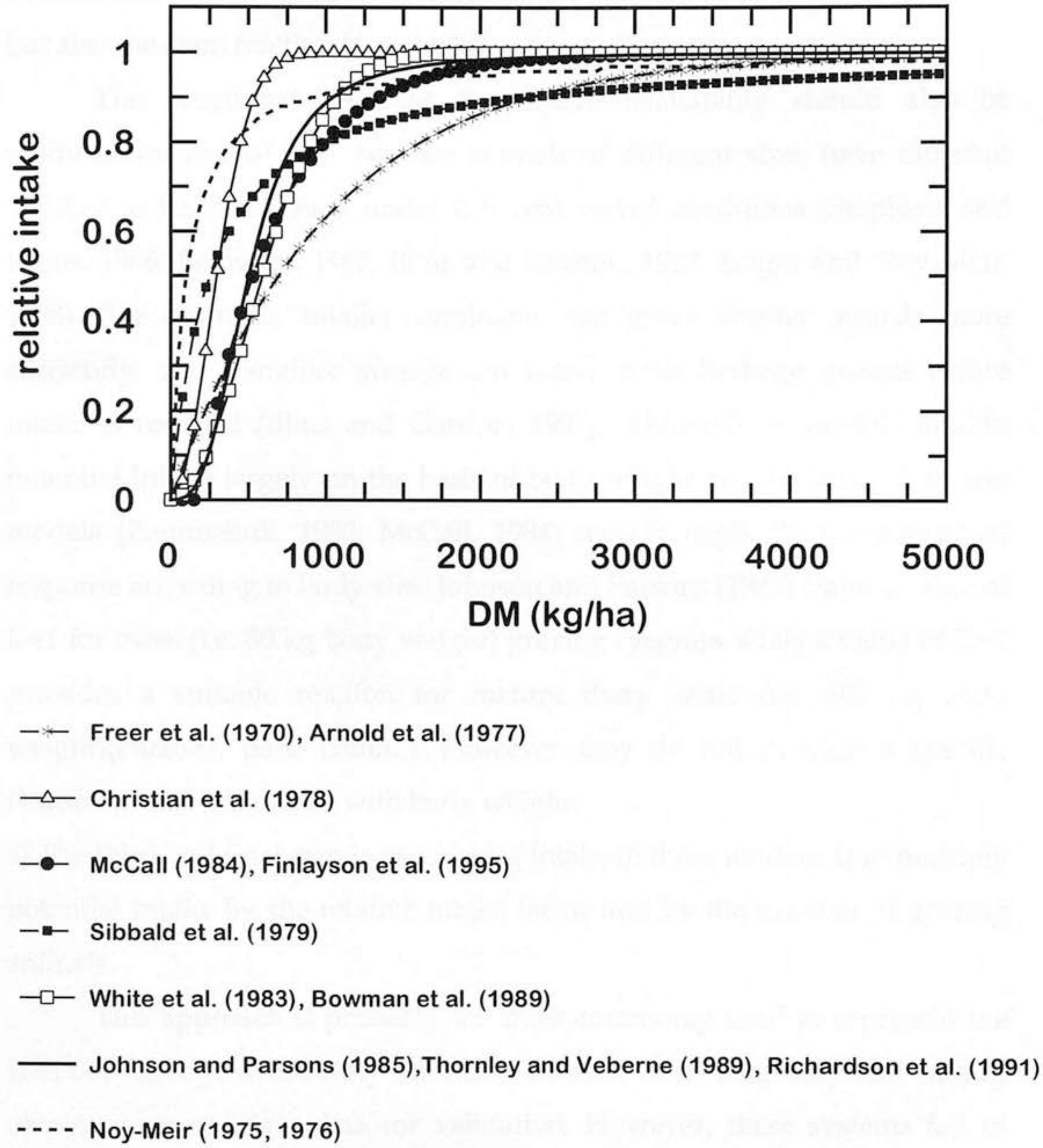

Figure 4.2. The relation between herbage availability and intake at grazing in different models

This is an interesting concept, since LAI provides an appropriate physiological interface between pasture removal (grazing) and regrowth (resource capture by photosynthesis). However, under most practical circumstances LAI is not measured, and some types of animals not only remove LAI which is associated with the leaf components of the sward only, but also the stem fraction (e.g. cattle).

The functional response to pasture availability should also be modified by animal size, because animals of different sizes have different abilities to harvest forage under different sward conditions (Stephens and Krebs, 1986; Belovsky, 1987; Illius and Gordon, 1987; Ungar and Noy-Meir, 1988). For example, smaller ruminants can graze shorter swards more efficiently, and therefore swards can reach lower herbage masses before intake is reduced (Illius and Gordon, 1987). Although all models modify potential intake largely on the basis of body weight or a function of it, few models (Zemmelink, 1980; McCall, 1984) modify explicitly the functional response according to body size. Johnson and Parsons (1985) claim a value of K=1 for ewes (i.e. 80 kg body weight) grazing ryegrass while a value of K=2 provides a suitable relation for mature diary cattle (i.e. 600 kg body weight)(Parsons, pers. comm.). However they do not provide a specific relation of this parameter with body weight.

3) The third and final step in calculating intake in these models, is to multiply potential intake by the relative intake factor and by the number of grazing animals.

This approach is probably the most commonly used to represent the effect of herbage availability on intake because of its simplicity and ease of obtaining appropriate data for validation. However, these systems fail to represent the mechanics of grazing and therefore fail to provide full understanding about the sward variables affecting intake. Therefore, for some purposes, more detailed models, usually based on grazing behaviour measurements, are used to represent these relations.

4.3.1.3 Prediction of intake from grazing behaviour measurements

The prediction of intake from grazing behaviour measurements (for recent reviews see Hodgson et al. (1994), Demment et al. (1995), and Laca and Demment (1996)) has been largely based on the early work of Allden (1962); Arnold and Dudzinski (1967a,b); Allden and Whittaker (1970); Stobbs (1970, 1973, 1974) and Chacon and Stobbs (1976). Allden and Whittaker (1970) postulated that intake at grazing could be predicted as:

$$\mathbf{Intake = IB*RB*GT} \tag{2}$$

where, IB = bite size, RB = biting rate, and GT = grazing time .

Intake per bite is the most sensitive variable to sward characteristics, while biting rate and grazing time are partly dependent on bite size, and act as compensatory mechanisms when bite size is too small to obtain the desired intake level (Hodgson, 1981). Chambers et al. (1981) and Newman et al. (1994a) suggested that biting rate declines at high bite sizes, because of an increase in the ratio of manipulative to biting jaw movements, hence it is also partly dependent on sward characteristics. This subject has been clearly depicted by Laca et al. (1994), who found that time per bite (TB) was linearly associated with the total number of jaw movements per bite (JM):

$$\mathbf{TB = 0.43 + 0.682\ JM,\ r^2 = 0.96} \tag{3}$$

The proportion of total manipulative jaw movements that performed manipulation and mastication (MJM) increased with bite size asymptotically (Figure 6b) by the following relation:

$$\mathbf{MJM = \frac{1.028IB - 0.246}{0.234 + IB},\ r^2 = 0.69} \tag{4}$$

As bite size decreases, biting rate and/or grazing time increase to compensate for this reduction. However, this compensation is sometimes partial (Allden and Whittaker, 1970; Stobbs 1973; Jamieson and Hodgson, 1979; Hendricksen and Minson, 1980; Hodgson, 1981), thus potential intake cannot be attained. Hodgson (1986) claims that this is the reason why variations in daily herbage intake frequently reflect closely the observed variations in bite size.

In most modelling studies, maximum values of biting rate and grazing time from experimental studies, are often used as behavioural limits of the grazing process, while most efforts are concentrated on modelling bite dimensions. Maximum biting rate is close to 36000-40000 bites/day (Stobbs, 1973, Chacon and Stobbs, 1976; Jamieson and Hodgson, 1979), while maximum grazing time is about 12-13 h/day. These values are similar for cattle and sheep (Hodgson, 1982; Hodgson, 1985; Forbes, 1988; Demment et al., 1995).

Bite size is positively related to herbage mass or sward height (Black and Kenney, 1984; Hodgson, 1985; Forbes, 1988; Burlison et al., 1991). Burlison et al. (1991), working in swards ranging from 5-55 cm in height, explained 78% of the variation in IB of sheep with the following relation:

$$\mathbf{IB = 33 + 5.2\ H} \qquad (5)$$

The slope of this relationship was similar to those reported by Hodgson (1981) and Forbes (1982) when expressed on the basis of bite size/kg body weight. Burlison et al. (1991) also argued that due to the bias caused by changes in bulk density across grazed horizons, the responses often found were asymptotic, thus confirming the results of other authors (Penning, 1986; Ungar and Noy-Meir, 1988; Baker et al. 1992).

A better understanding of how changes in sward characteristics affect bite size can be achieved by describing this variable at a lower, more detailed, level of aggregation. Burlison et al. (1991) describes the components of bite size in Figure 4.3.

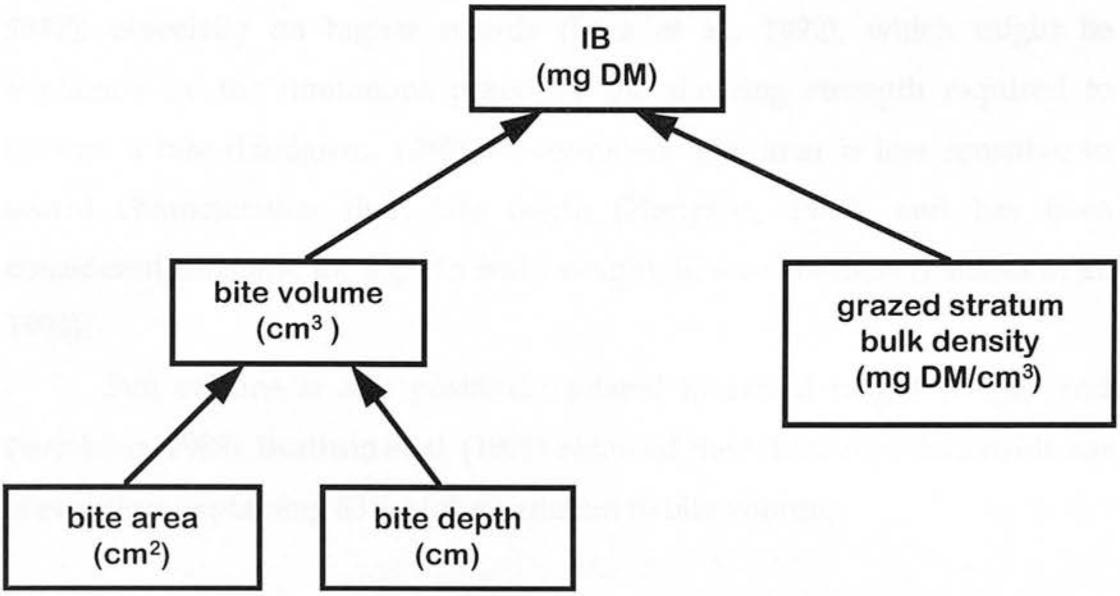

Figure 4.3. The components of bite size.

Bite depth is generally proportional to sward height (Milne et al., 1982; Wade et al., 1989; Laca et al., 1992; Ungar et al., 1992; Demment et al., 1995), but it may decrease depending on the relative height of stem material in the grazed horizons (Barthram and Grant, 1984; Forbes, 1988; Flores et al., 1993). Burlison et al. (1991) found the following relation for sheep and explained 93% of the variation in bite depth.:

$$\textbf{Bite depth} = -1.0 + 0.37\,H \qquad (6)$$

Since sward height is a good predictor of LAI (Parsons et al., 1994), which in turn reflects leaf mass (see equation 7), these results are in close agreement with the relation between leafiness and bite size found in several pastures (Stobbs, 1975; Chacon and Stobbs, 1976; Hendricksen and Minson, 1980; Hodgson, 1986).

Bite area increases with sward height (Burlison et al., 1991; Laca et al. 1992). However, it also increases with decreasing bulk density (Burlison, 1987), especially on higher swards (Laca et al., 1992), which might be explained by the limitations posed by the shearing strength required to harvest a bite (Hodgson, 1985). Nevertheless, bite area is less sensitive to sward characteristics than bite depth (Hodgson, 1986), and has been considered constant, for a given body weight, in some models (Parsons et al. 1994).

Bite volume is also positively related to sward height (Ungar and Noy-Meir, 1988). Burlison et al. (1991) obtained the following relationship for sheep, thus explaining 83% of the variation in bite volume:

Bite volume = -32 + 8.0 H (7)

There are some factors unrelated to sward structure which affect grazing behaviour, mainly grazing time. For example, Brumby, (1959) and Journet and Demarquilly (1979), showed that cows increased their grazing time by 5 min/kg milk between yield of 5 and 25 kg of milk, and 12 min/kg milk between 20 and 35 kg of milk, respectively. Similarly, Arnold and Duzinski (1967a) and Arnold (1975) found increases of 7-12% in grazing time during early lactation of sheep. Dougherty et al. (1989) found no difference in biting rate, bite size and grazing time when cattle were supplemented with ground corn at levels up to 4.5 kg/animal. However, other authors (Holder, 1962; Marsh et al., 1971; Leaver, 1986; Mayne and Wright, 1988; Rook et al., 1994) suggest that grazing time is reduced with supplementation, with the level of reduction being dependent on the type and level of supplementation. For example, Marsh et al. (1971) found reductions in grazing time of 22 min/kg concentrate fed, while Mayne and Wright (1988) found reductions of 43 min/kg when silage was fed. The type of supplement and its interactive effects with the basal diet might be the reason why Dougherty et al. (1989)

could not find differences in grazing time at various levels of supplementation. In temperate regions, the largest proportion (70-90%) of grazing time occurs during daylight (Penning et al., 1991; Rook et al., 1994), however, in the tropics night grazing is frequently observed due to high ambient temperatures during the day (Humphreys, 1991). The largest proportion of rumination time also occurs during daylight (Rook et al., 1994). Mastication and rumination increase with increased neutral detergent fibre (NDF) concentration in forages (Demment and Greenwood, 1988) or reduced digestibility (Arnold, 1981), in order to reduce particle sizes of the foraged consumed for passage through the gastrointestinal tract. Fasting increases grazing time and reduces rumination time (Greenwood and Demment, 1988).

Comparison of predicted intakes from grazing behaviour measurements against limited experimental data has shown agreement (Gordon, 1995). However, these models still require considerable effort to be widely validated, thus their range of application has been limited mostly for research purposes. Nevertheless, they have provided a significant contribution to the understanding of intake from grazed grasslands in the past two decades, and have given valuable insights to assist design of appropriate management strategies in some grazing systems.

A recognised criticism of this approach, is that a large part of grazing behaviour is caused by the animals' need for nutrient supply (Ungar and Noy-Meir, 1988). Most models do not integrate both processes, and those which do have not integrated mechanistic models of digestion and metabolism at the same level of aggregation as they treat grazing behaviour. Considerable research needs to be done to address these issues.

4.3.2 *Diet selection*

Diet selection is one of the crucial elements in grazing systems models for appropriate prediction of animal performance (see above). The two basic distinctions that are made are: 1) selection within pasture species and, 2) selection between plant species. Following Thornley et al. (1994), it is possible to describe the approaches for modelling diet selection as 1) empirical (descriptive), 2) goal-oriented (teleonomic) and 3) mechanistic (reductionist). The application of a particular approach is dependent on the type of pasture and animal models used.

There is general agreement that ruminants prefer to eat leaf instead of stem or dead material, and that the material eaten is usually of a higher nutritive value than the material on offer. Ruminants also tend to avoid plants with anti-nutritional compounds (e.g. tannins, alkaloids). In rangelands, abundance, nutritive value and spatial distribution are interraled. For example, plants of a higher nutritive value are less abundant than low quality ones (Belovsky, 1987). Management practices and the spatial distribution of plant species creates grazing routes that animals follow, which have an influence on the diet selected. Animals also tend to graze closer to the water source in arid and semi-arid environments (Arnold, 1981). Even when some basic empirical rules, such as the previously mentioned, appear to exist, the mechanisms used by animals to select their diet have not been fully elucidated.

Empirical representations of diet selection are the most common in grazing models, and, in general, they use the basic principles described above. Examples of these can be found in Christian et al. (1978), Illius (1986), Blackburn and Kothmann (1991), Baker et al. (1992) and Freer et al. (1997). These models assign 'selectivity coefficients' on the basis of digestibility or palatability of different morphological units (Illius, 1986; Blackburn and Kothmann, 1991), or plant physiological states (e.g. Freer et al., 1997). A problem that arises with assigning these types of coefficients on a plant species basis, is that they are modified depending on the species composition of the patch, and therefore may modify diet selection. For example, in terms of acceptability for an animal, the selectivity coefficient of the species changes depending on the other species present. Arnold (1981) argues that little progress is going to be made in understanding diet selection, as long as nutritive value is expressed with traditional analyses (e.g. digestibility, cell wall constituents, nitrogen) because these cannot be described at a molecular level, and therefore the substances determining 'palatability' cannot be fully determined.

Goal-seeking diet selection models are based on foraging theory (Stephens and Krebs, 1986). The general principle behind them is optimisation of the diet selected using the predator-prey concept. The ruminant (predator) will try to maximise its *benefits* (e.g. energy retention in most cases), relative to the *costs* of obtaining them (e.g. energy expenditure due to searching, handling and walking), by optimally selecting between plant species and/or plant parts (preys). These models are used mostly for ecological research (Belovsky, 1987; Thornley et al., 1994; Newman et al., 1994b).

Few mechanistic models of diet selection are available (Parsons et al., 1994), and it is recognised that a mechanistic representation is still far from complete due to the lack of knowledge to describe mechanistically some of the factors affecting diet selection. Certainly, this is an area that requires more research in order improve understanding of the mechanisms involved, and to make better predictions of the diets selected by grazing ruminants.

4.4 Modelling animal performance

From the viewpoint of whole grazing systems, it is now clear that the plant-animal interface is not completely represented if the consequences of grazing and other nutritional management practices on the animal (e.g. production), are not modelled. A series of papers and books relate to the subject (e.g. Forbes and France, 1993; van Soest, 1994; Journet et al., 1995), but there appears to be no consensus on the best approaches to modelling these processes. Nevertheless, the following represent, broadly, the most common approaches:

4.4.1 *Empirical relations between stocking rate and animal production*

It is widely recognised that stocking rate (SR) is one of the major determinants of animal production from pastures and the sustainability of the grazing system. There have been an number of mathematical descriptions of the relationship between SR and animal performance (e.g. Mott, 1961; Petersen et al., 1965; Edye et al., 1978), but the most commonly used was derived by Jones and Sandland (1974), who suggested that: 1) the relation between animal performance per head (kg/hd) and SR could be described by a linear regression, and 2) the relation between animal production per hectare (kg/ha) and SR was quadratic.

Apart from SR, other authors have used different statistical relations between animal performance and herbage availability (see Humphreys, 1991), level of N fertilisation (Karnezos et al., 1988), rainfall (Bransby, 1984); pasture species (McCaskill and McIvor, 1993; McIvor and Monypenny; 1995) and others. These relationships will not be considered further, since we believe they are not appropriate to be used in grazing systems models because: they are statistical relationships of specific datasets, and as such, only represent the data from which they are derived (slopes and intercepts vary significantly between studies), they do not provide understanding of the factors influencing animal performance, and are not flexible to represent changes in management practices within the system. Therefore they are not suitable to test alternative strategies on the behaviour of the system and its parts. However, for a full explanation of these types of relationships see Humphreys (1991).

4.4.2 Systems of nutritional requirements

The energy requirements of ruminants have been estimated with reasonable accuracy, and differences between the systems used in different countries (i.e. INRA, 1989; NRC, 1989, 1996; SCA, 1990; AFRC, 1993) seem to be small (McDonald et al., 1995). Traditional 'requirements systems' were not designed to predict intake, but to assess the nutritional and productive consequences of different feedstuffs to the animal once their intake was known. Therefore, a criticism that often arises is that the effective calculation of nutrient supply to the animal, and hence the quality of the predictions of animal performance, are largely dependent on the accuracy of the intake estimate used for the calculations. Hence, the importance of the representation of intake prediction in grazing systems models.

Several models of grazing systems, whether designed for sheep or beef or dairy cattle, rely on one form or another of energy 'requirements system' to represent animal performance (Vera et al., 1977; Christian et al., 1978; Sibbald et al., 1979; Konandreas and Anderson, 1982; White et al., 1983; Doyle et al., 1989; Walker et al., 1989; Richardson et al., 1991; Seman et al., 1991; Hanson et al., 1994; Thornley et al., 1994; Freer et al., 1997).

However, from the nutritional management viewpoint, these systems *per se* present some inadequacies that need to be addressed by other mechanisms to improve their flexibility:

1. These systems are static and digestibility estimates are central to the calculation of energy in feedstuffs in the appropriate units (e.g. DE, ME, NE). In 'requirements systems' these estimates are an input and are fixed for a particular feedstuff. However, effective digestibility is a consequence of degradation and passage through the gut, and therefore is dependent on plant and animal characteristics (Demment and Greenwood, 1988; Illius and Gordon, 1991). Due to the inherent selection by grazing animals on the basis of chemical and physical characteristics of different plants

and/or plant parts (see Section 3), it is necessary to model degradation and passage before describing digestibility and consequent nutrient supply. This requires dynamic models.

2. Even the most recent 'requirements systems' do not take into account explicit protein/energy interactions (Oldham, 1984; Preston and Leng, 1987). Lack of rumen degradable protein reduces microbial growth and depresses the rate of structural carbohydrate digestion (Ørskov, 1992). Therefore, the effect of some supplementation strategies on animal performance cannot be predicted adequately (Preston and Leng 1987).
3. Most requirements systems do not take into account interactions between different feeds (except limited interactions modelled by Sniffen et al., 1992; and NRC, 1996). For example, the reduction in cell wall digestibility is a well known consequence of reduced rumen pH caused by feeding large quantities of concentrates (Istasse et al., 1986; Argyle and Baldwin, 1988), and this, and the subsequent forage/concentrate substitution rates, cannot be predicted adequately by some 'requirements systems'.
4. 'Requirements systems' require the knowledge of the current level of production to calculate requirements, and are therefore not *predictors* of animal performance. Since they were designed mainly from observations from stall-fed animals, they were implemented to calculate the quantities and types of feeds to give to an animal of a known level of production. In other words, animal performance was not predicted, it was usually an input to the calculation (even when using the intake prediction equations in these systems). The rationale behind prediction of animal performance in grazing systems should be exactly the opposite: i.e. what level of production can be attained, relative to the potential production of an animal, of a given size and in a given physiological state, by following a particular grazing and overall nutritional strategy? Potential production is a function of the animal's genetic characteristics (Oldham and Emmans, 1988), while actual production is dependent on the resources available to

the animal, the way it can utilise them, and the overall management of the grazing system.

We believe that the place of these systems in grazing systems models lies in the estimation of the potential requirements only; which are dependent mainly on, body weight, physiological state, and level of production. However, the estimation of the supply of nutrients to meet those requirements needs a different approach, namely dynamic models of digestion.

4.4.3 Dynamic models of digestion

A wide range of dynamic models of digestion can be found in the literature (e.g. Waldo et al., 1972; Mertens and Ely, 1979; Forbes, 1980; Black et al. 1980; Bywater, 1984; Fisher et al., 1987; Hyer et al., 1991; Illius and Gordon, 1991, 1992; Sniffen et al., 1992; Fisher and Baumont, 1994). These types of models have been recently reviewed by Illius and Allen (1994), while Baldwin (1995, 1997) reviewed research models representing metabolism and the formation of end products of fermentation in ruminants* (e.g. Baldwin et al., 1970, 1977, 1987; Gill et al., 1984; Murphy et al., 1986; Danfaer, 1990; Dijkstra et al., 1992, 1993; Poppi et al., 1994). A range of approaches to model digestive processes can also be found in Forbes and France (1993).

The basic objectives of dynamic models of digestion are to predict potential intake, digestibility and animal performance as a function of the nutritional quality of plants on offer and a range of animal characteristics. There is evidence that such models provide improvements in the prediction of nutrient supply and animal performance than 'requirements systems' (Fox et al., 1992, 1995; Ainslie et al., 1993). However, there are certain basic aspects

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* Readers are referred to Baldwin (1995) for further information, since metabolic models will not be covered in this chapter.

that need to be considered that define the accuracy and flexibility of the model. These are:

1. *Description of feed fractions*: the basic fractionation of feedstuffs is represented in Figure 4.4. The separation of dry matter into its basic chemical entities is important because different feed fractions of different forages have different degradation and passage rates (Illius and Gordon, 1991; Russell et al., 1992), and therefore have different digestibilities. Consequently, they supply different amounts of nutrients to the animal (Murphy et al., 1982; Gill et al., 1990). These fractionations are also important to predict effects of supplementation on the rate of cell wall digestion (Argyle and Baldwin, 1988), to model protein/energy interactions, and to use recent standards of protein requirements (e.g. Fox et al., 1992; O'Connor et al., 1993; AFRC, 1993). Nevertheless, other authors consider that the nutritional description of the potentially degradable fractions of feedstuffs requires yet further fractionations (Mertens and Ely, 1979; Sniffen et al., 1992), although it is questionable that they provide better predictions than simpler approaches (Illius and Allen, 1994). The fractionation presented here is robust, simple and suitable for use in whole grazing systems models.

2. *Degradation kinetics*: The concentration and potential degradation kinetics of the cell wall of forages are one of the important determinants of intake and digestibility (Mertens, 1987; Illius and Gordon, 1991). The degradation kinetics of the crude protein fraction reflect N supply to rumen microbes (Czerkawski, 1986; Ørskov, 1992; AFRC, 1993), and therefore have an effect on cell wall degradation rates. Potential degradation characteristics are a function of plant characteristics (Russell et al., 1992; Ørskov, 1994).

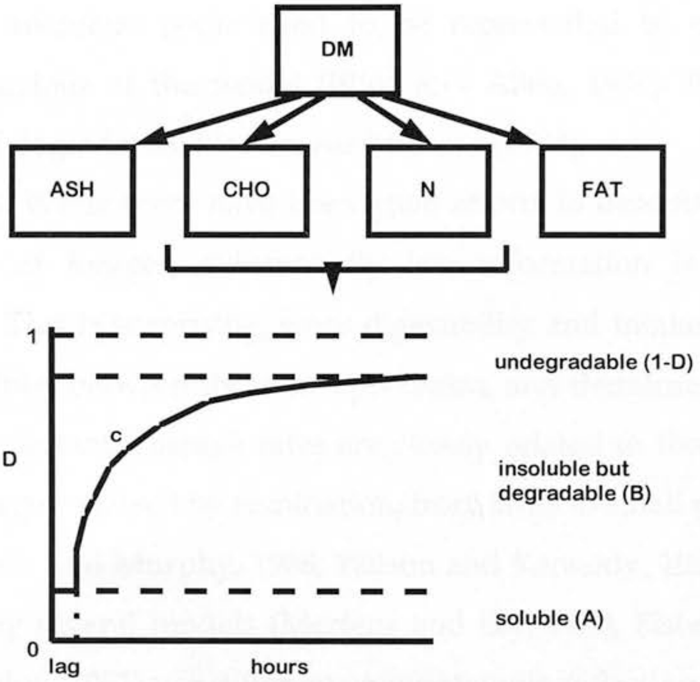

Figure 4.4. Basic nutritional characterisation of forages.

Parameters reflecting the potentially degradable fraction can be obtained from dacron bag studies (McDonald, 1981; Dhanoa, 1988) or *in vitro* gas production measurements (Herrero and Jessop, 1996, 1997; Herrero et al., 1996c; Jessop and Herrero, 1996; Jessop et al., 1996) by fitting the first order model described by Waldo et al. (1972) and McDonald (1981), where the rate of degradation is proportional to the amount of substrate:

$$\mathbf{D = A + B(1 - exp^{-c(t-lag)})} \qquad (8)$$

where D = degradation, A = soluble fraction (usually determined as the washing loss in degradation studies), B = insoluble but potentially degradable fraction, degraded at a fractional rate c (/h); lag = lag phase before degradation begins (h) and t = time. See Jessop and Herrero (1996) and Herrero and Jessop (1996) for a description of the method when gas production measurements are used. Second order models are also used to describe degradation kinetics, but the complexity of the analysis increases, since several microbial pools need to be represented to ensure proper biological behaviour of the model (Illius and Allen, 1994). For alternative descriptions of degradation kinetics see Mertens (1993).

3. *Passage rates*: While there have been great efforts to describe degradation characteristics of forages, substantially less information is available on passage rates. This is surprising, since digestibility and intake are functions of the competition between these two processes, and therefore passage rates are equally important. Passage rates are closely related to the mechanics of breakdown, largely caused by rumination, from large to small particles in the rumen (Kennedy and Murphy, 1988; Wilson and Kennedy, 1996), and this is the reason why several models (Mertens and Ely, 1979; Fisher et al., 1987; Illius and Gordon, 1991) use different compartments reflecting pools of large to small particles, to describe the different carbohydrate fractions. However, the required number of compartments to describe adequately particle dynamics and whether fractionation is really necessary to improve intake predictions is not known (Illius and Allen, 1994). Obviously, with this approach the understanding of the processes controlling the flow of material through the gut is greater, and this (depending on modelling objectives) should be seen as an advantage. It is convenient to represent rates of breakdown and passage as a function of animal characteristics (Illius and Gordon, 1991) since this improves the accuracy of predictions of intake (Illius and Allen, 1994). Illius and Gordon (1991) found the following relations for breakdown of large to small particles (BR):

$$\mathbf{BR = 0.144ICW^{-0.144}BW^{-0.27}}, \ r^2 = 0.62 \qquad (9)$$

where ICW = indigestible cell wall (g/kg) and BW = bodyweight (kg).

They also found the following relationships for passage through the whole gut (PWG, the inverse of mean retention time), and passage of small particles (SPR) from the rumen , respectively:

$$\mathbf{PWG = 0.071BW^{0.27}, r^2 = 0.76} \qquad (10)$$

$$\mathbf{SPR = 0.75PWG, c.v.\ 15.5\%} \qquad (11)$$

Passage rates also depend on the feeding level of the animal (AFRC, 1993). To account for effects of feeding level (FL, in multiples of maintenance), these should be multiplied by 0.25*FL and a similar scaling rule to that claimed by Sniffen et al. (1992) is obtained. Other relations can be found in Sauvant et al. (1995) but for total DM. Certainly more work is required on this subject to understand the factors affecting passage rates (e.g. buoyancy and its relation to particle fermentation and density). For concentrate feeds, Sniffen et al. (1992) describe the following passage rate (PRC):

$$\mathbf{PRC = -0.424 + (1.45\ PR)} \qquad (12)$$

4. *Rumen size*: for intake predictions, most dynamic models require to set a threshold value for the maximum capacity of the rumen or total gut. Accurate allometric relations for these parameters are found in the literature (see Peters, 1983; Demment and van Soest, 1985; Mertens, 1987; Demment and Greenwood, 1988; Illius and Gordon, 1991). Illius and Gordon (1991) determined this allometric relation for 18 species and found that the relationship of the weight of dry matter in the rumen (DMR) with body weight could be described by:

$$\mathbf{DMR = 0.021BW, r^2 = 0.98} \qquad (13)$$

Mertens (1987) found a very similar relation when expressing rumen contents on the basis of neutral detergent fibre.

Dynamic models of digestion, and their descriptions of feed and animals are useful for the integration of other processes within the grazing system. Since models of this nature monitor the flow of feed components through the gastrointestinal tract, they predict their excretion patterns and the composition of excreta, which are integral to link the animal with the soil fertility subsystems, and their consequent effects on pasture growth in grazing models.

4.5 Other relations between plants and animals

There are other relations that need to be taken into consideration when modelling the plant-animal interface, which are particularly difficult to model. For example, treading, poaching and fouling can reduce herbage availability and the subsequent regrowth of the sward (Brockington, 1972; Christian, 1981; Wilkins and Garwood, 1986).

Forage is damaged due to trampling and poaching, especially in wet soils (Wilkins and Garwood, 1986) and/or in very high swards (Herrero, unpublished), but as Christian (1981) states, it would be difficult to account for these effects in a grazing model.

Dung pats and urine affect herbage availability and modify diet selection patterns of ruminants (Brockington, 1972), thus leading to the spatial effect of patchy swards in some cases. The effects of excreta are greater than those of urine, and are mediated by the number of dung pats, the area they cover and the stocking rate. The most common way to model these effects are by empirical relations which are usually dependent on stocking rate (Brockington, 1972; Hanson et al., 1994) to scale the amount of herbage available to the animal. Dung pats can also affect herbage growth by excluding light from the patches for several months (Wilkins and Harwood, 1986) but this effect can be reduced by management practices, at least in intensive systems. In rangelands, it is difficult to control but stocking rates are also lower and therefore the effect of dung on animal consumption is, perhaps, less important.

Nevertheless, quantification of these aspects is important, since significant amounts of dung can be deposited in pastures. Their contribution to nutrient cycles cannot be neglected due to their key role in the sustainability of the grazing system and the overall dynamics of the biology of grazing cycles. However, better approaches are required to quantify the fate of minerals from ruminant excretions to the soil, water and atmosphere (Scholefield et al., 1991; Humphreys, 1994).

4.6 Future research and development needs

Future research needs can be divided into two sections. First, research on aspects dealing with the knowledge acquisition and representation of the main biological processes. Second, definition of an integrated approach for the selection of management interventions leading to sustainable grazing systems.

4.6.1 Biological processes

In terms of biological processes, there are aspects, both in plant and animal sciences that need to be addressed. For example, while mechanistic models of single pasture species are available and have proven robust in their predictions, there is a need for better understanding of the processes controlling growth in grass/legume associations and rangelands. Understanding competition for resources (light and nutrients) by different species and to find suitable mathematical definitions that reflect the biological processes is not a trivial task. This is closely linked with the representation of grazing processes and diet selection, even in single species pastures. Most representations of diet selection have been empirical and until the mechanisms that control diet selection have been elucidated, little progress is going to be made in modelling diet selection. A key issue in order to solve this problem, is to link the behavioural aspects of grazing to digestion and metabolism models, since the release the balance of nutrients and pattern of supply play an important part in controlling rates of intake and what the animal chooses to eat (Gill and Romney, 1994). In terms of intake prediction, it appears that the weakest information is related to the flow of material through the gut. More efforts should be directed towards research on the factors controlling passage of feed particles through the gastrointestinal tract.

4.6.2 Decision-support systems - an integrated approach

Models can be built solely to increase our understanding about systems under study and the nature of the functional relations between parts of the system. For example, many authors have investigated the effect of certain variables on the stability and steady states of grazing systems (Noy-Meir, 1975, 1976, 1978; Johnson and Parsons, 1985; Thornley and Veberne, 1989), other scientists have looked at more fundamental relationships between the animal and plant communities in terms of body weight effects (allometry)(Belovsky, 1987; Demment and van Soest, 1985; Illius and Gordon, 1987; Taylor et al., 1987), grazing behaviour (Ungar and Noy-Meir, 1988, Ungar et al., 1991; Laca et al., 1992; Parsons et al., 1994), diet selection (Belovsky, 1987; Parsons et al., 1994; Newman et al., 1994b), or digestive processes (Illius and Allen, 1994; Baldwin 1995). Increased understanding of these processes has lead to improved methods for modelling grazing systems at various levels of detail. However, it is important to emphasise the trade-off between the objective of the model, and its accuracy and level of detail, if cost-effective models are to be built.

For some purposes, the use of grazing systems models is not complete, if mechanisms to select between alternative grazing strategies are not available. This is specially valid, if the models are to be used in farm management or in a regional planning context.

The classical approach to selection of management strategies has been to use linear programming (LP) models with the objective of optimising economic performance (Dent et al., 1986; Conway and Killen, 1987; Kleyn and Gous, 1988; Olney and Kirk, 1989), but these have not used whole systems simulation models to provide the inputs for the LP models. Two important things need to be considered. First, it is well recognised that economic optimisation is only one, but not necessarily the main objective of farmers (Gasson and Errington, 1993; Perkin and Rehman, 1994; Dent et al., 1994; Dent, 1996). Therefore, the selection mechanism needs to consider several simultaneous objectives and trade-offs between them. It is considered that the use of multiple-criteria decision-making models (MCDM), which are extensions of linear programming models, can be linked to a simulation system to create a DSS and provide options for the management of the grazing system. A similar approach was used by Veloso et al. (1992) with crop models. Since a range of multiple objectives can be represented, they have the flexibility of dealing with different types of farmers and their managing capacities. The simulation system provides the dynamics of the system under a variety of management scenarios, and the MCDM selects the best alternatives according to the farmer's objectives. Improved selection of strategies can be gained if the objectives of the farmers are better represented, and this requires a further substantial input from the social and behavioural sciences (Dent, 1996).

Chapter 5

Modelling grass growth and grazing processes[*]

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[*] Parts of this Chapter have been adapted from:
Herrero, M. (1996) Grassland modelling: a decision-support tool. In: *Animal Production in Central America: Conservation and Sustainable Development*. Proceedings of a Workshop on Sustainability of Livestock Production Systems held in San José, Costa Rica. Sept 8-12, 1995. *Ciencias Veterinarias*, Voumen Especial, 17: 72-79. (Appendix 1).

Chapter 5

Modelling grass growth and grazing processes

5.1 Introduction

In pastoral ruminant production systems, grassland management is one of the key determinants of their success (Hodgson 1990, Humphreys 1991, Clark and Jans 1995). Together, with environmental variables, it determines the quantity and quality of herbage available and the physical structure of the sward, factors which will subsequently determine pasture intake and animal performance. However, sustainable grazing management should ensure the ecological stability of the grazing system and therefore requires knowledge about the processes controlling growth and utilisation of pasture species.

This chapter describes how a simple mechanistic model representing the growth of pasture under rotational or continuous grazing with responses to N fertiliser, temperature and irradiance can be used as a tool to study management options for the development of sustainable grazing systems. It also shows the role of this model in the context of the whole cattle farm decision-support system (DSS). The effects of different environmental conditions, N fertilisation regimes and grazing intensities are analysed, and physiological concepts are used to aid in the interpretation of the responses obtained. The model demonstrates the importance of flexible management guidelines depending on environmental conditions. It stresses the need for an increased understanding of the processes controlling the development and senescence of the sward, since these largely influence the responses to nutrients and determine sward structure. Examples are given with reference to kikuyu grass (*Pennisetum clandestinum*) growth and utilisation.

5.2 Model description

5.2.1 *General characteristics*

The objective of the model is to predict growth, instantaneous herbage mass and sward structure of a vegetative pasture sward under rotational or continuous grazing with responses to N fertiliser applications, temperature and irradiance. The model was built in SB-ModelMaker (Zeton Tech, Nottingham, UK) and runs at daily timesteps.

The main processes represented include light interception and photosynthesis, leaf area expansion; growth, ageing and senescence of plant tissues, recycling of substrates from senescing tissues, nitrogen uptake, mineralisation of soil organic N, N leaching and grazing.

The sward is divided into leaves, stems and roots of different age categories to simulate the ageing processes leading to senescence, accumulation and turnover of dead material (Johnson and Thornley 1985). The division of the above-ground dry matter into leaves, stems and dead material is necessary for an adequate description of the effect of grazing management practices on sward structure, which is an important factor controlling intake of grazing ruminants and to simulate diet selection (Stobbs 1973; Chacón and Stobbs 1976; Hodgson 1985; Ungar and Noy-Meir 1988). Sward height and bulk density are also incorporated from empirical relations obtained from experimental observations.

The two main substrates controlling plant growth are modelled. Carbon (C), synthesised from photosynthesis by the canopy leaf area index (LAI) and N, obtained from the soil by the roots from mineralisation of organic N and N fertiliser. Recycling of nutrients from dead material also contribute to the C and N pools. Substrates are partitioned towards new growth of the above or below ground plant parts or are lost by maintenance and growth respiration in the case of C or by leaching in the case of N.

The basic structure of the grass growth model was derived from the ryegrass models of Johnson and Thornley (1983, 1985) and Thornley and Veberne (1989) (often referred to as 'the Hurley pasture models'). These were chosen as the starting point because:

1) they were mechanistic, and therefore, the description of the physiological processes represented could be used to simulate the growth of, not only kikuyu grass, but of a range of pasture species. This was an important objective for future work in other agroecological zones (increased flexibility).
2) they were driven by environmental and management variables, hence, the model could be calibrated for agro-ecoregions and production systems with different characteristics (increased adaptability and portability).
3) they were robust and flexible models which had been validated.
4) the user-defined management parameters and variables were simple and easily obtainable at farm level. They represented the variables that farmers currently use to make grazing management decisions. For example, stocking rates (animal numbers), bodyweight of animals (sizes), rate of N fertiliser application, paddock rotation lengths (rest period and grazing days), and land area available for grazing.

Several steps were followed for the construction of the model. The first step consisted in writing the Johnson and Thornley (1985) model with parameters for ryegrass in SB-ModelMaker. Comparison of outputs against the original source code showed good agreement (Herrero and Thornley, unpublished). The second step was to adopt some changes of the model of Thornley and Veberne (1989), which was an expansion of the Johnson and

Thornley (1983, 1985) models. These were: 1) above-ground biomass was separated into leaves, stems and dead material for a better definition of the plant/animal interface (see Chapter 4). 2) Photosynthesis was described by a non-rectangular hyperbola to obtain biologically meaningful parameters and a better fit of the photosynthesis data (Johnson and Thornley 1984, Johnson et al. 1989, Hanson et al. 1988). 3) The functions describing the partitioning of nutrients between roots and shoots were also changed. The teleonomic functions described by Thornley and Veberne (1989) were used to allow the maintenance of a substrate-dependent equilibrium between shoot and root maximum growth. 4) Grazing was incorporated using the Johnson and Parsons (1985) model based on LAI and implemented in Thornley and Veberne (1989) model. This was further adapted to account for larger sward structure differences of tropical pastures (Stobbs 1975). The next step consisted of a sensitivity analysis of model outputs to changes in parameter values. This step was considered very important for the definition of an efficient data gathering process and the parameterisation of the model to the species in question (see below). The model was not sensitive to changes in some parameters. Values for these were not changed, even if they did not reflect the real values for the species modelled. The adaptation and parameterisation of the model to kikuyu grass started after these basic steps had been followed. The last stages consisted of model validation and an analysis of grazing management practices.

The following sections describe the model. A summarised description can be found in section 5.5. A similar definition as the Hurley models has been used, unless otherwise stated.

5.2.2 *Sward components*

The sward was divided into 3 components: leaf laminae ($WL_{1\text{-}4}$), sheaths and stems ($Wsh_{1\text{-}4}$), and roots ($Wr_{1\text{-}4}$) (all in kg structure/m^2). All components were represented using four compartments for each component to describe the ageing processes of the sward (1=new to 4=senescent) and to appropriately describe tissue turnover within the sward:

Leaves

$$\frac{dWL_1}{dt} = fLGsh - 2GammashWL_1 - grl_1 \tag{1}$$

$$\frac{dWL_2}{dt} = 2GammashWL_1 - GammashWL_2 - grl_2 \tag{2}$$

$$\frac{dWL_3}{dt} = GammashWL_2 - GammashWL_3 - grl_3 \tag{3}$$

$$\frac{dWL_4}{dt} = GammashWL_3 - GammashWL_4 - grl_4 \tag{4}$$

Stems

$$\frac{dWsh_1}{dt} = (1 - fL)Gsh - 2GammashWsh_1 - grs_1 \tag{5}$$

$$\frac{dWsh_2}{dt} = 2GammashWsh_1 - GammashWsh_2 - grs_2 \tag{6}$$

$$\frac{dWsh_3}{dt} = GammashWsh_2 - GammashWsh_3 - grs_3 \tag{7}$$

$$\frac{dWsh_4}{dt} = GammashWsh_3 - GammashWsh_4 - grs_4 \tag{8}$$

Roots

$$\frac{dWr_1}{dt} = Gr - 2GammarWr_1 \qquad (9)$$

$$\frac{dWr_2}{dt} = 2GammarWr_1 - GammarWr_2 \qquad (10)$$

$$\frac{dWr_3}{dt} = GammarWr_2 - GammarWr_3 \qquad (11)$$

$$\frac{dWr_4}{dt} = GammarWr_3 - GammarWr_4 \qquad (12)$$

where,

fL is the fraction of new structure partitioned to the production of new leaves.

Gammash and Gammar are temperature-dependent rates of appearance (/d) of new leaves/stems and roots, respectively, which are taken to be similar between them.

Gsh and Gr are the rate of production of new leaves and stems, and root structure, respectively (kg structure/m^2/d).

grl$_{1\text{-}4}$ and grs$_{1\text{-}4}$ are the leaf and stem structural fractions removed by grazing, respectively (kg structure/m^2/d). See below for a description of grazing processes.

Therefore, total live leaf (WL), stem/stolon (Wsh) and root (Wr) structural masses (kg structure/m^2) are, respectively:

$$WL = \sum_i WL_i \qquad (13)$$

$$Wsh = \sum_{i} Wsh_i \tag{14}$$

$$Wr = \sum_{i} Wr_i \tag{15}$$

Since the last compartment (i=4) comprises senescing material, it is assumed that only 0.5 of each of these compartments in alive.

The above ground (Wag) and total sward live structural weight (Wg) then become, respectively (kg structure/m^2):

$$Wag = WL+Wsh \tag{16}$$

$$Wg = WL+Wsh+Wr \tag{17}$$

The total crop weight is described by its structural and storage weights, with the storage compartment representing the fractional substrate pools within the plant parts. Although there are differences in the substrate concentrations of above-ground plant parts of kikuyu grass (Chapter 3), their distribution between roots and above ground plant parts is considered homogeneous, therefore:

$$Wagt = fshWs + \sum_{i} WL_i + \sum_{i} Wsh_i \tag{18}$$

$$Wrt = frWs + \sum_{i} Wr_i \tag{19}$$

where,

Wagt and Wrt are the total above and below ground dry weights (kg DM/m^2), respectively.

fsh and fr are the above-ground and root structural fractions, defined by:

$$\mathrm{fsh} = \frac{\mathrm{WL} + \mathrm{Wsh}}{\mathrm{Wg}} \tag{20}$$

$$\mathrm{fr} = \frac{\mathrm{Wr}}{\mathrm{Wg}} \tag{21}$$

Ws is the total storage dry weight:

$$\mathrm{Ws} = \frac{\mathrm{MC}}{12}\mathrm{WC} + \frac{\mathrm{MN}}{14}\mathrm{WN} \tag{22}$$

where

WC and WN are the C and N substrate pools , respectively.

MC and MN are the molecular masses of the C and N, respectively, relative to ^{12}C and ^{14}N. This implies that substrate is available in only one form, in this case sucrose and nitrate. The substrate concentrations (C, N) (kg C or N/kg structure) within the total weight of the sward can now be written:

$$\mathrm{C} = \frac{\mathrm{WC}}{\mathrm{Wg}} \tag{23}$$

$$\mathrm{N} = \frac{\mathrm{WN}}{\mathrm{Wg}} \tag{24}$$

5.2.3 *Leaf area index, light interception and photosynthesis*

The main input to the C cycle comes from photosynthesis as a product of light interception by the canopy leaf area index (LAI). Each structural compartment $\mathrm{WL}_{1\text{-}4}$ contribute to the LAI ($\mathrm{L}_{1\text{-}4}$) as follows:

$$\mathrm{LAI} = \sum_{i} \mathrm{L}_i \tag{25}$$

where the contribution of each leaf compartment is represented by:

$$\frac{\mathrm{dL}_1}{\mathrm{dt}} = \mathrm{SLAfLGsh} - 2\mathrm{GammashL}_1 - \mathrm{garea}_1 \tag{26}$$

$$\frac{\mathrm{dL}_2}{\mathrm{dt}} = 2\mathrm{GammashL}_1 - \mathrm{GammashL}_2 - \mathrm{garea}_2 \tag{27}$$

$$\frac{\mathrm{dL}_3}{\mathrm{dt}} = \mathrm{GammashL}_2 - \mathrm{GammashL}_3 - \mathrm{garea}_3 \tag{28}$$

$$\frac{\mathrm{dL}_4}{\mathrm{dt}} = \mathrm{GammashL}_3 - \mathrm{GammashL}_4 - \mathrm{garea}_4 \tag{29}$$

In equation 26, SLA represents the specific leaf area (m^2 leaf/kg structure). This parameter is dependent on the carbon concentration (C), hence on irradiance and photosynthesis (Ludlow and Wilson, 1971; Jones, 1992)(see below), and is defined as:

$$\mathrm{SLA} = \mathrm{SLAMAX}(1 - \mathrm{SLApC}) \tag{30}$$

where
SLAMAX is the maximum specific leaf area of first fully expanded leaves.
SLAp is an incremental specific leaf area parameter (kg structure/kg C).
$\mathrm{garea}_{1\text{-}4}$ represent the fraction of leaf area removed by grazing.

The original Hurley model (Johnson and Thornley 1983) used a rectangular hyperbola to represent single leaf photosynthesis, however it was replaced by a non-rectangular hyperbola (Johnson and Thornley, 1984; 1990) in the subsequent models (Johnson and Thornley 1985; Thornley and Veberne 1989) because it provided better descriptions of photosynthesis data and it had biologically interpretable parameters (Johnson et al. 1989; Jones, 1992; Hanson et al. 1994). It is described by:

$$\mathrm{Pg} = \frac{1}{2\mathrm{theta}}[\mathrm{alphaI} + \mathrm{P\,max} - \{(\mathrm{alphaI} + \mathrm{P\,max})^2 - 4\mathrm{alphaIthetaP\,max}\}^{0.5}] \tag{31}$$

where

Pg is single leaf photosynthesis (mg $CO_2/m^2/s$).

alpha is the light utilisation efficiency of leaves (mg CO_2/J).

Pmax is the asymptote value of Pg at saturated irradiance, which is temperature-dependent.

theta is a dimensionless parameter (0 < theta < 1).

I is irradiance (W/m^2) in photosynthetic active radiation (PAR).

To obtain the canopy gross photosynthetic rate (Pc), the single leaf photosynthesis is integrated over the LAI, and distributed over the depth of the canopy using Beer's Law (Monsi and Saeki, 1953). Therefore:

$$\mathrm{Pc} = \int_0^{\mathrm{LAI}} \mathrm{Pg}(\mathrm{I_L})\,\mathrm{dLAI} \tag{32}$$

where

I_L is the light attenuation factor (Beer's Law), and is defined as:

$$\mathrm{I_L} = \left(\frac{\mathrm{k}}{1-\mathrm{tau}}\right)\mathrm{I_o}\mathrm{e}^{-\mathrm{kLAI}} \tag{33}$$

k is the canopy extinction coefficient.

tau is the leaf transmission coefficient.

I_o is the light flux density at the top of the canopy.

The results have to be expressed on a daily basis to obtain the daily carbon input to the sward (P, kg C/m²/d). Therefore, they are integrated over the daylength (h, s/d) and expressed on the basis of the carbon mass of photosynthate (12) relative to carbohydrate (44):

$$P = \frac{12}{44}\int^{h} Pc\,dt \qquad (34)$$

5.2.4 *Growth and substrate partitioning and utilisation*

The growth and partitioning of nutrients between plant parts is dependent on substrate concentrations and on environmental parameters such as temperature and irradiance (Thornley and Johnson 1990, Jones 1992). In the previous section, the input to the C cycle was described. The present section describes the use, or outputs, of substrate C from the pool.

The rates of structural growth of above (Gsh, eqs. 1, 5) and below (Gr, eq. 9) ground organs are given by:

$$Gsh = WshGCNLAMBDAsh \qquad (35)$$

$$Gr = WshGCNLAMBDAr \qquad (36)$$

where G is a growth coefficient that determines the magnitudes of the growth rates.

LAMBDAsh and LAMBDAr are functions that determine the partitioning of new growth towards above or below ground organs. The teleonomic approach of Thornley and Veberne (1989) was chosen to allow the maintenance of a substrate-dependent equilibrium between shoot and root maximum growth, as is commonly observed (Mears and Humphreys, 1974a).

For example, if N is limited, the plant would tend to partition substrates to the roots to increase root mass to try to increase N uptake. These functions are given by:

$$\mathrm{LAMBDAsh} = \frac{\mathrm{P}}{1 + \mathrm{P}} \tag{37}$$

$$\mathrm{LAMBDAr} = \frac{1}{1 + \mathrm{P}} \tag{38}$$

where the teleonomic partitioning function (P) is,

$$\mathrm{P} = \frac{(\mathrm{frN} / [\mathrm{N} + \mathrm{fN}])}{(\mathrm{fshC} / [\mathrm{C} + \mathrm{fC}])} \tag{39}$$

with

fC and fN being the fractional C and N concentrations in the live structure (kg/kg live structure), respectively.

The growth rates of live structure (eqs. 35 and 36) require fluxes from the C and N substrate pools (kg (C)(N)/m^2/d). These are given by:

$$\mathrm{fC(Gsh{+}Gr)} \tag{40}$$

$$\mathrm{fN(Gsh{+}Gr)} \tag{41}$$

Three respiratory costs are calculated by the model: maintenance respiration (Rm, kg C/m^2/d) which is proportional to the structural weight of the different plant parts (McCree 1970), growth respiration (Rg, kg C/m^2/d), which is proportional to the growth rates Gsh and Gr; and the respiration costs of N uptake (Rn, kg C/kg N). All are outputs from the C substrate pool and are described by:

$$\mathrm{Rm} = \mathrm{fC}\sum_{\mathrm{i}}(\mathrm{Msh_i WL_i} + \mathrm{Msh_i Wsh_i} + \mathrm{Mr_i Wr_i}) \tag{42}$$

$$\mathrm{Rg} = \mathrm{fC(Gsh + Gr)(1 - Y) / Y} \tag{43}$$

$$\mathrm{Rn} = \mathrm{sigmasoilN} \tag{44}$$

where

$\mathrm{Msh_i}$ and $\mathrm{Mr_i}$ are different temperature-dependent maintenance coefficients (/d) for the different categories of leaves, stems and roots, respectively.

Y is the efficiency of use of substrate C for the production of new structure, and also determines the rate of use of substrate C for new growth by:

$$\mathrm{fC(Gsh{+}Gr)/Y} \tag{45}$$

sigma is a specific temperature-dependent activity parameter (kg soil/kg root structure) of the young roots.

Ns is the soil N concentration (kg N/kg dry soil).

5.2.5 *Nitrogen uptake*

The rate of nitrogen uptake (UN, kg N/m²/d) is dependent on the C and N concentrations in the plant, and on the specific activity of roots, which decreased with age (see Johnson and Thornley 1985). It is defined by:

$$\mathrm{UN} = \frac{\mathrm{sigma(Wr_1 + v2Wr_2 + v3Wr_3 + v4Wr_4)}}{1 + \frac{\mathrm{KC}}{\mathrm{C}}(1 + \frac{\mathrm{N}}{\mathrm{KN}})} \tag{46}$$

where

v2-v4 are dimensionless root activity weighting coefficients to describe the reduced activity efficiency as roots age (Penning de Vries 1975).

KC and KN are root activity parameters.

5.2.6 *The soil and nutrient cycling*

The model uses a simple description of the soil and nutrient recycling based on the approach of Johnson and Thornley (1985), but modified to include excretion of faeces and urine by grazing animals:

$$\frac{\text{soilN}}{\text{dt}} = \text{Bn} + \frac{\text{An}}{\text{soildendr}} + \text{LitterN} + \text{ExcretionN} - \frac{\text{UN}}{\text{soildendr}} - \text{betasoilN} \quad (47)$$

where

soilN is the total available soil N (kg N/kg dry soil).

Bn is the N available from mineralisation of soil organic matter (kg N/kg dry soil, temperature dependent).

An is N from fertiliser. It is assumed to be homogeneously distributed throughout the soil. Therefore it is divided by the soil density (soilden, 10^3 kg/m^3) multiplied by the rooting depth (dr, m).

Litter (LitterN) and faecal and urinary N (ExcretionN) also contribute to the soil N content (kg N/m^2/d). ExcretionN is dependent on stocking rates (SR), diet quality and animal body weight (see below).

UN is nitrogen uptake by the plant, which occurs homogeneously through the soil layer (eq. 46).

beta is a fractional leaching parameter, which is proportional to the soil N content.

The litter fraction [0.5(WL_4 and Wsh_4)] contains fractional C (DC) and N (DN) contents in the degradable structure (kg C or N/m^2/d). Therefore, the degradable fraction is:

$$\frac{fN}{FNd}(WL_4 + Wsh_4 + Wr_4) \tag{48}$$

and contains,

$$DC = k\deg \frac{FCdfN}{FNd}(WL_4 + Wsh_4 + Wr_4) \tag{49}$$

$$DN = k\deg fN(WL_4 + Wsh_4 + Wr_4) \tag{50}$$

where

kdeg is the decomposition rate (/d) of litter, and is dependent on the N concentration:

$$k\deg = \frac{kd}{N + kd} \tag{51}$$

The dependency of kdeg on the N concentration of the plant agrees with the results of Handayanto et al. (1997). However, these authors also found that kdeg was more closely related to the protein-binding capacity, the polyphenol concentrations, or ratios of forage quality variables, notably, the polyphenol:N or lignin:N ratios of the plant litter (Parton et al. 1979, Thomas and Asakawa, 1993). Parton et al. (1979) have used the latter to predict decomposition in their model (CENTURY). According to Giller and Cadisch (1997), the ability of these forage quality variables to predict decomposition changes depends on the stage of decomposition of plant litter, and therefore caution must be taken when comparing results from different authors.

For simplicity, the relation with N concentration proposed in the original Hurley models will be maintained until a more detailed, and easy to parameterise, soil model is developed. It is unlikely that these estimates will affect significantly the outcomes of the present model, since the direct contribution of litter to the total N requirement for the growth of tropical grass species is close to 6% (Cadisch et al. 1994, 1996), and can range from 2-13% (Thomas and Asakawa, 1993). These aspects are more important in grass/legume systems (Thomas, 1992, Cadisch, et al. 1994, Toledo, 1994), where the legume can contribute to up to 76% of N requirements of the forage present (Thomas and Asakawa, 1993).

For some purposes, this description of the soil and nutrient cycling might be oversimplistic. However, the main problem with soil models, which can vary largely in degree of complexity, is to find appropriate data for their parameterisation and validation (see below). Since methodologies are still not sufficiently developed, some of the flows are not currently verifiable, or large errors are associated with their measurement (McGill et al., 1981; Thornley and Veberne, 1989; Whitehead, 1995). Thornley and Veberne (1989) incorporated in the Hurley models a more detailed description of soil nutrient dynamics. They argue that the model is relatively simple compared to other models, but even then, they were unable to parameterise it with experimental data and opted for a subjective validation based on attaining realistic results. This is the case with the vastly studied temperate grasslands, therefore it is unrealistic to expect an appropriate parameterisation for tropical grasslands where data are scarce, and where efforts in this area have been largely concentrated in forests and crops. Certainly this area requires a substantial amount of research.

5.2.7 *Temperature-dependent variables*

The model contains 13 temperature dependent parameters: Pmax, Gammash, Gammar, sigma, BN, Msh_{1-4}, and Mr_{1-4}. In tropical grasses, Pmax has been found to be linearly dependent on temperature from 15 - 40 °C (Ludlow and Wilson, 1971; Ehrlinger and Björkman, 1977; Ludlow, 1981;

1985), while there is strong evidence of this temperature dependency for rates of leaf appearance (Murtagh, 1987; Jones, 1992; Crawley, 1997), maintenance respiration (McCree, 1970; Jones, 1992), and soil N mineralisation (Brady, 1973; Frissel and van Veen, 1981; Whitehead, 1995). In the model, all processes were assumed to be linearly dependent on temperature (see Johnson and Thornley, 1983), and are given by:

$$X(T) = X(20)\frac{(T - Tc)}{(20 - Tc)} \tag{52}$$

where

X is the value of the parameter at daily temperature T (^{o}C).

X(20) is the value of the parameter at a reference temperature, in this case 20^{o}C, which represents well the regions where kikuyu grass grows (see Chapter 3).

Tc is the temperature at which crop growth ceases.

5.2.8 *Grazing*

There are several ways to model grazing processes, all of which have different degrees of complexity (Chapter 4). Calculation of intake from grazing behaviour measurements is probably one of the most common methods to predict intake of grazing ruminants (see Chapter 4). An attempt to implement this approach was made in the earlier stages of model construction, but it was abandoned because of 2 reasons:

1) while the defoliation responses of grazing ruminants to different sward characteristics (i.e. bite dimensions) are relatively well understood, the inability to predict grazing times due to the state-dependence of intake constraints, limits the accuracy of the intake predictions from grazing behaviour measurements in some circumstances (Illius, 1997).

2) the scarce and inconclusive data on the effects of supplementation on grazing behaviour makes it impossible to predict intake of grain-supplemented ruminants by this method. These effects are largely mediated through modification of grazing times, and hence by the variability and incomplete additivity of intake constraints mentioned recently by Illius (1997). The integration of behavioural, ingestive and digestive constraints is a formidable task, and it will probably require a better understanding of the control of meal sizes, which even in stall-fed animals are not well understood (Gill and Romney, 1994).

Hodgson (1985) claims that variations in daily herbage intake frequently reflect closely the variations in bite mass, which is the single best intake determinant from a grazing behaviour standpoint (see Chapter 4). Therefore, a simpler approach based on the functional relationship between intake and different descriptions of herbage mass and sward structure should define the effects of sward conditions on intake, and is justifiable.

In this case, the approach taken was to modify the Johnson and Parsons (1985) grazing function used in the Hurley models and by other authors (Crawley, 1983; Richardson et al. 1991; Schwinning and Parsons, 1996). This function is based on defoliation of LAI only, therefore it was adapted to deal with different sward structures and animal bodyweights; aspects which were not taken into account in the previous studies. The function was also expressed on the basis of different measurements of herbage mass to increase its on-farm applicability, without losing the physiological functional relationship with LAI. Intake of individual grazing animals (intake, kg DM/d) was described by:

$$\mathrm{intake} = \mathrm{intmax}\frac{(\mathrm{LAI}/\mathrm{K})^{q}}{1+(\mathrm{LAI}/\mathrm{K})^{q}} \qquad (53)$$

where

intmax is the potential intake of the animal (kg DM/d) (see Chapter 6).

q determines the sigmoidicity of the response. A value of q = 3 gives realistic responses to grazing (Johnson and Parsons, 1985).

K is the value of L for half maximal response of intake (Le Du et al. 1979; Hodgson et al., 1986). The Hurley models use a value of K = 1 for sheep (Johnson and Parsons, 1985; Thornley and Veberne, 1989); while an appropriate value for dairy cows is K = 2 (Parsons, pers. comm.). K is a very important parameter since it determines at what LAI, height or herbage mass, intake begins to be limited in ruminants of different body sizes. According to Illius and Gordon (1987) and Gordon et al. (1996), small animals are able to graze more efficiently in shorter swards than large animals, therefore intake begins to decrease at lower LAI values or herbage masses. They claim that these differences in grazing ability can be related to mouth size (incisor arcade breadth) and that incisor arcade follows an allometric relationship with bodyweight (BW, kg). This concept can provide a basis for explaining changes in K by development of a scaling rule with the same allometric coefficient (0.36) for incisor arcade breadth proposed by Illius and Gordon (1987)(see discussion on validation). Therefore:

$$K = 0.229BW^{0.36} \quad (54)$$

The grazing function was also adapted to different variables related to herbage mass and sward structure. This was mainly done because LAI measurements are often not available at farm level. Nevertheless, other variables can be derived from LAI with the knowledge of three parameters that are estimated by the model, and that can be easily measured in the field: the specific leaf area (SLA), the leaf mass (WL) and the proportion of leaf in the sward (pL). Results can then be expressed on the basis of leaf, green or total herbage mass, while at the same keeping the physiological relationship with LAI.

The leaf and green herbage mass provide better descriptors of pasture availability in tropical grasses than total herbage mass because of the preferential selection of leaf by ruminants, and because often the leaf component does not represent the highest proportion of the herbage mass (Stobbs, 1975; Cowan et al. 1976; Hendricksen and Minson, 1981; Humphreys, 1991). Green herbage mass and the proportion of leaf in the sward have been used as the basis for the calculations. The effect of bodyweight on the functional response between green herbage mass and intake at grazing can be observed in Figure 5.1. Results are presented for a sward with a 0.5 proportion of green leaf.

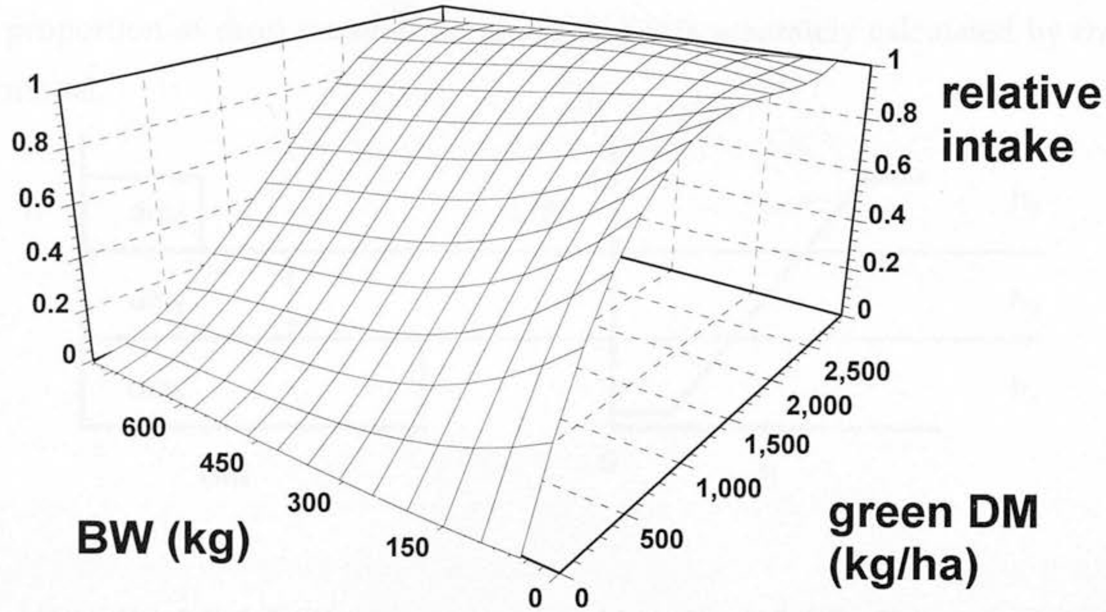


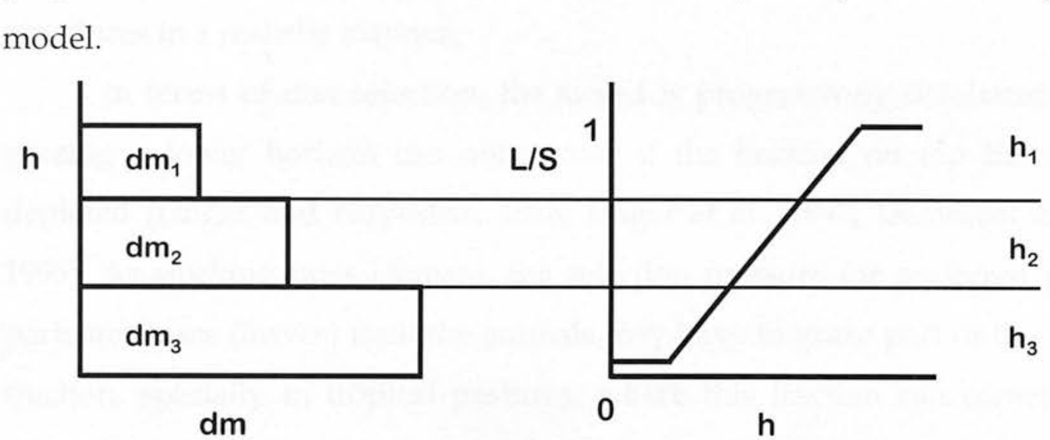
Figure 5.1. Effect of different body weights on the shape of the functional response between green herbage mass and intake at grazing.

The Hurley models did not include a description of variables related to sward structure (i.e. vertical distribution of plant parts, sward height, bulk density) which are known to affect grazing processes. A simple and flexible method was developed using the following simple statements and graphically described in Figure 5.2.

1) A sward with a surface height (swardHT, m) and total herbage mass (Wagt), can be described as a series of j discrete horizons (h_j) of herbage mass dm_j; where, dm_j is composed of variable proportions of leaf and stem (L/S), and dead material. The concept of sward horizons or layers in grassland modelling is well recognised, and is useful for the representation of grazing processes (Stobbs, 1975; Ungar and Noy-Meir, 1988; Ungar et al., 1992; Demment et al., 1995).

2) As h decreases, the amount of dm_j in h_j increases (Figure 5.2a), leading to increased bulk density in the lower sward horizons, as is commonly observed (Stobbs, 1975; Illius and Gordon, 1987; Mayne et al., 1987).

3) As h increases, the leaf/stem ratio (L/S) increases (Figure 5.2b). The proportion of dead material decreases, but it is separately calculated by the model.



a) vertical distribution of herbage mass

b) vertical distribution of plant parts

Figure 5.2. Representation of the vertical distribution of herbage mass and plant parts within a monospecific pasture sward.

Following the nomenclature described above, it is possible to divide the herbage mass (Wag_i) of a sward into 3 horizons as follows:

$dm_1 = WL_1+f_1Ws$ (55)

$$dm_2 = WL_2+Wsh_1+Wsh_2+f_2Ws \tag{56}$$

$$dm_3 = WL_3+WL_4+Wsh_3+Wsh_4+f_3Ws \tag{57}$$

where

f_i the fraction of Ws associated with the plant material in dm_i. Note that the different horizons are related to different categories of plant parts, rather than a specific sward height. This allows the definition of different sward horizons independent of sward height, which varies depending on environmental and management conditions. Horizon height is variable, and therefore, can accommodate differences in bulk density of different sward structures in a realistic manner.

In terms of diet selection, the sward is progressively defoliated and grazing a lower horizon can only occur if the horizon on top has been depleted (Ungar and Noy-Meir, 1988; Ungar et al., 1992; Demment et al., 1995). As stocking rates increase, the selection pressure for preferred plant parts increases (leaves) until the animals may have to graze part of the stem fraction, specially in tropical pastures, where this fraction can sometimes comprise a large proportion of the green herbage mass. Nevertheless, animals will generally prefer to decrease intake rather than having to graze large proportions of stem material (Stobbs, 1975; Chacon and Stobbs, 1976; Hodgson, 1985). It has been suggested that this aversion for the stem fraction is possibly due to physical characteristics such as a higher shearing strength and resistance to defoliation (Laredo and Minson, 1973; Chacón and Stobbs, 1976; Hendricksen and Minson, 1981; Wilson, 1991). Since the functional response of intake with LAI was maintained, then these aspects are implicitly included in the model.

The original Hurley models used selectivity coefficients based on the different categories comprising the LAI. These were adapted, and expressed on the basis of structural components to be able to simulate grazing of the stem fraction. Therefore:

$$grl_i, grs_i = \text{intake} \frac{(nL, nS)_i (WL, Wsh)_i}{\sum_i nL_i WL_i, nS_i Wsh_i} SR \tag{58}$$

where,

grl_i and grs_i represent the structural fractions of leaf and stem removed by grazing, respectively (kg structure/m^2/d)(eqs. 1 - 8).

SR is the stocking density (animals/m^2).

nL_i and nS_i represent different selectivity coefficients for the different categories of plant parts WL_i and Wsh_i. There are 8 of these coefficients, and their values will depend on the pasture species modelled and their different sward structures. In this case, the values of each coefficient changes as the sward is defoliated in sequential horizons.

The flexibility of the modelling structure permits representation of a large number of sward structures since the number of horizons and the type and quantity of plant parts comprising them can be changed without altering the functionality and robustness of the original plant models. At the same time, it has useful attributes in modelling intake and diet selection by different methods.

5.3 Parameterisation

The data required to parameterise the model for kikuyu grass was obtained from the literature (Chapter 3), and where no data were available, specific experiments where designed and carried out to find the parameters required. This section only cites the parameters that were changed from the model, due to their high sensitivity. All other values have been kept as in the original Hurley models. Data for parameterisation can be divided into 4 categories.

5.3.1 *Environmental parameters*

Environmental, as well as soil parameters, are the driving force of the model, since they define the aerial and below ground growing environment and determine the major inputs to the C and N cycles.

From an analysis of 15 years of climatic data from the Poás region (latitude 10.01°N, 4 meteorological stations), it was found that mean daily air temperature ranged from 16.3 to 17.8 °C throughout the year. These data suggested very constant conditions and therefore a mean value of 17°C was used for modelling activities. Mean daily soil temperature was taken to be the same as air temperature (France and Thornley, 1984).

Rainfall was assumed to be non-limiting, as the analysis of 30 years of monthly data showed that average total rainfall was 3440 mm/year and the three driest months had an average rainfall of 110 mm/month. Water relations were not included in the model because calculation of water balance budgets for the Poás region demonstrated that water did not limit plant growth during the mild dry season. Similar observations were made by Babbar and Zak (1994) working in coffee agroecosystems in nearby highland regions. They found that rainfall during the driest months was 89 mm/month, while evapotranspiration was 66 mm/month. Modifications of the model to deal with water stress in dryer agroecological zones are obviously required, and will be included in the future.

Irradiance (I, W/m^2) and daylength (h) were the only two environmental variables considered for simulation due to the lack of measurements from the region, and were calculated using standard methods.

Total global radiation was measured from the hours of bright sunshine recorded by meteorological stations and the Angström formula: -

$$J = R[a + b(n / N)] \tag{59}$$

where

J is the total radiation actually received (J m^2/d).

R is the Angot's value and determines the amount of radiation reaching the earth in the absence of an atmosphere (J/m^2).

n is the actual duration of bright sunshine (h).

N is the maximum bright sunshine on a cloudless day (h).

a and b are empirical constants which depend on the latitude and the climate.

Angot's values (R) were taken from Berkhout and van Keulen (1986) for latitude 10°N. The Meteorological Institute of Costa Rica provided the n monthly values, and the a and b constants for humid tropical zones were obtained from FAO (Frere and Popov 1979). A sine wave was fitted to N figures in Berkhout and van Keulen (1986) as described by Charles-Edwards (1981).

Photosynthetic active radiation (PAR) is the proportion of the light that plants utilise for photosynthetic processes. A standard method of obtaining PAR values from J is by assuming PAR is 0.5J (Charles-Edwards 1982; Johnson and Thornley 1990). The irradiance (I)(W/m^2) which is the radiation actually received by the canopy integrated over the daylength (eqs. 31 - 34), is the main environmental variable driving photosynthesis in the grass growth model. Daylength was estimated using the method described by France and Thornley (1984). Although variations in daylength exist, these are small due to the equatorial latitude (10.1°N) of the Poás region.

Daylength throughout the year is 12 h ± 35 minutes and it does not have a marked effect on seasonal irradiance levels.

5.3.2 *Plant parameters*

These are parameters describing the physiological constants for the species of interest. Data on light response curves, respiration, partitioning of nutrients, responses to temperature, rates of leaf appearance and senescence, and LAI development were required and are described as follows.

Partitioning coefficients (fL). Johnson and Thornley (1985) used a coefficient of 0.7 to define the fraction of new growth partitioned to lamina iin ryegrass pastures. The coefficient was changed to 0.6 following the observations made by Murtagh (1987) and Murtagh et al. (1987) on assimilate partitioning in kikuyu grass.

Canopy extinction coefficient (k). Ludlow (1985) reports extinction coefficients ranging from 0.36 to 0.94 for tropical grasses, while Murtagh (1987) assumed an extinction coefficient of 0.55 in pot experiments with kikuyu. Hodgson (pers. comm.) suggested that the upper part (excluding stolons) of a kikuyu canopy could be treated as that of a ryegrass sward, and Johnson and Thornley (1983) and Ludlow (1985) estimated that k values for ryegrass were between 0.50 and 0.63. Therefore a value of k = 0.60 has been used in the present study.

Temperature at which grass growth ceases (Tc). Tc is very important, since it determines the magnitude of the temperature responses in the model. Johnson and Thornley (1985) used a basal temperature of 0 ^{o}C for ryegrass reflecting the temperate nature of this grass species. Kikuyu grass is a tropical grass species which withstands subtropical temperatures and Ivory and Whiteman (1978a) found that its growth ceased at around 8 °C. Similar basal temperatures were obtained by Colman and O'Neill (1978) in another study.

5.3.2.1 Studies on the physiology of kikuyu grass

Some of the most important changes in the model involved studying the physiology of kikuyu grass due to the lack of existing data (Chapter 4). Three aspects where information was required were studied.

Single leaf photosynthesis of kikuyu grass. Kikuyu grass stolons were brought from Costa Rica to Edinburgh in 1993 and they were planted individually in pots in a glasshouse kept at 20±1°C.

Single leaf photosynthesis was measured on four occasions in three first fully expanded leaves each time. Measurements were done on a LICOR LI-6200 portable photosynthesis system at water vapour pressure deficits of 0.7 kPa with ambient CO_2 levels never exceeding 350 vpm. PAR levels (corrected for light source) varied from 0 to 480 w/m^2. Data were fitted by least-squares (Marquardt algorithm) to the non-rectangular hyperbola described in equation 31 to obtain values for the parameters required. The data fitted accurately ($R^2 = 0.97$), and the values obtained were 1.8×10^{-7} kg $CO_2/m^2/s$, 2.3 $mg/m^2/s$ and 0.87 for alpha, Pmax, and theta, respectively. Figure 5.3 shows the single leaf light response curve obtained.

These results agree with the data of Ludlow (1985) who summarised the results of 11 tropical grasses and found that alpha was 1.7×10^{-7} kg $CO_2/m^2/s$, and that it was not temperature dependent over the range 15 - 40 °C. Similar values for Pmax and theta were found by Johnson et al. (1989) for *Panicum maximum*.

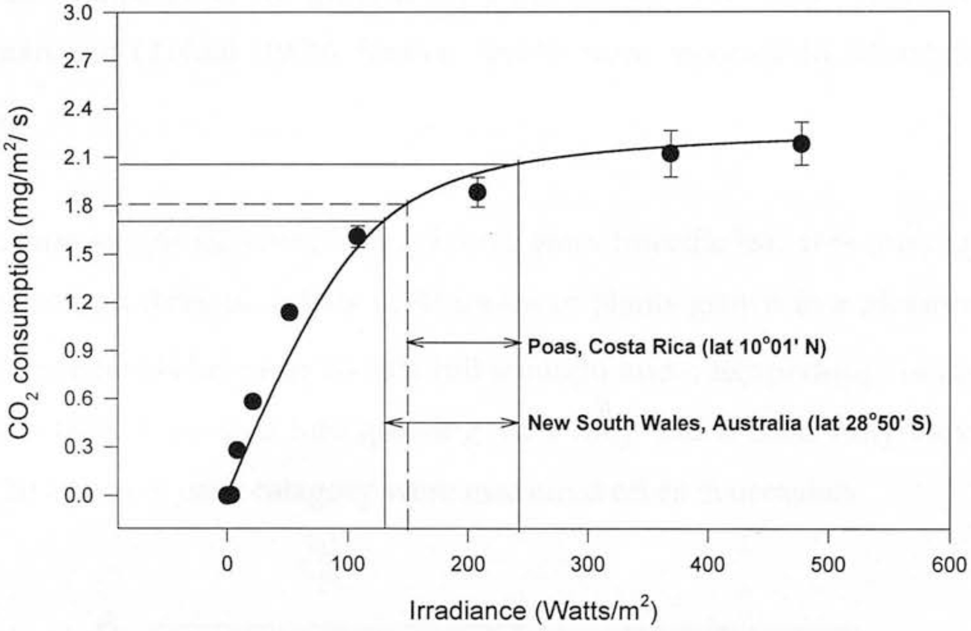


Figure 5.3. Single leaf light response curve of kikuyu grass at 20ºC.

Effects of temperature on rate of leaf appearance. As in Johnson and Thornley's (1985) model the rate of leaf appearance of ryegrass is linearly dependent on temperature and is one of the most sensitive variables controlling yield, a study to investigate the effect of temperature on this parameter in kikuyu grass was carried out.

Eighty kikuyu grass plants grown in the glasshouse were transferred to controlled environment rooms and were kept at temperatures of 15, 20, 25 and 30ºC. Appearance of successive leaves in the same stem was measured daily for 3 experimental periods of 35 days each. The grass was cut at 5 cm between experimental periods. The results can be observed in Figure 5.4. Increasing the temperature decreased the time interval at which one new lamina appeared, and a linear response was observed between 15 and 25ºC. The results at 30ºC were not linear, but they are outside the temperature ranges where kikuyu grass usually grows (see Chapter 3), and is above the optimal temperature for growth (25°C) found by Ivory and Whiteman and Colman and O'Neill (1978). Similar results were reported by Murtagh et al (1987).

Maximum specific leaf area (SLA) of kikuyu grass. Specific leaf area (m^2/kg) was measured on three occasions in 30 leaves of plants grown in a glasshouse at irradiance levels between 70-90% full sunlight and a temperature of 20±1°C. Leaves were separated into growing, first fully and second fully expanded and 10 leaves of each category were measured on each occasion.

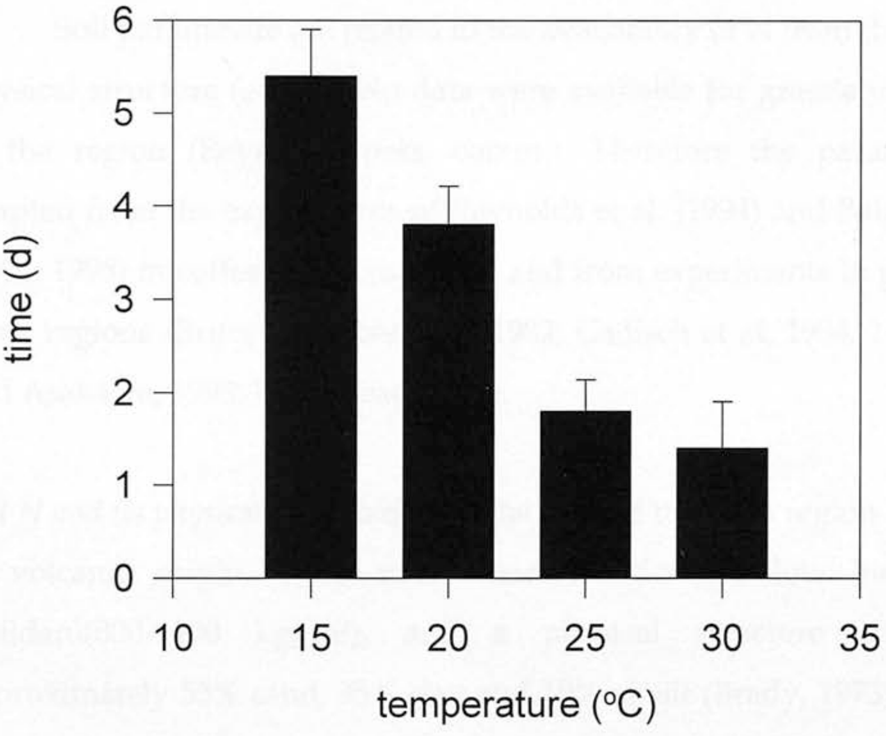


Figure 5.4. Effect of different temperatures on the time taken for one new leaf to appear on the same stem of kikuyu grass.

Results suggest that maximum SLA of kikuyu is around 25 m^2/kg which agrees with the value of 24 m^2/kg used by Murtagh (1988a) for modelling purposes. The highest values were obtained for second fully expanded leaves which are deep in the canopy and received less light while lowest values (21.4 m^2/kg) were obtained for growing leaves. These results are explained by the observations of Ludlow and Wilson (1971) that SLA increases at low light levels, and explain why SLA is dependent on the C substrate concentration of the live structure (Johnson and Thornley, 1985).

5.3.3 *Soil parameters*

Soil parameters are related to the availability of N from the soil and its physical structure (eq. 47). No data were available for grassland ecosystems in the region (Reynolds, pers. comm.). Therefore the parameters were adapted from the experiments of Reynolds et al. (1994) and Babbar and Zak (1994, 1995) in coffee agroecosystems and from experiments in grasslands in other regions (Bruce and Ebersohn, 1982; Cadisch et al. 1994, 1996; Thomas and Asakawa, 1993; Whitehead, 1995).

Soil N and its physical characteristics. The soils of the Poás region are andosols of volcanic origin. Their main characteristics are low bulk densities (soilden)(800-1100 kg/m^3), and a physical structure composed of approximately 55% sand, 35% clay and 10% of silt (Brady, 1973; Babbar and Zak, 1995). A bulk density of 1000 kg/m^3 was used for these studies. These soils exhibit a strong phosphorus fixation (Bertsch, 1986), a N concentration of 0.4 - 0.55%, C:N ratios of 14:1, a pH of <6.0 and a soil organic matter content of 5.5 - 9.0% (Babbar and Zak, 1994). Rooting depth (dr) of kikuyu in these soils was assumed to be 0.8 m (see chapter 4). Based on these data, parameter BN was estimated to be close to 3×10^{-6} kg N/kg dry soil.

Litter degradation. The structural degradation rate of the litter (kdeg) of tropical grasses ranges from 0.0012 and 0.002/d, while that of legumes can be up 0.004 (Bruce and Ebersohn, 1982; Thomas and Asakawa, 1993). The higher value for the grasses, which is similar to the one used by Johnson and Thornley (1985) has been maintained in these studies, as it might reflect better the structural degradation of kikuyu grass.

Excretion from grazing animals. Excretion of N by ruminants is variable, and is dependent on diet quality. The model assumes that N consumed can have 4 fates: it can be incorporated into animal products (meat and/or milk) or microbial matter, or can be excreted in faeces and urine. Calculation of all values can be found in Chapter 6.

There are a number of environmental (eg temperature, rainfall), soil (eg pH, C:N), and plant (eg growth rate) factors that determine the fate of minerals from animal excretions and its incorporation in the soil (see Whitehead, 1995). However, a detailed soil model would be required for their precise calculation (see section 5.6.2. for comments). The model assumes that approximately only 30% of the total N excretions are incorporated in the soil and are available for plant growth, the rest is lost by volatilisation, denitrification and leaching. Justification for this assumption comes from the work of Scholefield et al. (1991) and Whitehead (1995). Similar figures were used by Cadisch et al. (1994) for modelling nutrient cycles in grazing systems in Brazil. Only 25 % of N dung is mineralisable, and since its concentration is low compared to urine, it is not the major source of readily available N from animal excretions. Volatilisation of urine N can be close to 20 - 30%, while denitrification rates of 0.15 - 0.2 kg N/d were cited as common by Whitehead (1995). Leaching losses from urine are probably small and similar to N leaching from other sources, mainly because pastures are not heavily fertilised (< 200 kg N/ha/yr). Babbar and Zak (1995) found leaching losses of approximately 5% of the available N, in highland soils under coffee plantations.

5.3.4 *Grazing parameters*

The most important grazing parameters to modify (eq. 53) were the potential intake of the animals (calculated as described in Chapter 6), and the selectivity coefficients (eq. 58) to distribute the removed plant tissue across the different sward components. Modifications for all other parameters have been explained above.

Since the sward is described in sequentially grazed horizons, the coefficients nL_i and nS_i assume values in Table 5.1.

Table 5.1. Selectivity coeficients for different plant parts of kikuyu grass as defoliation progresses

	h_1	H_2	h_3
nL_1	1.00		
nL_2		0.70	
nS_1		0.15	
nS_2		0.15	
nL_3			0.40
nL_4			0.10
nS_3			0.50

With these values, a similar diet selection pattern to that claimed by Stobbs (1975) and Chacón and Stobbs (1976) is obtained as the sward is progressively defoliated. The stem/stolon fraction can comprise up to 40% of the diet of cattle at high stocking rates. Note that the last stolon fraction (Wsh_4) is not grazed at all ($nS_4 = 0$), since it is believed that it is physically unavailable to the animals. Different diet selection patters of animals of different bodyweight are intrinsically incorporated in the grazing function due to the allometric scaling function.

Sward height was estimated empirically by linear regression from LAI data (Parsons et al. 1994) collected from 5 commercial farms from the Poás region. The relationship, swardHT = 0.059(±0.0023)LAI, explained 61.3% of the variation in sward height ($n = 45$, $p < 0.0001$). Inclusion of a quadratic term or other variables did not improve the accuracy of the predictions.

5.4 Model performance and analysis of management practices

5.4.1 *Herbage mass, responses to fertiliser and sward growth*

The performance of the model was tested in several ways using data from the Poás region and data from various authors.

The data from the Poás region consisted of herbage mass and botanical composition of rotationally grazed paddocks from 4 farms (Herrero et al., unpublished). Unfortunately, since cows were highly supplemented with concentrates (Chapter 2), pasture utilisation was consistently low (15 - 30% GDM) across all farms, thus masking any management effects on pasture production (see below). There was little variation in the pre-grazing instantaneous herbage mass between farms (5.6 - 6.4 t/ha), even when rest periods varied from 25 to 35 days. Nevertheless, model outcomes were within 10% (5.2 - 6.4 t/ha) of the observed results. When the results were expressed on a GDM basis, model outcomes were equally close to the field data (observed 3.6 - 5.2 t/ha vs. predicted 3.2 - 5.0 t/ha). Similar results were obtained when simulating the data of Whitney (1976).

It was shown in Chapter 3, that the efficiency of response of kikuyu grass to N fertiliser ranged from 13 - 27 kg DM/kg N (Mears, 1970; Kemp, 1975; Colman and O'Neill, 1978 and Cook and Mulder, 1984a; Soto *et al.* 1980; Consentino *et al.*, 1985; and Tainton *et al.* 1982). The model was tested up to N fertiliser levels of 400 kg N/ha at temperatures between 10 and 20°C and the responses obtained ranged from 11.7 - 23 kg DM/kg N, which are clearly in the range observed in the literature. The magnitude of the response was dependent on the growth stage of the pasture (see below) and on the basal soil N content. The lower the N content of the soil, the higher the response to applied fertiliser; and the higher the fertiliser application the lower the response to additional N. Both factors are qualitatively correct and the magnitude f the responses agree with the literature.

It is difficult to validate this type of model from a physiological perspective, since data for comparisons are usually scarce. However, Murtagh (1987) and Murtagh et al. (1987) did some experiments on the respiration rate of kikuyu grass, and quoted values of 11 and 15 mg/g/d for specific maintenance respiration rates at 15 and 20°C, while the model predicts rates of 10.1 and 18 mg/g/d, respectively. Another way of testing the physiological responses, was to observe the magnitude of the storage fraction (Ws) relative to the total crop weight. This fraction contributed to less than 10% of the total herbage mass and declined with temperature; which confirms the results of Betteridge (1979), Ito et al. (1985), Marais and Figenschou (1990) and Reeves et al. (1996), who suggested that kikuyu had a low storage/structural carbohydrate ratio. These results suggest that the physiological relations of the C cycle in the model are accurate enough for predictive purposes.

The root sections of the model are also difficult to assess since there is no accurate data. However, Mears and Humphreys (1974a) in an experiment in New South Wales, Australia, included data on root mass and above/below ground plant organs, and found that root mass was generally similar or higher than the above-ground herbage mass, which agrees with the model outcomes. This is due mainly to the structure of the partitioning functions, which try to optimise a balance between both above and below ground organs.

In general terms, estimation of pasture availability was surprisingly accurate and responded realstically to the environmental variables tested, which suggests that the structure of the Hurley models is robust and also convenient for modelling tropical pasture growth in vegetative stages.

5.4.2 *Responses to grazing*

Assessment of the responses to grazing was done by testing the grazing function (eq. 53) and the allometric scaling of parameter K (eq. 54). Simulations were run for swards with green herbage masses close to were intake begins to be limited (1200 - 2400 kg GDM/ha) and with proportions of leaf commonly found in the literature (0.3 - 0.7). Results were obtained for animals ranging from 50 - 800 kg BW in 50 kg increments and response surfaces where constructed to present the results. As stated before, the rational behind using the simple intake function described in these equations derives from the following simple logical statements:

1) The size of the incisor arcade allometrically scales (B = 0.36) with body weight (BW) and is a good predictor of bite mass (BM)(Illius and Gordon, 1987). This claim has been supported with experimental data (Illius, 1989; Gordon et al., 1996).

2) Stobbs (1973) and Hodgson (1985) stated that BM, which is the most sensitive grazing behaviour variable, in most circumstances reflects the variations observed in the herbage intake at grazing (intake) due to changes in variables related to herbage mass (eg. height, leaf mass, LAI, GDM).

3) Therefore, the functional response of intake at grazing also has to scale allometrically to $BW^{0.36}$. Mathematically, this can be simply represented as:

If $\mathbf{BM \cong \mathit{f}BW^{0.36}}$ **and** $\mathbf{BM \cong \mathit{f}intake}$**, then** $\mathbf{\mathit{f}intake \cong \mathit{f}BW^{0.36}}$

Although larger animals are able to consume the stem fraction to a certain limited extent (modified by the density of the lower sward horizons), their intake is more affected as the proportion of leaf (i.e. which reflects LAI, and therefore sward height) is reduced, which agrees with the results of

Stobbs (1975) and Illius and Gordon (1987). Smaller animals have a great advantage due to their higher capacity to graze in shorter swards. Figure 5.5 shows model results for the effects of altering the proportion of green leaf in the sward on the functional response between intake and green herbage mass for animals of different body sizes.

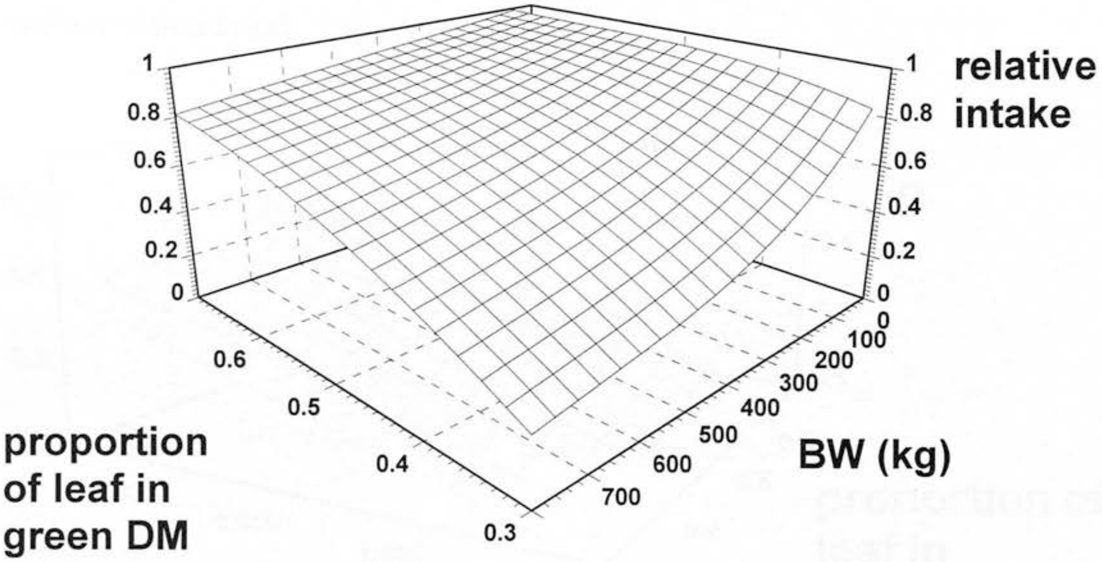


Figure 5.5. Effect of changes in the morphological composition of green DM (@ 1500 kg/ha) on the relative pasture intake of ruminants of different body sizes.

In swards where potential intake can be attained, intake scales allometrically to $BW^{0.75}$ (Brody, 1945; ARC, 1980; Peters, 1983; Illius and Gordon, 1987), while on short swards the allometric coefficient tends to decrease (Illius and Gordon, 1987). However, there might be partial compensation at low herbage masses due to body size differences in diet selection as animals may weight energetic costs and benefits of harvesting plant fractions (Hodgson 1985; Illius et al. 1995), with larger animals being able to graze less selectively (Stobbs, 1975; Gordon et al. 1996). Taking the 0.75 allometric coefficient as the base level, deviations from potential intake were calculated for animals of different body sizes grazing at 5 green herbage masses between 1200 - 2400 kg/ha and 5 proportions of leaf material from 0.3 - 07. Allometric equations, $X= A*BW^B$, were fitted on the deviations from intake for each combination, and the B parameter was graphically represented in Figure 5.6. All equations were fitted accurately ($R^2 = 0.85 - 0.99$), and parameters were obtained with very low coefficients of variation (C.V. < 10%). The A parameter always decreased (0.24 to 0.0008) as the B coefficient increased.

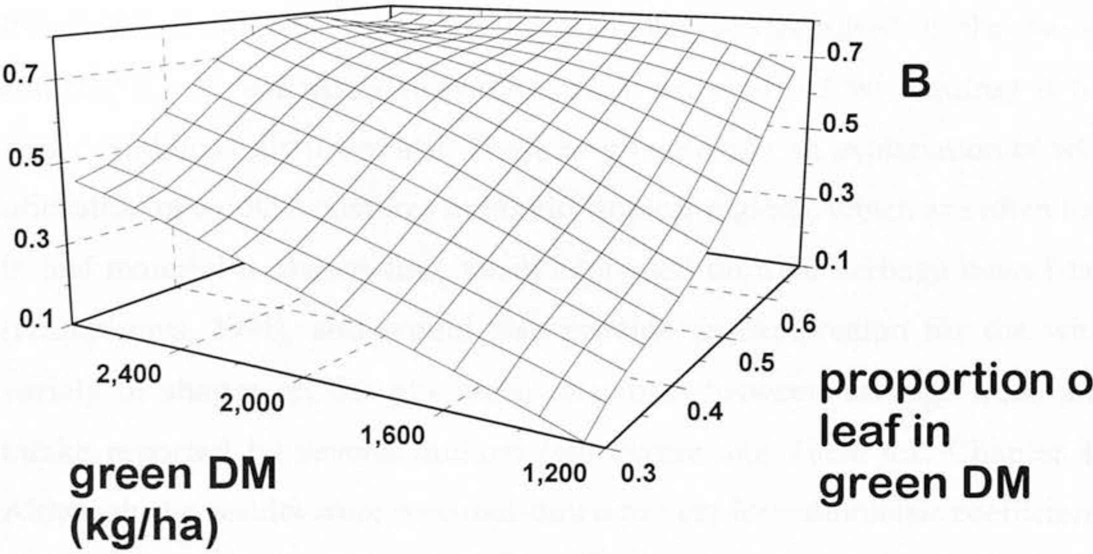


Figure 5.6. Effect of herbage mass and botanical composition on the allometric scaling coefficient (B) of intake of grazing ruminants.

Figure 5.6 is very useful. It demonstrates that the effects of reducing the proportion of leaf in the swards on the allometric coefficient, are greater than the effects of herbage mass per se; and demonstrates why smaller animals can graze at lower herbage masses before reductions in intake occur. This gives further justification to the fact that leaf mass, which is a predictor of sward height or LAI (Penning et al. 1991; Parsons et al. 1994) largely determines the responses of ruminants to grazing (Johnson and Parsons, 1985; Illius and Gordon, 1987; Laca et al. 1992; Flores et al. 1993; Illius et al.

1995), and also explains why studies based on total herbage mass without considering the morphological composition of the sward or attributes representing it (LAI, sward height), often fail to describe grazing processes adequately (Allden and Whittaker, 1970; Hodson, 1986; Ungar and Noy-Meir, 1988).

The response surface in Figure 5.6 is also useful to estimate at what herbage masses, intake stops being proportional to $BW^{0.75}$. Different sward characteristics produce different ways of achieving intakes proportional to $BW^{0.75}$. For example, only 1500 kg GDM/ha are required if the sward contains 0.7 of leaf material, while almost twice would be required if the sward contains only 0.4 of leaf. These results provide an explanation of why utilisation of tropical pastures in humid tropical regions, which are often low in leaf material is always low, when expressed on total herbage mass basis (Humphreys, 1991), and would also provide an explanation for the wide variety of shapes on the functional responses between herbage mass and intake reported by several authors (see Figure and Table 4.2, Chapter 4). Although the results were reported down to very low allometric coefficients (<0.36), it is quite likely that below this level, the forage might be physically unavailable to grazing animals, or animals might be reluctant to graze due to the relative energetic costs of harvesting the material.

This simple equation, provides a major advantage over other empirical relationships between sward characteristics and intake of grazing ruminants. While other relationships (see Chapter 4, Table 4.2) are fixed, have empirical coefficients and are commonly related to total herbage mass, this equation acknowledges the effects of body size and sward morphology on the functional response in a realistic and biologically explainable way. It also links physiologically the resource capture by plants with the grazing process by maintaining the relationship with LAI.

5.4.3 Applications to grassland management.

Several simulations were done to study how sensitive was the regrowth of kikuyu grass to changes in temperature and irradiance, in order to represent kikuyu grass growing in different highland regions or latitudes. In real life, these two effects are very difficult to separate since both variables follow the same seasonal cycle. For example in the subtropics or temperate regions, daylength is shorter (i.e. less irradiance) and temperature is lower at the same time (winter); while in the tropics, high rainfall cannot be separated from high cloud cover (wet season), thus masking possible lower irradiance effects. These limitations simply show the advantages of using simulation models to study independently these effects.

Irradiance. An analysis of solar radiation records from Wollongbar, New South Wales, Australia (lat 28° 50' S)(Murtagh, 1990b) and Poás, Costa Rica (lat 10° 01' N) fitted to the 20 °C light response curve (Figure 5.3.), indicated that solar radiation is unlikely to be a major source of variation in photosynthesis between latitudes, because of the small difference in their seasonal irradiance ranges and the small slope of the light response curve as it reaches its asymptotic value at saturating light levels (PMax). This would explain why Murtagh (1988a) found no significant effect of total solar radiation (300-3000 nm) on kikuyu grass growth rate between 12 and 30 $MJ/m^2/day$ in experiments at Wollongbar.

Temperature. The temperature effects on the regrowth of kikuyu grass can be observed in Figure 5.7. It shows that the rest period of kikuyu grass paddocks should be different at different temperatures if high green herbage masses are required. As temperature increases, the regrowth period should decrease. These results also show that for example, at 17 °C, the year round temperature in Poás, with rotation lengths of more than 25 days, increased senescence and respiration losses would prevent the net accumulation of DM

(Parsons et al. 1983; 1988). These effects are mediated via two processes. First, temperature has a marked effect on the rate of leaf appearance of kikuyu grass (Figure 5.4). The interval required for one new leaf to be produced increases with decreasing temperatures. Second, there is a linear reduction in the asymptote single leaf photosynthesis as temperature decreases. Both processes affect canopy development and light interception and therefore retard dry matter accumulation. These observations point out the need for flexible management strategies depending on the seasonal or regional environmental conditions, and can largely explain latitudinal differences in the production of kikuyu grass.

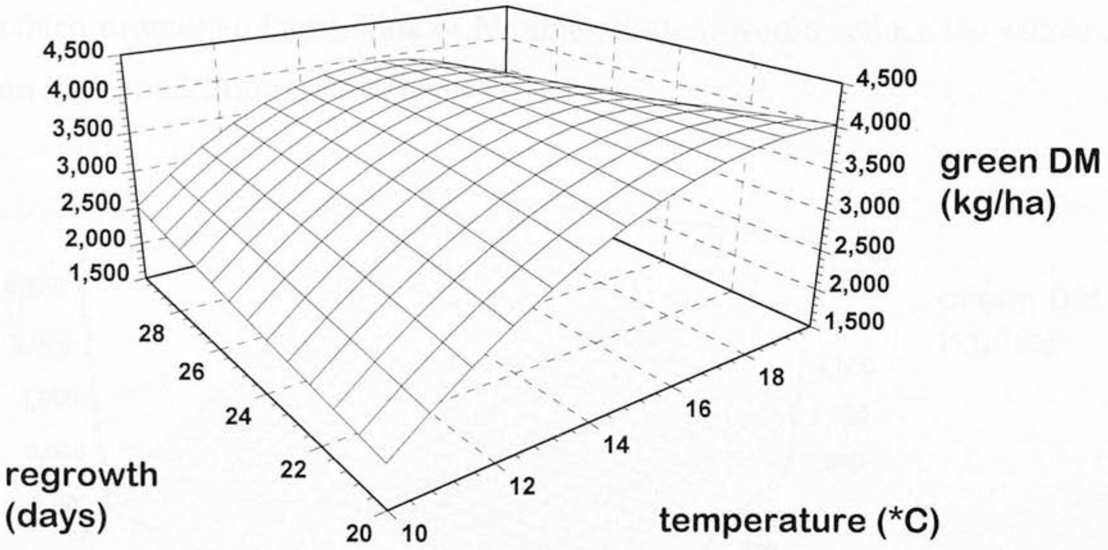


Figure 5.7. Effect of temperature and regrowth period on the accumulation of green DM of kikuyu grass fertilised with 100 kg/N ha.

N Fertiliser use. The model was also used to study responses to N fertilisation. Figure 5.8 shows the green dry matter accumulation of kikuyu grass at different levels of N fertiliser and rest periods. Two important characteristics can be observed. There is a strong interaction between fertiliser use and rest period. The overall effect of N fertilisation is to linearly increase the net growth of the pasture at short regrowth periods, mainly because it promotes LAI development and thus, higher canopy photosynthesis, without the onset of high losses due to increased respiration and senescence. However, as the regrowth period increases, high losses are observed, suggesting that low fertiliser levels should be associated with longer regrowth periods. This suggests that the level of N fertiliser applied plays an important role in determining the length of the rotation. It is important to observe that the contribution of N mineralisation from the soil organic matter is notable in these regions, and relatively high grass yields can be obtained without fertiliser. This is certainly a process that deserves more attention for the development of more sustainable grassland systems. Management practices which promote a higher rate of N mineralisation would reduce the reliance on high applications of inorganic N.

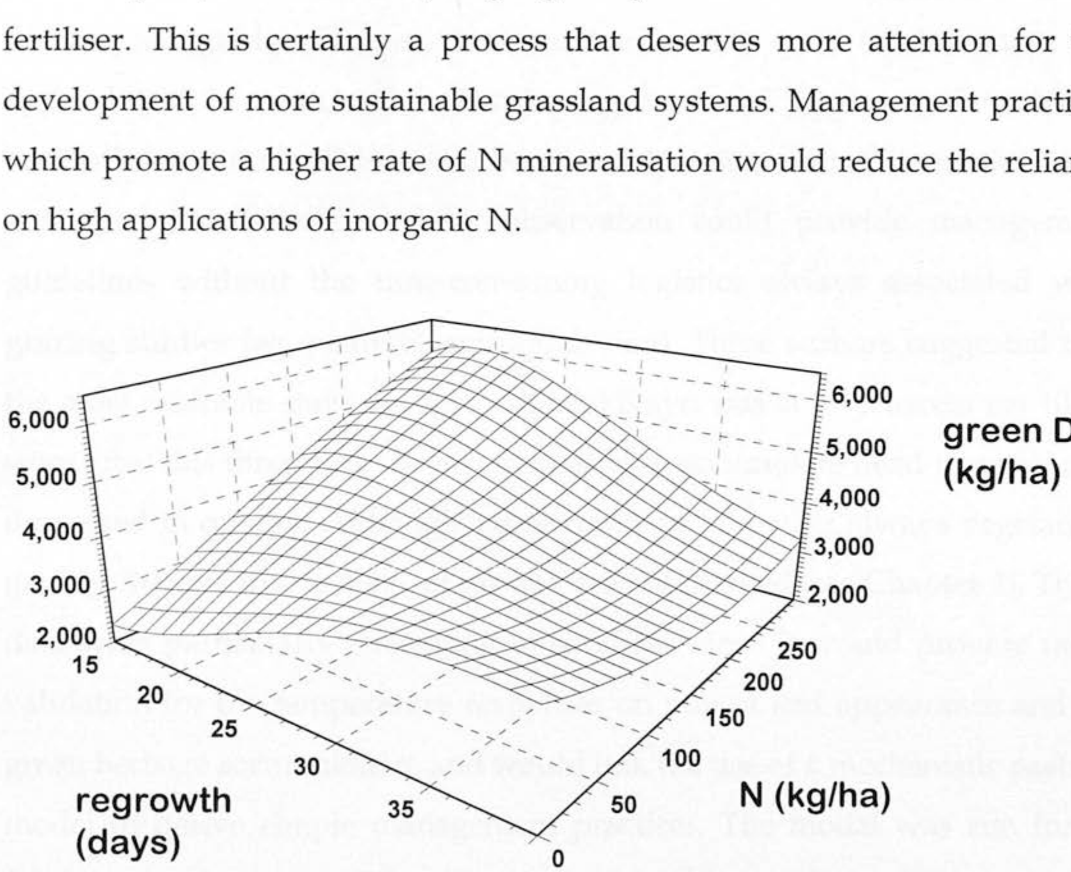


Figure 5.8. Interaction between N fertilisation and regrowth period on the net accumulation of green dry matter of kikuyu grass growth at 17^{O}C.

Nevertheless, delicate balance would exist between keeping the swards in a good state to obtain the desired levels of animal production while optimising plant growth. Another well known option would be the use of legumes, but again, careful management and understanding of the ecophysiology of grass/legume associations is required to ensure their long term success. These compromises need to be studied, and it is clear that mechanisms to select between alternative strategies to optimise several processes simultaneously, while considering farm characteristics and production objectives, are required.

Recent Australian studies (Reeves et al., 1996) have suggested the use of morphological indicators, leaf number in this case, to determine the optimal time to graze, rather than having rotational grazing systems based on fixed rest periods. This would be extremely convenient at farm level, since a simple variable obtained by observation could provide management guidelines without the time-consuming logistics always associated with grazing studies (eg quadrats, cutting, drying). These authors suggested that the most desirable stage of regrowth for kikuyu was at 4 - 5 leaves per tiller, since after this threshold, the sward started to accumulate dead material and decreased in quality. Although, since common kikuyu is always vegetative, quality changes due to stage of growth are not marked (see Chapter 3). These data were particularly interesting to simulate, since it would provide more validation for the temperature responses on rate of leaf appearance and on green herbage accumulation, and would link the use of a mechanistic pasture model to derive simple management practices. The model was run for N fertiliser levels between 0 - 300 kg N/ha and at different temperatures. Results are presented in Figure 5.9.

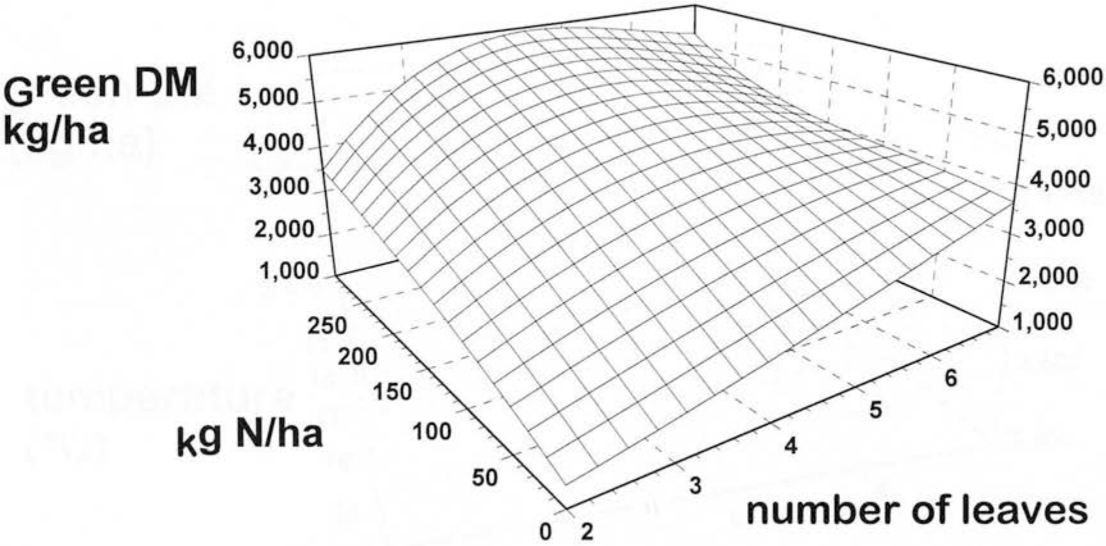


Figure 5.9. The relationship between number of leaves, N fertiliser level and green dry matter accumulation for kikuyu grass grown at 17^{O}C.

The model confirmed the results from Reeves et al. (1996), who used high fertiliser levels. However, an interaction between fertiliser level and optimal number of leaves was found. Without fertiliser, the number of leaves should be close to 7, while above 100 kg N/ha; the simulations suggest that to maximise the net accumulation of green dry matter, kikuyu should be maintained at 4 - 6 leaves, depending on N fertiliser level. Since the effects of fertiliser are to increase the rates of leaf extension, less leaves are required to achieve the same leaf area, thus physiologically explaining why the number of leaves should is reduced as fertiliser levels increase.

This response was also studied at different temperatures (Figure 5.10) in a simulated kikuyu swards fertilised with 150 kg N/ha. The optimal number of leaves was again between 4 - 6, and the range was temperature dependent. Six leaves were required at higher temperatures, mainly because since specific maintenance respiration rates increase with temperature (McCree, 1970; Murtagh et al., 1987), specific leaf areas decrease, thus producing thinner leaves, which when expressed on the basis of leaf number, decrease green dry matter production.

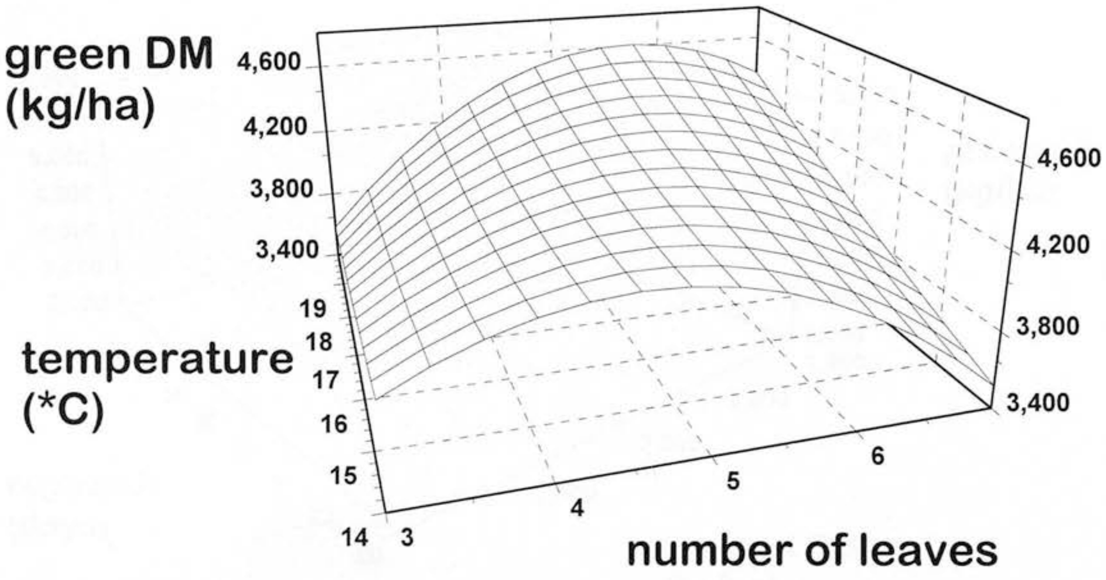


Figure 5.10. The relationship between the number of leaves, temperature and green dry matter of a kikuyu pasture fertilised with 150 kg N/ha.

Grazing intensity. The effect of grazing intensity on the regrowth of kikuyu grass was also studied. Figure 5.11. shows the effect of different levels of green dry matter utilisation on the subsequent growth of a kikuyu sward fertilised with 100 kgN/ha/yr and grazed after 30 days, which would be a common strategy in the Poás region. The model shows that increasing the degree of utilisation of the pastures, as defined by the residual GDM after grazing, has a marked effect on the 30-day regrowth of the sward. Although the final instantaneous amount of green dry matter is relatively similar between the treatments, net growth was higher in the more intensively grazed sward. Similar observations have been made in temperate swards (Parsons et al. 1983, 1988). Since animals remove a greater fraction of the LAI at higher grazing intensities (Johnson and Parsons 1985; Thornley and Veberne 1989), the sward has more scope to regrow without the losses due to senescence or increased respiration associated with higher initial LAIs caused by sward underutilisation (Parsons et al. 1988). This also explains the lack of variation in green herbage mass in farms of the Poás region.

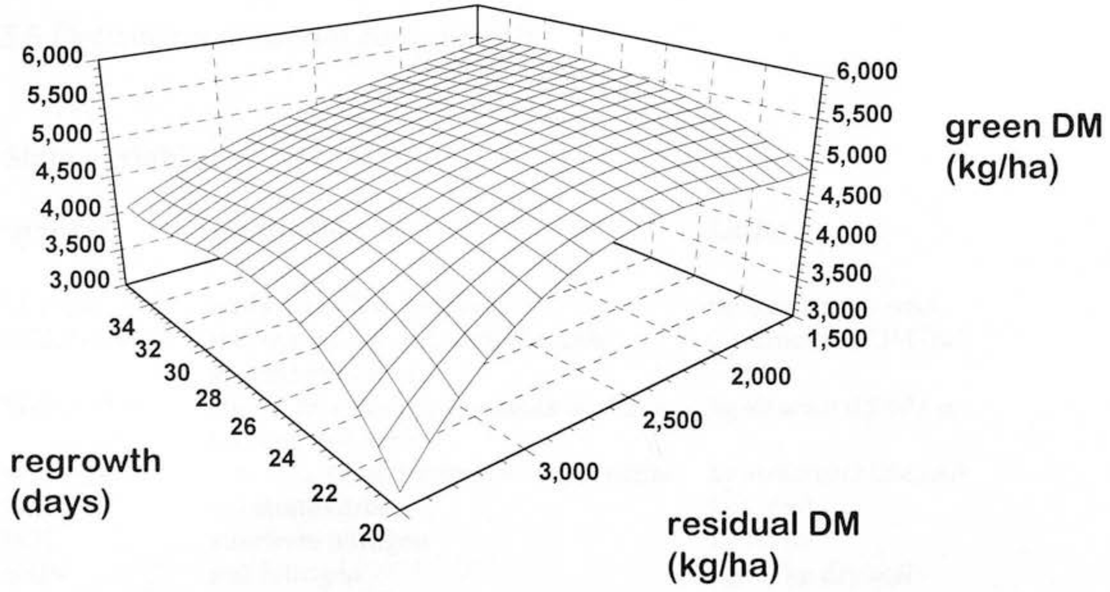


Figure 5.11. Effect of grazing intensity on the regrowth of kikuyu grass.

The importance of the effects of tissue senescence on sward growth have not receive enough attention in tropical grasses (Thomas and Asakawa, 1993) and they require further research, since increases in the efficiency of use of N fertiliser may lead to reduced N applications. For example, in these simulations, all the pastures received the same amount of fertiliser but the net accumulation of material during the 30-day rest period was higher for the more intensively grazed sward, suggesting a better utilisation of the applied N. Reductions in leaching losses would occur if the pasture was maintained at high growth rates (Whitehead, 1995). Options like these have environmental implications that could be studied.

Surprisingly, very little information is available on the physiology of tropical grasses to conduct these type of studies (Ludlow, 1985) and a substantial amount of research needs to be done to gain understanding about their growth habits and responses to grazing. This would possibly lead to better management guidelines, as has been the case with temperate species (Parsons et al. 1988, Fulkerson and Slack 1994, Wilkins 1995).

5.5 Definition of model components

State variables

Symbol	Definition	Units
Li, i=1-4	leaf area index components	m^2 leaf/m^2 ground
WLi, i=1-4	leaf lamina components of above ground structure	kg structural DM/m^2
Wshi, i=1-4	sheath and stem components of above ground structure	kg structural DM/m^2
Wr, i=1-4	root structural dry matter components	kg structural DM/m^2
WC	substrate carbon	kg C/m^2
WN	substrate nitrogen	kg N/m^2
SoilN	soil nitrogen	kg N/kg dry soil

Other variables

Symbol	Definition	Units
P	total daily photosynthetic input	kg C/m^2/d
PC	canopy gross photosynthesis	kg CO2/m^2 ground/s
Pg	single leaf gross photosynthesis	kg CO2/m^2 leaf/s
Pmax	light saturated single leaf gross photosynthesis	kg CO2/m^2 leaf/s
LAI	leaf area index of the sward	m^2 leaf/m^2 ground
SwardHT	sward surface height	m
C	substrate carbon concentration	kg C/kg structural DM
N	substrate nitrogen concentration	kg N/kg structural DM
DC, DN	supply of substrate C and N from degraded structure	kg C and N/m^2/d, respectively
fr, fsh	fraction of root and shoot dry matter	
Gr, Gsh	rate of production of new root and shoot structure	kg structural DM/m^2/d
Wagt	total live crop structural DM	kg structural DM/m^2
WL	total live leaf structural DM	kg structural DM/m^2
Wsh	total stem structural DM	kg structural DM/m^2
Wdead	total senescent structural DM	kg structural DM/m^2
Wag	total above ground structural DM	kg structural DM/m^2
Wr	total root structural DM	kg structural DM/m^2
Ws	storage substrate dry weight	kg storage DM/m^2
LAMBDAsh	partitioning function for shoot production	

LAMBDAr	partitioning function for root production	
G	growth coefficient	/d
Rm	maintenance respiration rate	kg C/m^2/d
Rg	growth respiration rate	kg C/m^2/d
Rn	respiration cost of N uptake	kg C/m^2/d
UN	nitrogen uptake rate	kg N/m^2/d
I	instantaneous light flux density, irradiance	W/m^2 leaf
SLA	specific leaf area	m^2 ground/kg leaf
Phi	fraction of recycled senescent degradable structure	
PT	teleonomic partitioning function between above and below ground structure	
PropL	live leaf as a proportion of total DM	
PropS	live stem as a proportion of total DM	
PropDead	dead material as a proportion of total DM	
An	N application rate	kg N/m^2
dm1	green DM in sward horizon 1	kg DM/ha
dm2	green DM in sward horizon 2	kg DM/ha
dm3	green DM in sward horizon 3	kg DM/ha
GDM	total sward green DM	kg DM/ha
GC	flux of substrate C to grazing	kg C/m^2 ground/d
GN	flux of substrate N to grazing	kg N/m^2 ground/d
grL_i, gs_i, i=1-4	flux of lamina structural DM to grazing	kg structural DM/m^2/d
$gareaL_i$, i=1-4	flux of lamina area to grazing	m^2 leaf/m^2 ground/d
$gdmL_i$, i=1-4	flux of lamina DM to grazing	kg DM/m^2/d
Animals	stocking density	animals/m^2
GrazeK	half life of LAI	
intake	pasture intake	kg DM/d/animal

Parameters

Symbol	Definition	Value	Units
Plant			
alpha	light utilisation efficiency	0.00000018	kg CO$_2$/J
theta	leaf photosynthesis parameter	0.87	
k	canopy extinction coefficient	0.6	
FN	fractional N in live structure	0.025	kg N/kg live structure
FNd	fractional N in degradable structure	0.015	kg N/kg deg. structure
FC	fractional C in live structure	0.5	kg C/kg live structure
FCd	fractional C in degradable structure	0.45	kg C/kg deg. structure
tau	leaf transmission coefficient	0.1	
Y	yield factor for structural growth	0.75	
RN	respiration cost of N uptake	0.5	kg C/kg N
v_I, i=2,3,4	root activity weighting parameters	0.5, 0.25, 0.1	
ISLAmax	maximum specific leaf area	25	m^2/kg structure
FL	fractional new growth partitioned to	0.6	

	lamina		
MC	molecular mass of sucrose relative to C	28.5	
MN	molecular mass of nitrate relative to N	62	
pm20	light saturated gross photosynthetic rate at 20°C	0.0000023	kg CO_2/m/s
GAMMAr(20)	fractional rate of root turnover	0.05	/d
$Mr_i(20)$, $Msh_i(20)$, i=1-4	fractional maintenance coefficients of root and shoot structural components	0.02, 0.02, 0.015, 0.01	/d
KC, KN	root activity parameters	0.05, 0.005	
G(20)	growth coefficient at 20°C	150	/d
Kdeg	structural degradation parameter	0.002	/d
Islap	incremental specific leaf area parameter	2.5	

Environment and management

An	N fertiliser application		kg N/ha/yr
N applications	number of fertiliser applications		applications/yr
stocking rate	stocking rate		animals/ha
grazing area	land available for grazing		ha
rest period	rest period for grazing paddocks		d
T	air temperature		°C
Tc	temperature at which growth ceases	8.0	°C

Soil

dr	rooting depth	0.8	m
soilden	soil bulk density	1000	kg/m^3
beta	fractional rate of leaching	0.05	/d
Bn(20)	inorganic soil N at 20°C	0.000003	kg N/kg soil/d
sigma(20)	root activity parameter	3000	kg soil/kg root structure

Animal and grazing

BW	bodyweight		kg
imax	potential intake		kg DM/d
nL_i,nS_i i=1-4	intake selectivity coefficients for different compartments		
q	intake parameter	3	

Chapter 6

Modelling intake, digestion and animal performance from ruminants

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Chapter 6

Modelling intake, digestion and animal performance from ruminants

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6.1 Introduction

The present chapter describes a simulation model for predicting potential forage intake, digestion and animal performance from ruminants. As discussed in Chapter 4, this is one of the central components of any grazing systems model, since the effect of alternative nutritional strategies on animal production and on the whole system can only be tested if forage intake and the subsequent responses to available nutrients by ruminants can be predicted.

The main idea behind the construction of this model was to produce a flexible tool incorporating recognised theoretical principles, but at the same time, driven by variables easily obtainable at farm level. The outcome was a dynamic 'hybrid model' based on a mechanistic platform but with site-specific parameters, and resulted from adapting approaches used in previously published models across a range of levels of aggregation. Empirical representations of some processes were used, where the level of detail required for an adequate theoretical and mathematical representation was beyond the objectives of the present study, and where it would have been impractical for decision-support at farm level. The validity and necessity of using this approach for model-building have been discussed in Chapter 1.

6.2 Model description

6.2.1 *General characteristics*

The model is designed to predict potential intake, digestion and animal performance of individual ruminants, in this case dairy cows, consuming forages, grains and other supplements. The rationale behind the model is that a ruminant of a given body size, in a known physiological state, and with a target production level, will have a potential forage intake determined by physical or metabolic constraints imposed, both, by plant and animal characteristics. Potential forage intake is defined as the intake achievable without the constraints imposed by herbage mass, sward characteristics, or behavioural limitations (see Chapter 5).

The model assumes that the reticulo-rumen is the most important site of the gut controlling intake, and that intake can be estimated from the knowledge of degradation and passage of feeds through this organ (Illius and Gordon, 1991).

The model was largely derived from the work of Illius and Gordon (1991, 1992), Sniffen et al. (1992)(Cornell Net Carbohydrate and Protein System, CNCPS) and AFRC (1993). It was implemented in SB-ModelMaker V2.0 (Zeton Tech, Nottingham, UK), and can be divided into two functional sections:

1) A *dynamic* section, which describes the flow and digestion of feeds through the gastrointestinal tract and its consequent nutrient supply to the animal. This section consists of a series of first-order differential equations estimating intake, the pool sizes of feed fractions in the rumen, small and large intestines of the animal, the pools of digested material and excretion of indigestible residues. This section runs on an hourly basis, but results are aggregated to a day (24 h) for an appropriate coupling to the *static* section of the model. An hourly model has been used, since, as described in Chapter 4,

this is the adequate time scale to represent digestion and passage of feeds through the gut of ruminants (Waldo, 1972; Mertens and Ely, 1979; Ørskov and McDonald, 1979; Sniffen et al., 1992; Illius and Allen, 1994).

2) A *static* section which estimates potential nutrient requirements of the animal, mainly on the basis of AFRC (1993; readers are referred to this publication for a complete description of this system). The difference with AFRC (1993), and the similarity with the CNCPS, is that the model predicts animal performance on a daily basis from the estimates of intake and nutrient supply obtained from the *dynamic* section of the model. This is a major step from requirements systems (i.e. INRA, 1989; NRC, 1989, 1996; AFRC, 1993), where animal performance is predicted from digestible of metabolisable energy estimates of feeds and intake 'predictions' are obtained from linear or multiple regressions (i.e. NRC, 1989, 1996; SCA, 1990; AFRC, 1993). The model of Sniffen et al. (1992), estimates nutrient supply from a dynamic model of digestion, however, they still use regression equations for intake prediction. Unfortunately, this reduces the flexibility and accuracy of their model when extrapolating to other situations.

Two pathways controlling intake were used in the model. The first one was the physical constraint on intake caused primarily by low digestibilities; while the second one was a simple metabolic constraint. If the supply of nutrients equalled the requirements of the animal, the animal stopped eating.

6.2.2 *Feed fractions and their digestion and passage through the gut*

6.2.2.1 Feed fractions

A description of parameters used in the model can be found in section 6.4. Feeds are described by 4 main constituents: ash, fat, carbohydrate and protein. The dynamic section of the model focuses on the carbohydrate and protein fractions, which are further divided into soluble, insoluble but potentially digestible and indigestible (Ørskov and McDonald, 1979; AFRC, 1993).

For the ith feedstuff, the carbohydrate fractions represent non-structural carbohydrates ($CELLCC_i$), potentially digestible cell wall ($DNDF_i$), and the indigestible residue ($INDF_i$). For concentrate feeds, the proportion of starch (starchconc) in the $CELLCC_i$ is also required (Sniffen et al., 1992). Starch and fat in forages are almost negligible (Minson, 1990), but they can be important fractions in grains (Istasse et al., 1986; Ørskov, 1992).

The protein fractions described here are the same as those estimated in the metabolisable protein (MP) system proposed by AFRC (1993), with the difference that their representation in this model is dynamic. For example, the pools of soluble protein ($SOLCP1_i$), degradable protein ($DEGCP1_i$) and undegraded protein ($UNDEGCP1_i$) represent the terms quickly (QDP) and slowly (SDP) degraded crude protein, and undegraded (UDP) crude protein of the AFRC (1993) MP system, respectively.

6.2.3 *Forage intake and digestion and passage through the rumen*

The representation of intake, digestion and passage of feed fractions was adapted from Illius and Gordon (1991). Dry matter intake (DMI) over a 24 h period is determined by the clearance of digesta from the rumen due to degradation and passage. Once the total rumen load equals the maximum rumen capacity of the animal, it stops eating. A meal recommences when 70% of the rumen load has been cleared (Illius and Gordon, 1991). Sensitivity analysis showed that alterations to this threshold value for recommencing a meal did not alter the daily intake estimations from the model. The maximum rumen capacity (Maxrumen, kg DM) is determined from the bodyweight (BW) of the animal as derived by Illius and Gordon (1991):

$$\text{Maxrumen} = 0.021\ \text{BW} \tag{1}$$

The rumen load (RumenDM, kg DM) is the sum of the pool sizes of the different feed fractions plus the microbial DM pool:

$$\text{RumenM} = \sum_{i} \text{CELLCC1}_1 + \text{DNDF1}_1 + \text{INDF1}_i + \text{SOLCP1}_i + \text{DEGCP1}_i + \text{MICROBES} \tag{2}$$

where the pool sizes of feed constituents in the rumen are:

$$\frac{\text{dCELLCC1}_i}{\text{dt}} = \sum_{i} \text{Intake rateCC}_i - \text{k1}_i\text{CELLCC1}_i - \text{k0CELLCC1}_i \tag{3}$$

$$\frac{\text{dDNDF1}_i}{\text{dt}} = \sum_{i} \text{Intake rateDNDF}_i - \text{k2}_i\,\text{DNDF1}_i - \text{k3}_i\,\text{DNDF1}_i \tag{4}$$

$$\frac{\text{dINDF1}_i}{\text{dt}} = \sum_{i} \text{Intake rateINDF}_i - \text{k3}_i\,\text{INDF1}_i \tag{5}$$

$$\frac{\text{dSOLCP1}_i}{\text{dt}} = \sum_{i} \text{intake rateSCP}_i - \text{k5}_i\,\text{SOLCP1}_i\,\text{kQDP} - \text{k0SOLCP1}_i \tag{6}$$

$$\frac{\text{dDEGCP1}_i}{\text{dt}} = \sum_{i} \text{intake rateDCP}_i - \text{k6}_i\,\text{DEGCP1}_i - \text{k3}_i\,\text{DEGCP}_i \tag{7}$$

$$\frac{dUNDEGCP1_i}{dt} = \sum_i \text{intake rateUDCP}_i - k3_i\,UNDEGCP_i \quad (8)$$

The terms CC_i and SCP_i represent soluble carbohydrate and protein concentrations in the ith feedstuff, respectively. $DNDF_i$ and DCP_i represent insoluble but degradable cell wall and CP, respectively; while $INDF_i$ and $UDCP_i$ are indigestible residues of cell wall and CP. All have units g/kg DM and can be estimated using the appropriate solubility (A) and potential degradability (B) coefficients from *in vitro* or *in sacco* degradation kinetics studies, as described by the standard procedures of Ørskov and McDonald (1979) and McDonald (1981) (see Chapter 4).

The fractional rate constants $k1_i$ and $k5_i$, represent the digestion rates of soluble carbohydrate and protein, respectively; while $k2_i$ and $k6_i$ represent those of the potentially digestible cell wall and protein. Note that equation 6 contains the term kQDP which is the efficiency of utilisation of soluble N (AFRC, 1993). Rate k0 is the liquid passage rate. $K3_i$ is the passage rate of the digestible cell wall fraction, which represent mostly small particles and is applied to both the digestible and indigestible fractions. Outflow of soluble protein is similar to the liquid passage rate (k0). Rumen passage rates of degradable and undegradable protein ($k7_i$) are similar to the passage rates $k3_i$, (Ørskov, 1992; 1994).

The model includes a lag phase (h) before fermentation of the cell wall fraction begins. This is calculated from the model of McDonald (1981) to in sacco or in vitro degradation data.

Degraded material in the rumen (RD) is accumulated in the pools of digested carbohydrate and protein. These later become the major source of energy supply to the animal:

$$\frac{dRDCELLCC1_i}{dt} = \sum_i k1_i\,CELLCC1_i \quad (9)$$

$$\frac{dRDIGNDF1_i}{dt} = \sum_i k2_i\, DNDF1_i \qquad (10)$$

$$\frac{dRDSOLCP_i}{dt} = \sum_i k5_i\, SOLCP1_i\, kQDP \qquad (11)$$

$$\frac{dRDIGCP_i}{dt} = \sum_i k6_i\, DEGCP1_i \qquad (12)$$

6.2.4 *Digestion in the small and large intestines*

Feed material escaping ruminal digestion flows to the small and large intestines. Amounts of soluble carbohydrate and nitrogen escaping digestion in the rumen are small, since they are immediate nutrient sources for rumen microbes (Baldwin et al., 1977, 1987). However, if they pass the rumen, they are subsequently fully digested in the small intestine (Ulyatt et al., 1975; Illius and Gordon, 1991; Ørskov, 1992). In the model they are described, respectively, by:

$$\frac{dSIDCELLCC1_i}{dt} = \sum_i k0CELLCC1_i \qquad (13)$$

$$\frac{dSIDSOLCP1_i}{dt} = \sum_i k0\; SOLCP1_i \qquad (14)$$

The only components that enter the large intestines are potentially degradable and undegradable residues of carbohydrate and protein that escaped ruminal digestion, and rumen microbes. Exceptions to this rule occur with feeds, especially grain supplements, containing large proportions of bypass protein, starch or fat (NRC, 1989; AFRC, 1993). The pool sizes of carbohydrate and nitrogen in the large intestine are:

$$\frac{dDNDF2_i}{dt} = \sum_i k3_i DNDF1_i - k2_i DNDF2_i - k4_i DNDF2_i \qquad (15)$$

$$\frac{dINDF2_i}{dt} = \sum_i k3_i INDF1_i - k4_i INDF2_i \qquad (16)$$

$$\frac{dDEGCP2_i}{dt} = \sum_i k3_i DEGCP1_i - k6_i DEGCP2_i (1 - k8_i) \qquad (17)$$

$$\frac{dUNDEGCP2_i}{dt} = \sum_i k11_i UNDEGCP1_i - k6_i UNDEGCP2_i \qquad (18)$$

where, $k2_i$ and $k4_i$ are the digestion and passage rates of cell wall and residues in the large intestine, and $k8_i$ is the digestion rates of undegradable N entering the large intestine. Note that $k2_i$ is the same for rumen and large intestine (Illius and Gordon, 1991). All others have been previously defined. The pools of digested cell wall ($LINDF2_i$) and N ($LIDCP_i$) in the large intestines then become:

$$\frac{dLINDF_i}{dt} = \sum_i k2_i DNDF2_i \qquad (19)$$

$$\frac{dLIDCP_i}{dt} = k1_i \, DEGCP2_i \tag{20}$$

The final residual compartments are:

$$\frac{dCEXCRETION_i}{dt} = \sum_i k4_i \, INDF2_i + k4_i \, DNDF2_i \tag{21}$$

$$\frac{dNEXCRETION_i}{dt} = \sum_i k6_i \, UNDEGCP2_i + k6_i \, DEGCP2_i (1 - k8_i) \tag{22}$$

6.2.5 *Estimation of the rates of passage*

One of the crucial elements determining the accuracy and flexibility of the model is the estimation of the rates of passage. Passage rate estimates are not easy to find in the literature, and it would be a real disadvantage if these needed to be provided by the user of the model. The approach of Illius and Gordon (1991) was chosen, since it predicts the passage rate estimates of animals of different body sizes by allometric scaling rules. This method is particularly useful for decision-support models because a generic description of a ruminant is provided, rates are adjusted according to animal size, and fundamentally, they are predicted from easily collectable observations.

However, the model does not consider explicitly particle dynamics and a simpler model was derived from Illius and Gordon (1991). This simpler description is a summary model, and was obtained by implementing the Illius and Gordon (1991) model, and calculating independently the contribution of large particles and small particles to passage of their proportional rumen dry matter contents. According to Illius and Gordon (1991), the proportion of large particles entering the rumen is 0.66 and the rest are small particles. Since large particles are also comminuted to small particles, their real contribution to passage is small (Kennedy and Murphy, 1988). Therefore the composite passage rate was inherently corrected for comminution and reflected largely the passage rate of the small particles. The model was run for bodyweights from 50 - 800 kg and for INDF concentrations of 0.2 - 0.6. The results demonstrated that a composite passage rate of 0.95*k3 gave quite similar intake results to the original model (see below). The effects of bodyweight and INDF on large particle passage rate were very small (the coefficient changes from 0.94 - 0.960, since the largest effects were absorbed in the comminution corrected passage of small particles. The same allometric equations for estimating body size effects on passage were used.

For example, whole tract mean retention time (MRT, h) is scaled to body weight by the equation:

$$\mathrm{MRT} = 14.1\mathrm{BW}^{0.27}, \; r^2=0.76 \qquad (23)$$

The rumen (k3i) and large intestine (k4i) passage rates of small particles of digestible cell wall are then estimated from the MRT as:

$$k3_i = \frac{1}{0.75\mathrm{MRT}} + \mathrm{FLscaling} \qquad (24)$$

$$k4_i = \frac{1}{0.2\mathrm{MRT}} \qquad (25)$$

Feeding level affects ruminal passage rates of carbohydrate and protein fractions (Eliman and Ørskov, 1984; NRC, 1989; Sniffen et al., 1992; AFRC, 1993). Illius and Gordon (1991) did not estimate feeding level effects on passage rates. Therefore, a scaling rule for feeding level (FLscaling) was derived from the data of Sniffen et al. (1992) and applied to the predicted passage rates:

$$\text{FLscaling} = 0.25\text{FLk}_i \qquad (26)$$

where FL = feeding level expressed as multiples above maintenance and k_i the rate constant predicted by the model, to be scaled.

The liquid passage rate (k0) was estimated from the composition of the basal forage diet and the body weight of the animal as:

$$\text{k0} = (-0.0487 + 0.176\text{CC}_{\text{forage}} + 0.145\text{DNDF}_{\text{forage}} + 0.0000231\text{BW}) + \text{FLscaling} \qquad (27)$$

For concentrate feeds, the model estimates the rates of passage as described by Sniffen et al. (1992) from the equivalent rates for the basal forage diet ($\text{ki}_{\text{forage}}$). This applies to rates $k3_i$ and $k4_i$, and the equations have the following form:

$$k_i = [-0.424 + (1.45 * (\text{ki}_{\text{forage}} * 100))] / 100 \qquad (29)$$

where k_i is the respective rate to be calculated.

Intake was also adjusted for ambient temperatures as in SCA (1990). If temperature exceeded 25°C, potential intake is reduced by 2% per 1°C in *Bos taurus* breeds, by 1% in *Bos taurusXBos indicus* crosses and no adjustment is made for *Bos indicus* breeds.

6.2.6 Nutrient supply from digested feed fractions.

The pools of digested nutrients obtained from the model were used to calculate the supply of nutrients, namely metabolisable energy (ME) and protein (MP), to the animals. In terms of energy, three main sources were available: fermentable ME from the rumen, which was by far the largest pool; energy obtained from the digestion of carbohydrates in the lower intestines, and the energy associated with true protein coming mostly from microbial production.

Some assumptions were made to simplify the model. Czerkawski (1986) and Preston and Leng (1987) reported that between 10 - 30% of fermented OM was not available for VFA production and was partitioned towards microbial matter. The values fluctuate because it is well known that microbial efficiency is not constant (Leng, 1982; Czerkawski, 986). In the model, this partitioning was fixed and a conservative estimate of 20% has been taken, since this represents a typical figure for moderately energy supplemented animals consuming tropical forages (Preston and Leng, 1987). A more detailed mathematical representation would probably be required to simulated partitioning adequately and maybe more than one microbial pool would be necessary to reflect different substrate utilisation by microbes (Illius and Allen, 1994; Baldwin, 1995). These aspects are acknowledged but beyond the scope of this model.

The rest of rumen digested organic matter (0.8) was used for volatile fatty acid production (VFA). The stoichiometric calculations of Murphy et al. (1982) and Gill et al. (1990) were used for the calculations of VFAs produced, while energy release from VFAs was estimated with the enthalpies of combustion presented by Blaxter (1989).

Digested material in the lower intestines contributed to the pool of available energy, and calculations were done as in AFRC (1993) assuming a gross energy value of 18.4 MJ/kg DM. The energy value of true protein was obtained from Blaxter (1989). All results were multiplied by 0.81 to express them on the basis of metabolisable energy for a proper interface with the requirements system of the model, which was left as it is described in AFRC (1993).

The effects of low pH caused by feeding grain supplements to ruminants consuming forage diets (eg Istasse et al. 1986; Ørskov, 1988) was incorporated using the empirical relationship proposed by Argyle and Baldwin (1988). According to these authors, the digestion rate of the cell wall fraction diminishes linearly below pH 6.2; and ceases at around pH 5.4. Similar figures were reported by Sniffen et al. (1992). Interaction between forages and supplements was obtained with this relationship.

Explicit protein:energy interactions were not modelled in this study, since it was believe that the complexity of the model would have increased substantially. Nevertheless, these interactions are useful especially when protein is limiting nutrient, which is not the case with kikuyu grass. An adequate rumen environment is thought to be achieved at ERDP:FME ratios of at least 9:1 (Oldham 1984) and this figure would be used for correcting diet that do not achieve this minimum threshold (Ørskov, 1992). The model could be adapted to more explicitly represent this interaction if simple methods were available. Certainly, these interactions would need to be considered more explicitly if diets were N substantially N limited.

6.3 Parameterisation and validation results

The parameterisation and validation of the model was done in two stages. Although it was less extensive than the other parts of the DSS since, these sections came from previously validated models.

The intake section of the model was tested first with data from 23 tropical and temperate forages presented by Minson (1972); Laredo and Minson (1973); Soto et al. (1980); Koster et al. (1992); Stensig et al. (1994) and

Shem et al. (1995). Body weight ranged from 36 - 750 kg, while NDF varied from 446 - 881 g/kg DM, with potential digestibilities and cell wall rates of degradation of 0.4 - 0.78 and 0.016 - 0.083/h. Protein was nonlimiting in all situations and therefore average parameters for grasses were used (see below). The results are presented in Figure 6.1.

Since the primary intake sections of the model were directly derived from the previously validated Illius and Gordon (1991) model, it was not surprising that model performance was relatively similar. The model explained 65% of the variation in observed intakes, with a mean prediction error of 7% (± 4.72 g/kg $BW^{0.75}$). The model was slightly biased towards overestimating intake at high observed intakes, and this is probably due to the simplification of the model in the estimation of passage rates. In terms of sensitivity of the quality variables, the most sensitive variables were the cell wall concentration and its potential degradation, which is also in line with the observations of Illius and Gordon (1991).

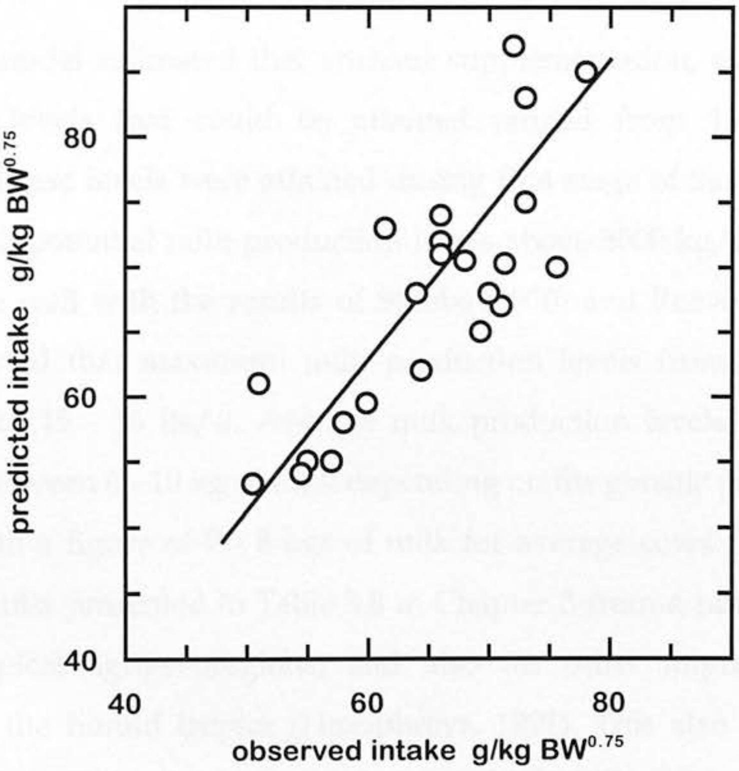

Figure 6.1. Observed vs. predicted intakes of 23 forages.

The animal performance section of the model was tested with data from kikuyu grass presented in Chapter 3. Parameterisation of the model was not straightforward, since apart from work carried out by Herrero et al. (1996, 1997) and Herrero and Jessop (1996) (see Appendix 2); only <u>one</u> of the references (Koster et al. 1992) cited, contained fermentation dynamics data for kikuyu grass; recognising the need for more research into the nutritional characterisation of forages. Unfortunately, these authors failed to describe the potential degradation accurately due to lack of data points at the late stages of fermentation. They stopped the incubations at 48 h. Therefore, average parameters for carbohydrate degradation of kikuyu grass obtained by Herrero et al. (1996) were used for these simulations. For nitrogen, Hart and Leibholz (1990) determined that potential N degradability of kikuyu grass was 0.8, which agrees with the data presented by AFRC (1993) and Sniffen et al. (1992). All parameters used for the simulations are presented in section 6.4.

The model estimated that without supplementation, maximum milk production levels that could be attained ranged from 15.1 - 16.7 kg milk/cow. These levels were attained during first stage of lactation only by animals with potential milk production levels above 5000 kg/lactation. This agrees quite well with the results of Stobbs (1970) and Reeves et al. (1996) who suggested that maximum milk production levels from kikuyu grass were close to 15 - 16 lts/d. Average milk production levels, nevertheless, fluctuates between 6 - 10 kg of milk depending on the genetic potential of the animals, with a figure of 7 - 8 kgs of milk for average cows. This is in line with the results presented in Table 3.8 in Chapter 3 from a range of tropical and subtropical agro-ecoregions; and also for other improved tropical pastures in the humid tropics (Humphreys, 1991). This also demonstrates that supplementation would be necessary if high milk yields from tropical pastures were to be attained.

The only datasets with appropriate data for validation of the responses to concentrate supplementation were the data of van der Grinten et al. (1991) and data from the VAMPP database from the farms in the Poás region. Using the parameters for the most commonly used concentrate for lactating cows in the region, it was found that feeding cows with the potential of producing 5800 kg/lactation, with a concentrate level of 6 kg/cow, milk production levels of 18.0 kg/milk could be attained, which is a similar figure to that found by van der Grinten et al. (1991) (18.9 kg milk/cow/d). Pasture intake decreased overall by 33% as a result of these levels of concentrate supplementation, suggesting that substitution effects were not very high. Total intakes were 12 kg DM.

Results from 5 farms demonstrated that at moderate levels of concentrate allocation (< 8 kg/cow) (with that particular nutritional composition), the model predictions were sufficiently accurate for decision support purposes. However, at higher levels of concentrate feeding, the model failed to predict responses accurately. Ths is probably caused by the simplifications employed to represent some aspects in the model. Perhaps if a more detailed definition of partition of nutrients would have been employed, the model would have predicted better the responses at higher levels of concentrate allocation. At these levels of concentrate feeding, it was observed that cell wall digestion rates started to decrease substantially. It is quite likely that the simple representation of pH effects from Argyle and Baldwin (1988) is not accurate for the diets under study. Also, it is well known that absorption of VFAs by the rumen wall is pH dependent (Dikstra et al. 1993). Perhaps if these effects would have been included, the models would have performed better. Certainly, these issues need to be address in the future.

6.4 Model definition

1. Animals

Parameter	Value	Units	Description	Reference
BW	0	kg	bodyweight	
bwloss	0	kg/d	potential bodyweight loss	
bwgain	0	kg/d	potential bodyweight gain	
potential_milk	0	kg/d	potential milk production	
Milk_fat	39.4	g/kg milk	milk fat concentration	AFRC (1993)
Milk_lactose	44.2	g/kg milk	milk lactose concentration	AFRC (1993)
Milk_prot	32.9	g/kg milk	milk protein concentration	AFRC (1993)
tcon	0	d	days to conception	AFRC (1993)
protper	3.29	%/kg milk	protein percentage in milk	AFRC (1993)
supplements_ intake	0	kg/d	intake of supplements	

2. Forages and supplements

Parameter	Value	Units	Description	Reference
k2forage	0.046		cell wall digestion rate of forage	
NDFconcentrate	120	g/kg DM	cell wall concentration in forage	
aCPconcentrate	0.33		solubility of CP, concentrates	
bCPconcentrate	0.57		potentially degradable fraction of CP, concentrate	
FATconcentrate	30	g/kg DM	fat concentration, concentrates	Sniffen et al. (1992)
starch	0.7		proportion of non-structural carbohydrates present as starch, concentrates	Sniffen et al.. (1992)
k1concentrate	0.3	/h	cell contents rumen digestion rate	Sniffen et al.. (1992)
k6concentrate	0.12	/h	degradation rate of rumen degradable CP	Sniffen et al. (1992), AFRC (1993)
k8concentrate	0.85		digestibility of rumen undegradable N in large intestine	AFRC (1993)

k9concentrate	0.15	/h	digestion rate of soluble N in rumen, concentrates	
k2concentrate	0.08	/h	cell wall digestion rate of concentrate	Sniffen et al.. (1992)
undegCPconc.	0.1		undegradable proportion of CP, concentrates	Sniffen et al.. (1992)
DCWconc.	100	g/kg DM	digestible cell wall, concentrates	
lagf	4	h	NDF digestion lag phase	
CCforage	0.15	g/kg DM	cell contents of forage	
DCWforage	420	g/ kd DM	digestible cell wall of forage	
aCPforage	0.30		solubility of CP protein forage	
bCPforage	0.50		potential degradation of CP	
k9forage	0.15	/h	rumen digestion rate of soluble N	Sniffen et al. (1992)
k6forage	0.07	/h	rumen digestion rate of potentially degradable N	Sniffen et al (1992), AFRC (1993)
k8forage	0.85		digestibility of rumen undegradable N in large intestine	AFRC (1993)
undegCPforage	0.2		proportion of indigestible N	
CPconcentrate	140	g/kg DM	crude protein of concentrate	
NDF forage	700	g/kg DM	neutral detergent fibre of forage	
conc_allocation	12	h	interval between concentrate meals	

3. Constants

Constants	Value	Units	Description	Reference
GE	18.4	MJ/kg DM	gross energy of DM	NRC (1976), Minson (1981)
DMRC	0.9		DM rumen contents	McDonald et al. (1988)
OMC	0.9		OM content of digested DM	Illius and Gordon (1991)
NEBWloss	19	MJ/kg BW	energy value of body weight loss	AFRC (1993)
EVg	19	MJ/kg BW	energy value of body weight gain	AFRC (1993)
NPg	138.0	g/kgBW	MP content of bodyweight	AFRC (1993)

			loss	
c1	1.0		age factor for fasting metabolism	AFRC (1993)
tpmilk	0.95		proportion of milk protein as true protein	AFRC (1993)
knl	0.68		efficiency of utilisation of amino acids for milk protein synthesis	AFRC (1993)
kQDP	0.8		efficiency of utilisation: urea, QDP	AFRC (1993)
knc	0.85		efficiency of utilisation of MP for pregnancy	AFRC (1993)
kng	0.59		efficiency of utilisation of MP for bodyweight gain	AFRC (1993)
kf	0.84		efficiency of utilisation of ME from bodyweight loss	AFRC (1993)
kc	0.133		efficiency of utilisation of ME for growth of conceptus	
partmicrobes	0.75		proportion of rumen degradable energy used for VFA production	Czerkawski (1986), Preston and Leng (1987)
molGlucose	0.180	kg/mol	mol/kg Glucose	Murphy et al. (1982), Gill (1990)
molNDF	0.162	kg/mol	mol/kg NDF	Murphy et al. (1982), Gill et al (1990)
molProtein	0.136	kg/mol	mol/kg Protein	Murphy et al. (1982), Gill et al (1990)
Eacet	874.5	kj/mol	enthalpy of combustion, acetate	Blaxter (1989)
Eprop	1527.0	kj/mol	enthalpy of combustion, propionate	Blaxter (1989)
Ebut	2183.0	kj/mol	enthalpy of combustion, butyrate	Blaxter (1989)

Chapter 7

Designing dairy grazing systems using integrated simulation and multiple-criteria decision-making (MCDM) models[*]

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[*] Herrero, M., Fawcett, R. H. and Dent, J. B. (1997) Designing dairy grazing systems using integrated simulation and multiple-criteria decision-making models. *In preparation.*

Chapter 7

Designing dairy grazing systems using integrated simulation and multiple-criteria decision-making (MCDM) models

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7.1 Introduction

Appropriate selection of holistic management strategies for livestock farming systems requires: 1) understanding of the system as a whole in its agro-ecoregional context, 2) understanding of the behaviour of and interrelations between the different parts of the system, 3) knowledge of the basic objectives of the decision-maker managing such an enterprise.

As stated in Chapter 1, validated simulation models provide a cost-effective means of representing the biological dynamics of the system and its components, while multiple-criteria decision making (MCDM) models allow for appropriate selection of resource allocation strategies depending on the different objectives and management 'styles' of particular individuals or households. Integration of both mechanisms provides the necessary elements for efficient decision-support at farm or ecoregional level.

A decision-support system (DSS) based on these techniques has been built to represent pastoral cattle production systems. The biological aspects (grass growth; grazing; digestion and metabolism; animal performance, and herd dynamics) are represented by simulation studies under a variety of management regimes using the models described in Chapters 5 and 6. The outputs from the simulation runs (such as pasture utilisation, stocking rates, milk yields, fertiliser use, etc.) are part of the data input to the MCDM models, and the latter have been used to select the management strategies which make the most efficient use of the farm's resources (i.e. land, animals, pastures, other inputs, etc.).

This chapter describes the MCDM models and the whole DSS, and demonstrates how they can be used in farm management and policy development. Examples are given with reference to highland dairy farming in Costa Rica (Chapter 2). The effects of different decision-maker objectives, and/or activity or constraint definitions on management strategy selection are analysed and discussed.

7.2 Multiple-criteria model definition

7.2.1 General characteristics

Any model derived from linear optimisation (i.e. MCDM models) has 3 basic elements (Dent et al., 1986; Romero and Rehman, 1986): 1) an objective function, which minimises or maximises a function of the set of activity levels; 2) a description of the activities within the system, with coefficients representing their productive responses; and 3) a set of constraints that define the operational conditions and the limits of the model and its activities. A number of examples referring to the basis and application of these modelling techniques can be found in the literature (Zeleny, 1982; Dent et al. 1986; Romero and Rehman, 1986; Romero, 1991; Williams, 1993; Winston, 1994).

Interaction between the simulation models (Chapters 5 and 6) and the MCDM model occurs by generating the coefficients (values) for the different activities of the system, in this case a dairy farm. The MCDM model reads a series of ASCII files containing data from simulations carried out under a variety of different management practices, and 'chooses' from the simulated runs, which maximises or minimises an objective function, subject to the set of constraints specified. This mode of interaction has the enormous advantage that, since activity coefficients are not constant, usually non-linear, and are generated from the simulation models, different objectives can be met, while at the same time taking into account the biological and managerial feasibility of the range of options available. It also provides the flexibility for tailor-made decision-support for individual farmers, since management practices can be reflected in the simulations. This does not happen often in conventional application of linear programming models, which are often too aggregated. In most cases activity coefficients do not represent the management strategies commonly practised by farm households; and/or the biological feasibility of the alternatives proposed for the system under study (Veloso et al., 1992; Fawcett, 1996). Therefore model outcomes represent optimal solutions, but do not represent realistically viable options, which may lead to their lack of adoption (Fawcett, 1996).

The aim of the MCDM model is to select the best combination of resources to produce milk in a highland dairy farm of Costa Rica with a fixed grasslands area and milk quota, and year-round calving patterns and grazing. The model assumes that forest areas within the farm cannot be cleared for milk production, and therefore it is constrained to using only the existing grazing land. Resources available consist of animals, pastures, labour, and purchased inputs; namely concentrates and nitrogen fertiliser.

The model calculates herd sizes and structures, pasture management strategies [paddock sizes, rest periods, utilisation intensities, N fertiliser use], number of farm personnel, and the supplementation strategies for the lactating dairy cows [concentrates use and method of allocation], required for meeting the milk quota. Alternative youngstock supplementation practices were not tested in this version of the model.

The model was defined for a single day. This was done for the following reasons:

- Since all farms operate in a continuous calving pattern, herds are managed on a 'steady-state'. Therefore, herd dynamics (i.e. lactating vs.

dry cows), and the reproductive (i.e. days open) and productive parameters (i.e. average days in lactation, milk production per cow) do not show marked seasonal fluctuations (van der Grinten et al., 1992; Camacho et al., 1995), and are relatively similar from day to day. This is largely caused by the stable environmental conditions of the region under study (see Chapter 2).

- Milk quotas in Costa Rica operate on a daily basis, presumably partly because the lack of extreme environmental conditions and the continuous calving patterns.
- A daily timestep permits the most precise integration between the simulation models and the general operational management practices of the farm. Cows eat grass, are fed concentrate, and produce milk on a daily basis. Linear programming models representing dairy farms (i.e. Conway and Killen, 1987; Westphal et al. 1989) usually use longer timesteps than a day, perhaps because a day would not represent properly the management dynamics of the production systems in their studies. This is probably related to the fact that these techniques have been mostly applied in temperate conditions, where seasonal impacts are severe. Therefore, carry-over effects of previous seasons, forage conservation and uneven calving patterns directly affect the yearly milk quotas, and become of paramount importance in the calculations. The same applies where linear programming has been applied to study the economics of reproductive policies in temperate dairy systems (i.e. Jalvingh, 1994). Nevertheless, an advantage of using daily models is that, if necessary, they have the flexibility of aggregating data for representing longer timesteps.

The matrix of the model consists of 1336 rows and 2047 columns, representing constraints and activities, respectively. It has 8534 matrix elements, 31 right hand side elements, 939 bound elements, 18 integer plus 921 binary variables, respectively. The matrix was generated and implemented using the industrial version of XPRESS-MP mathematical programming software (Dash Associates, 1994).

7.2.2 *Defining the herd*

The model describes a dairy herd composed of lactating and dry cows, and female youngstock. The model treats individual animals as integers. This is especially important in small herds, where the value of an individual animal acquires a higher relative significance in model outcomes than in bigger herds, since these can vary substantially depending on the total number of animals (i.e. integerising a model solution of 5.6 cows to 6 cows in a herd of 10 or 100 cows does not have the same relative importance on model outcomes).

Lactating cows (TOTLAC), of a similar bodyweight, are described by three variables: lactation number (i), potential milk production (g) and stage of lactation (s). The description of cows based on 3 lactation numbers has been shown to be adequate in lactation curve studies (Wilmink, 1987), and had been previously applied to lactation records from the Poás region (Camacho et al., 1995; Vargas and Solano, 1997). The definition of 3 milk production potentials and 3 stages of lactation is standard practice, and is useful from a managerial perspective. Therefore, the model described 27 possible cow states:

$$\mathrm{TOTLAC}_{igs} \qquad (1)$$

where,

i:imax = 3: 1 = first calving, 2 = second calving, 3 = three or more calvings.
g:gmax = 3: 1 = high, 2 = average, 3 = low milk production potential.
s:smax = 3: 1 = early, 2 = mid, 3 = late lactation.

7.2.2.1 Constraints on the herd structures

Several constraints were used to estimate the appropriate number of animals in each category. The values of the coefficients are herd-dependent, therefore they can be modified to represent herds under different management regimes or in other environmental conditions. These coefficients can be derived from existing farm monitoring services (Chapters 1 and 2) or farm records. In this case they were derived from the VAMPP database of 19 farms from the Poás region, previously used by van der Grinten et al. (1992).

1) *Lactation number constraints*: An analysis of the raw data demonstrated that, realistic herd structures were obtained by using the following simple rules:

a) The sum of the first and second calvers is greater than the number of animals with more than 3 or more calvings (3+)(NL1):

$$\mathrm{NL1}(g = 1\!:\!g\max)\!:\mathrm{LAC}_{1g} + \mathrm{LAC}_{2g} - \mathrm{LAC}_{3g} > 1 \tag{2}$$

where $\mathrm{LAC}_{i=1:i\max,g}$ represent the cows in the ith lactation accross all levels of potential milk production (g).

b) The number of second calvers is always greater than half the number of 3+ calvers (NL2).

$$\mathrm{NL2}(g = 1\!:\!g\max)\!:\mathrm{LAC}_{2g} - 0.5\mathrm{LAC}_{3g} > 0 \tag{3}$$

c) The number of 3+ calvers is always greater than the number of first calvers (NL3).

$$\mathrm{NL3}(g = 1\!:\!g\max)\!:\mathrm{LAC}_{3g} - \mathrm{LAC}_{1g} > 1 \tag{4}$$

d) The number of first calvers is always greater that the number of second calvers (NL4).

$$\mathrm{NL4}(g = 1\!:\!g\max)\!:\mathrm{LAC}_{1g} - \mathrm{LAC}_{2g} > 1 \qquad (5)$$

2) *Potential milk production constraints*: Milk yield is usually a normally distributed variable (Falconer, 1989). Cows with average milk production potential represent the largest proportion of the herd, and those with low or high potential are generally fewer. The proportions of animals in each category are subjective, since they depend on the different perceptions of individual farmers and/or managers of 'high', 'medium' or 'low' potential, relative to the mean and the variance of milk yield. Definition of basic constraints to realistically describe this distribution were also required [$\mathrm{GEN}_{1\text{-}3}$]. Cows with average potential milk production, GP_2; were considered to be at least 50% of all lactating cows, while cows with high [GP_1] or low [GP_3] milk production potential represented at least 20% and 10%, respectively. Since all animals were treated as integers, a 20% slack value on the number of lactating cows was left in the definition of this distribution to prevent overconstraining the model for finding feasible global solutions:

$$\mathrm{GEN(1)}\!:\!-\mathrm{GP}_1 + 0.1\mathrm{TOTLACT} < 0 \qquad (6)$$

$$\mathrm{GEN(2)}\!:\!-\mathrm{GP}_2 + 0.5\mathrm{TOTLACT} < 0 \qquad (7)$$

$$\mathrm{GEN(3)}\!:\!-\mathrm{GP}_3 + 0.2\mathrm{TOTLACT} < 0 \qquad (8)$$

where

$$\mathrm{TOTLAC} = \sum_g \mathrm{GP}_g \qquad (9)$$

Dry cows were also assumed to be equally distributed accross genetic potentials and lactation numbers. Theoretically, a farm with a continuous calving pattern, a 365 day calving interval and a 60-day dry period, should have close to 17% of dry cows at any point in time. Analysis of the VAMPP database demonstrated that with the reproductive standards of farms in the Poás region, in an average farm, the dry cows represented at least 20-25% of the total number of cows (TOTCOWS). Therefore the constraint determining the number of dry cows (DSIZE) was written:

$$\mathrm{DSIZE}{:}-0.25\mathrm{TOTCOWS}+\mathrm{DRY}>0 \qquad (10)$$

This figure is dependent on the reproductive policies of the herd and its dry period. Farms with longer calving intervals usually tend to have longer dry periods and a higher proportion of dry cows.

Youngstock [YS_z] were divided in three categories to represent animals at different stages of growth. YS_1 represented animals from 0 - 1 years, while YS_2 and YS_3 were heifers from 1 - 2 years and pregnant replacement heifers, respectively. These represented at least 0.2, 0.4 and 0.2 of the total number of cows, respectively. Again a slack value of 20% was left to satisfy the integer constraints:

$$\mathrm{YSTK}(1){:}-YS_1+0.2\mathrm{TOTCOWS}<0 \qquad (11)$$

$$\mathrm{YSTK}(2){:}-YS_2+0.4\mathrm{TOTCOWS}<0 \qquad (12)$$

$$\mathrm{YSTK}(3){:}-YS_3+0.2\mathrm{TOTCOWS}<0 \qquad (13)$$

In farms of the Poás region, youngstock represent close to 50% of the total herd size (van der Grinten et al. 1992; Solano, 1993). Therefore, a constraint (YSIZE) was applied so the number of youngstock had to be equal to the number of mature cows (TOTCOWS):

$$\text{YSIZE: TOTCOWS} - \sum_{z} \text{YS}_z = 0 \tag{14}$$

where the total number of cows is:

$$\text{TOTCOWS} = \text{TOTLACT} + \text{DRY} \tag{15}$$

7.2.2.2 Lactating cows and milk production

Calculation of the number of lactating cows is dependent on their pasture intake, their productive responses to concentrate supplementation, and their state, relative to the characteristics of the system (i.e. land, costs, milk quota, grazing management). Hence, it is largely dependent on the coefficients obtained from the simulation models.

The number of simulation runs is dependent on the number of nutritional strategies and supplementation levels that want to be evaluated, and these are user defined. For each nutritional strategy, an ASCII file (*.dat) is produced that contains 3 simulated output variables (1 column per variable): pasture intake, supplements intake, milk production for each of the 27 cow states described before. For the present example, 3 strategies were used: grazing only and grazing plus a commercial concentrate but with 2 different methods of allocation (flat rate or based on milk:concentrate relations). Additionally, within each concentrate regime there were 3 different levels of supplementation (j), therefore each of these ASCII files contained 81 rows of data (27 states X 3 levels of supplementation = 81 rows). The file containing the data for the grazing only regime had 27 rows. The model calculated, subject to the constraints imposed, the numbers of animals in each nutritional strategy and level of supplementation, according to lactation number, potential milk production, and stage of lactation, or a combination of these, to meet the milk quota according to the different objectives. For stratification according to potential milk production, the model defines the following:

$$-\sum_{i}\sum_{g=1}\sum_{s} \mathrm{W5P}_{igs} - \sum_{i}\sum_{g=1}\sum_{s}\sum_{j} \mathrm{W5A}_{igsj} - \sum_{i}\sum_{g=1}\sum_{s}\sum_{j} \mathrm{W5B}_{igsj} + \mathrm{GP}_1 = 0 \qquad (16)$$

$$-\sum_{i}\sum_{g=2}\sum_{s} \mathrm{W5P}_{igs} - \sum_{i}\sum_{g=2}\sum_{s}\sum_{j} \mathrm{W5A}_{igsj} - \sum_{i}\sum_{g=2}\sum_{s}\sum_{j} \mathrm{W5B}_{igsj} + \mathrm{GP}_2 = 0 \qquad (17)$$

$$-\sum_{i}\sum_{g=3}\sum_{s} \mathrm{W5P}_{igs} - \sum_{i}\sum_{g=3}\sum_{s}\sum_{j} \mathrm{W5A}_{igsj} - \sum_{i}\sum_{g=3}\sum_{s}\sum_{j} \mathrm{W5B}_{igsj} + \mathrm{GP}_3 = 0 \qquad (18)$$

where,

$\mathrm{W5P}_{igs}$, are the number of lactating cows under a 'grazing only' nutritional regime, accross potential milk production levels GP_g.

$\mathrm{W5A}_{igsj}$, are the number of lactating cows under a 'grazing plus concentrates' flat rate (nutritional regime A), accross potential milk production levels GP_g.

$\mathrm{W5B}_{igsj}$, are the number of lactating cows under a 'grazing plus concentrates' feeding strategy, with concentrates allowance based on a milk:concentrate relationship (nutritional regime B), accross potential milk production levels GP_g.

j = level of supplementation within the nutritional regime, where jmax=3.

The stratification of lactating animals by a combination of lactation number X genetic potential [LR_{ig}] then becomes, for i=1:imax, g=1:gmax:

$$-\sum \mathrm{W5P}_{igs} - \sum_{s}\sum_{j} \mathrm{W5A}_{igsj} - \sum_{s}\sum_{j} \mathrm{W5B}_{igsj} + \mathrm{LAC}_{ig} = 0 \qquad (19)$$

Two further constraints were applied to the distributions of the lactating herd.

1) In farms with continuous calving patterns, the distribution of lactating cows accross stages of lactation is similar (30-35% in each stage). Therefore, for i=1:imax,g=1:gmax:

$$W5P_{ig1}+\sum_j W5A_{ig1j}+\sum_j W5B_{ig1j}-W5P_{ig3}-\sum_j W5A_{ig3j}-\sum_j W5B_{ig3j}>-1 \tag{20}$$

$$W5P_{ig2}+\sum_j W5A_{ig2j}+\sum_j W5B_{ig2j}-W5P_{ig1}-\sum_j W5A_{ig1j}-\sum_j W5B_{ig1j}>0 \tag{21}$$

$$W5P_{ig3}+\sum_j W5A_{ig3j}+\sum_j W5B_{ig3j}-W5P_{ig2}-\sum_j W5A_{ig2j}-\sum_j W5B_{ig2j}>0 \tag{22}$$

2) Theoretically, the model could calculate separate feeding strategies for the 27 groups of lactating animals. However, from a practical standpoint, it would be extremely complicated to apply them at farm level, since farmers rarely stratify lactating cows in more than 3 or 4 groups for feeding. The model was designed to select the single best nutritional management strategy for each stage of lactation (i.e 3 groups), which is one of the common systems for supplementing dairy cows in the highlands of Costa Rica (Campabadal, 1988; van der Grinten et al., 1992). For i=1:imax, g=1:gmax; the constraints were defined as:

$$-W5A_{ig13}+W5A_{ig23}-W5B_{ig13}+W5B_{ig23}<0 \tag{23}$$

$$\sum_{j=2:3} W5A_{ig1j} + \sum_{j=2:3} W5A_{ig2j} - \sum_{j=2:3} W5B_{ig1j} - \sum_{j=2:3} W5B_{ig2j} < 0 \tag{24}$$

$$\sum_{j=1:3} W5A_{ig1j} + \sum_{j=1:3} W5A_{ig2j} - \sum_{j=1:3} W5B_{ig1j} - \sum_{j=1:3} W5B_{ig2j} < 0 \tag{25}$$

$$-W5A_{ig23} + W5A_{ig33} - W5B_{ig23} + W5B_{ig33} < 0 \tag{26}$$

$$\sum_{j=2:3} W5A_{ig2j} + \sum_{j=2:3} W5A_{ig3j} - \sum_{j=2:3} W5B_{ig2j} - \sum_{j=2:3} W5B_{ig3j} < 0 \tag{27}$$

$$\sum_{j=1:3} W5A_{ig2j} + \sum_{j=1:3} W5A_{ig3j} - \sum_{j=1:3} W5B_{ig2j} - \sum_{j=1:3} W5B_{ig3j} < 0 \tag{28}$$

Milk production was estimated from the number of cows calculated by the model multiplied by the respective columns from the ASCII files containing the milk production data for each nutritional strategy and each cow state. In this case, the ASCII files were named C5WP, C5W, B5W for the grazing only, nutritional regime A, and nutritional regime B, respectively. The milk production data was the third data item in the files. Therefore:

$$\begin{gathered} -\sum_{i}\sum_{g}\sum_{s} C5WP_{igs3}W5P_{igs} - \sum_{i}\sum_{g}\sum_{s}\sum_{j} C5W_{igsj3}W5A_{igsj} - \\ \sum_{i}\sum_{g}\sum_{s}\sum_{j} B5W_{igsj3}W5B_{igsj} + QMILK + XSMILK < 0 \end{gathered} \tag{29}$$

where,

QMILK is the daily milk quota (kg/day) and XSMILK is milk produced over the quota limit (kg/day). XSMILK was included as a variable, since in Costa Rica, milk produced above the quota limit is paid at 25% less than the price of milk, and farmers are not penalised in the long term for small (<10%) milk excedents. These usually even out on a yearly basis due to small changes in the number of lactating cows (± 3 or 4) through the year. (Dos Pinos R.L. dairy cooperative, pers. comm.).

Total concentrates use (CONC) was estimated in a similar manner, but the level of supplementation per animal on each nutritional strategy was the second item in the data files:

$$\sum_{i}\sum_{g}\sum_{s}\sum_{j} \mathrm{C5W}_{igsj2}\mathrm{W5A}_{igsj} + \sum_{i}\sum_{g}\sum_{s}\sum_{j} \mathrm{B5W}_{igsj2}\mathrm{W5B}_{igsj} - \mathrm{CONC} < 0 \qquad (30)$$

7.2.3 *Grazing management and land use*

It was assumed that the maximum amount of land available for pastures was fixed. Forest areas were not considered, since a primary interest was to find strategies for the existing pasture land, rather than considering the possibility of clearing forest for pasture production (see Chapter 2 for comments on deforestation).

Grazing management strategies were determined by 5 variables: residual herbage mass, N fertilisation level, rest period, number of consecutive grazing days; and the number of animals, which was calculated by the model. The first three variables were all obtained from simulations, and they were also stored in ASCII files and handled as described in previous sections. The number of consecutive grazing days was set to 1 for lactating cows, since this was the standard implemented by dairy farmers in the region under study (van der Grinten et al., 1992). For youngstock, which grazed with the dry cows, the model calculated the consecutive grazing days. The choice of grassland management regime for lactating cows, youngstock and dry cows, were constrained so that only one management regime could be selected for each class. This was done using binary (mutually exclusive) constraints.

Pasture supply for lactating cows (SUP) and for youngstock and dry cows (SUPY) were calculated as:

$$-\sum_{l}\sum_{n}\sum_{m} \mathrm{AGDM}_{\mathrm{ln\,m}}\mathrm{PAS}_{\mathrm{ln\,m}} + \mathrm{SUP} = 0 \tag{31}$$

$$-\sum_{l}\sum_{n}\sum_{m}\sum_{x} \mathrm{AGDM}_{\mathrm{ln\,mx}}\mathrm{PASY}_{\mathrm{ln\,mx}} + \mathrm{SUPY} = 0 \tag{32}$$

where,

l is the residual green herbage mass (t/ha), lmax=5.

n is the N fertiliser levels (kg/ha), nmax=5.

m is the rest period (days), mmax=4.

x is the number of consecutive grazing days, xmax=10.

AGDM is the file containing the instantaneous green dry matter data (kg/ha GDM) from the grassland simulations accross l, n and m; and x for youngstock.

PAS and PASY are the average paddock sizes (ha) for lactating cows and youngstock, respectively .

The model was designed so that from a biological standpoint, the maximum intake of pastures (local resource grown year round) in each nutritional regime was attained. Therefore supply had to be between 3 to 4 times the intake of the animals (see Chapter 4 and Chapter 6 for a discussion).

Pasture green dry matter demand for lactating cows (DEM) was calculated from the number of lactating cows and their simulated intake (first column in ASCII files):

$$-\sum_{i}\sum_{g}\sum_{s} C5WP_{igs1} W5P_{igsj} - \sum_{i}\sum_{g}\sum_{s}\sum_{j} C5W_{igsj1} W5A_{igsj} - \sum_{i}\sum_{g}\sum_{s}\sum_{j} B5W_{igsj1} W5B_{igsj} + DEM = 0 \qquad (33)$$

Similar calculations were performed for youngstock.

Calculation of total land used was done from the knowledge of the paddock sizes (PAS, PASY) and the rest period. In a rotational grazing system using a single group of animals, the total number of paddocks requires to be the rest period + 1. Therefore, total land use (LAND) is:

$$-\sum_{l}\sum_{n}\sum_{m} (16+5m) PAS_{lnm} - \sum_{l}\sum_{n}\sum_{m}\sum_{x} (16+5m) PASY_{lnmx} + LAND < ML \qquad (34)$$

where,

ML is the maximum land area that can be used.

Fertiliser use (FEZ) was calculated from the N fertiliser regime chosen for each group of animals multiplied by the land area were it was applied.

7.2.4 *Prices and objective functions*

Model behaviour and strategy selection are largely dependent on the prices of farm outputs and inputs. These were required to estimate the values of the different objective functions tested. Most prices were obtained from farmers and/or the main dairy cooperatives (i.e. Dos Pinos R.L.), and were expressed on a daily basis in pounds sterling (£, where for comparative purposes £1 = \$1.6). The prices of livestock were expressed on a per animal basis for calculations of asset values.

Derivation of the objective functions was done on the basis of net revenue (NETR), variable costs (CST) and the capital value of assets (VALUE):

$$\begin{aligned}&0.18\mathrm{QMILK} + 0.135\mathrm{XSMILK} + \mathrm{CULLED} - 0.0014\mathrm{FEZ} - \mathrm{WAGE} - \\ &0.15\mathrm{CONC} - 0.10\mathrm{TOTCOWS} - \sum_{z} 0.42\mathrm{YS}_z - \mathrm{OHDS} - \mathrm{NETR} = 0\end{aligned} \tag{35}$$

$$0.0014\mathrm{FEZ} + \mathrm{WAGE} + 0.15\mathrm{CONC} + 0.10\mathrm{TOTCOWS} + \sum_{z} 0.42\mathrm{YS}_z - \mathrm{CST} = 0 \tag{36}$$

$$20\mathrm{NETR}+550\mathrm{TOTCOWS}+180\mathrm{YS}_1+300\mathrm{YS}_2+410\mathrm{YS}_3\text{-}\mathrm{VALUE}=0 \tag{37}$$

where,

0.18 is the current price of milk (QMILK) in Costa Rica, which has been relatively constant since 1988 (Ruiz et al., 1994).

0.135 is 25% of the price of milk, which is price paid to farmers for milk produced above their quota limit (XSMILK).

CULLED is the price of culled cows. These are generally sold by weight, their prices vary but are usually dependent on the price of beef. Approximate prices of these animals (500 kg), are £0.51/day/animal. A culling rate of 10% was assumed for the calculations.

0.0014 is the price per kg of N fertiliser (FEZ) expressed on a daily basis.

WAGE represents the labour costs, based on the following earnings: manager £8.6/d, milkmen £6/d, other farm staff £4.8/d. (Ruiz et al. 1994; MITRAB, 1996).

0.10 is the value of other variable costs (i.e. medicines, disposables, semen) on a per day/cow (TOTCOWS) basis.

0.15 is the price per kg of a commonly used commercial concentrate.

0.42 is the added costs of rearing a heifer, and is composed of £0.32 on concentrates use, assuming that youngstock consume 2 kg/d (£0.16/kg), which is normal practice in the Poás region (van der Grinten et al. 1991); and £0.10 of other variable costs.

OHDS represent overhead costs such as electricity (£8/d), 1 monthly visit by a veterinarian (£2/d), farm maintenance* (14/d), others (£6/d). A very important feature of linear programming techniques is that changes in any fixed values, such as overheads, within the objective function, do not change the strategies selected by the model. They just change the value of the objective function (Romero, 1991; Williams, 1993).

20 is an annuity factor of the net revenue

550, 180, 330 and 410 are the prices of live cows and youngstock of different categories, respectively.

Estimation of the number of farm staff (MEN) was done by calculating the cow:men ratios for the region under study. These varied with herd size, and were between 10-12:1 in herds with up to 100 mature cows, while the ratios increased (13-20:1) as the number of cows was higher than 100. The minimum labour requirements in a farm were estimated to be 2 people, a manager/milkman and another person, while the rest of required staff were calculated by the model.

7.3 Applications of the DSS

The present sections deal with examples of how can the DSS be applied to support decision-making at different levels.

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* Includes cleaning materials, maintenance of infrastructure, roads, milking equipment, vehicles, fences, petrol costs, and others.

Results are presented for a farm with 50 ha of kikuyu grasslands (forests area not considered), 500 kg Holstein-Friesians, and a milk quota of 915 kg/day. This is representative not only of a medium sized farm in the Poás region, but of dairy farms in the Costa Rican central highlands (Camacho, 1989; Ruiz et al. 1994). All prices of input and outputs were obtained from the previous section. Simulations were also carried out as described in the previous sections using the data from the previous chapters.

Three nutritional regimes were tested: 1) grazing only, and supplementation with a commercial concentrate (see Chapter 5 for its nutritional description) offered at 2) a flat rate of 2, 4, or 6 kg/day; and 3) the same concentrate offered at milk:concentrate ratios of 2:1, 3:1 or 4:1. For this last strategy, the amount of milk produced from grazing only was calculated as in the strategy 1, then the milk:concentrate ratios were applied on the remaining milk production to calculate the amount of concentrate offered. In total 7 simulations per cow state were performed: 189 simulations. Additionally, 100 different grassland management practices were simulated: 5 N fertiliser levels (0, 50, 100, 200 and 300 kg N/ha) X 5 residual herbage masses (1.5, 2.0, 2.5, 3.0 and 3.5 t GDM/ha) X 4 regrowth periods (20, 25, 30 and 35 days of rest period). The model had available 18900 strategy choices (combinations of supplementation X grassland management options) for managing dairy cows, and 1000 grassland management options for youngstock paddocks (100 X a maximum of 10 consecutive grazing days).

Model outcomes were obtained for 4 different objective functions reflecting different farmers objectives or management styles:

1) Maximisation of net revenue (MAX NETR). This is probably one of the most common objectives of commercial dairy farmers.

2) Maximisation of capital assets (MAX VALUE). High asset values are important when inheritance and succession of the farm to the next generation is an issue (to be able to give enough animals to each son/daughter); or when the number of cattle in the farm is seen as a status

symbol, a method to reduce risk; or as a 'bank' where the savings or investments are placed. Increasing asset values is synonymous to increasing herd sizes.

3) Minimisation of variable costs (MIN CST). A 'cost minimiser' might be someone with a limited cash flow or a very risk-averse person, that does not like to invest to obtain higher yields.

4) Minimisation of concentrates use (MIN CONC). This was included, mainly because under the present situation, Costa Rican dairy farmers are demanding strategies to minimise concentrates use, which have almost doubled the price in the last 5 years. They want to increase the use of pastures, which are available year-round and is their primary local resource.

7.3.1 Decision-support for current dairy farming scenarios

Farm management scenarios obtained with current prices for the different objectives are shown in Table 7.1. The results demonstrate that different objectives generate different strategies to achieve the milk quota. However, two main tendencies show up. One that produces smaller herd sizes, utilises less land, but requires cows with higher milk yields and higher concentrate intakes (maximise net revenue and minimise variable costs, 'intensive'), and another one with larger herd sizes, lower milk productions/cow and less concentrates use, but that maximises the use of grazing land (maximise capital value and minimise concentrates use, 'less intensive'). For all objectives, it is clear that, with current prices and markets, dairy farming under highland conditions is profitable, but that there can be large differences in profit depending on the objectives of the farmer. An assessment of which system is best would be subjective. In terms of herd sizes, the model suggests that lactating 44 cows are required on an 'intensive scenario' while 63 cows are needed in the 'less intensive' scenario. These herd sizes are similar to what is commonly observed for this operation size in the Poás region (VAMPP database). The difference is that farmers are currently substocking their pastures, and therefore are subutilising the land. They are also feeding higher amounts of concentrates. For example, van der Grinten et al. (1992) quotes an average stocking rate of 2.0 cows/ha and an average concentrate use of 6.1 kg/cow/d for the Poás region. In the model, optimal concentrate intake varies from 3.0 to 4.7 kg/cow, depending on production objectives; while stocking rates are always between 2.9 and 3.2 cows/ha.

The fact that more land area is not used under the more intensive regimes suggest that additional incomes could come from alternative enterprises. A common one in the Poás region would be strawberries or flowers for export, or in slightly lower regions (1000-1500 mosl) coffee could be an alternative as long as labour costs are relatively low. These, and other alternatives need to be investigated. Labour represents 28% of the variable costs, while concentrates account for 53-56%, depending on production objectives. These two variables account for more than 80% of the variable costs and determine operation size and land use.

7.3.2 *Industrial scenario: What if more quota could be bought?*

At the moment, Costa Rica has limited options to expand its milk production industry partly due to a lack of infraestructural capacity. According to CATIE (1990), in the late 1980's, the main dairy farmers cooperative (Dos Pinos R.L.), which markets 80% of the processed milk of the country, was working at 85% of its capacity. In the early 1990's this cooperative stopped selling milk quota, and in 1994, farmers could only buy quota from other farmers. There is pressure from farmers to find more options. This section examines from a managerial standpoint, what would happen if the farmer above had the option of increasing its quota to 1100 kg/d (Table 7.1).

It is clear that if quotas could be bought, more milk could be produced from this amount of land. More cows are required and more land would be used, although not all the land is used in the 'intensive system.

. It seems preferable to intensify all the systems even more by supplying more concentrates (see Table 7.1 and Table 7.2), which could be fed at a 6 kg flat rate (intensive system) or at a 4:1 milk:concentrate ration (extensive system) during the first stage of lactation. Concentrates would account for 57-59% of the variable costs and fertiliser N is now required to achieve the required yields. Economic parameters increase substantially, because more milk is sold, but also because at these herd sizes, there would not be a need to increase the labour requirements.

The model was adapted to test, from a completely theoretical standpoint, what would be the largest quota achievable if all the grazing land was used. The results suggest that quotas of up to 1470 kg could be achieved with 64 lactating cows managed at 3.5 cows/ha on a 20-25 day rotational grazing system (100 kg N/ha), and consuming on average 5.6 kg concentrate/cow. This strategy probably does not reflect the true scenario because epidemiological and other aspects linked to high intensity farms are not included. What the model certainly shows is that there is still some productive potential in these farms, and there is evidence from the VAMPP database, that a few farms are close to these standards, at least in terms of production and concentrates intake. However, whether this could be sustainable in the long term and under future milk production policies, is another matter.

Table 7.1. Management strategies obtained under current price scenarios.

	Objectives			
Activities	MAX NETR	MAX VALUE	MIN CST	MIN CONC
Economic indicators				
Net revenue (£/d)	49.03	34.64	49.00	32.00
Capital (£)	49930	71923	49930	69670
Total variable costs (£/d)	85.70	102.90	85.70	101.00
Labour costs (£/d)	24.20	29.00	24.20	29.00
Supplementation costs (£/d)[1]	47.83	55.10	47.83	55.10
Labour				
Number of farm staff	4	5	4	5
Land use				
Total land use (ha)	40.0	49.6	39.2	48.3
Land for lactating cows (ha)	15.0	19.8	14.9	19.4
Land for youngstock (ha)	25.0	29.8	24.3	28.9
Herd				
Total herd size	118	168	118	168
Number of cows/youngstock	59	84	59	84
Lactating cows	44	63	44	63
Dry cows	15	21	15	21
Milk production				
Milk quota (kg/d)	915	915	915	915
Excess milk (10% of quota, kg/d)	0	63	0	0
Milk production/cow (kg/d)	20.8	15.5	20.8	15.5
Supplementation strategies[2]				
1st stage of lactation	MC4:1	MC4:1	MC4:1	FR6
2nd stage of lactation	MC4:1	MC4:1	MC4:1	MC4:1
3rd stage of lactation	MC4:1	FR2	MC4:1	GO
Mean concentrate use/cow (kg/d)	4.7	3.2	4.7	3.0
Grazing management - cows				
Stocking rate lact.cows (cows/ha)	2.9	3.2	2.9	3.2
Paddock size (ha)	0.70	0.64	0.71	0.63
Rest period (d)	20	30	20	30
Residual herbage mass (t GDM/ha)	3.5	3.5	3.5	3.5
N fertiliser use (kg N/ha)	0	0	0	100
Grazing management - dry cows+ystk				
Paddock size (ha)	0.55	0.88	1.01	1.00
Rest period (d)	35	30	20	25
Residual green DM (t/ha)	3.5	3.5	3.5	3.5
N fertiliser (kg N/ha)	0	0	0	100
Consecutive grazing days	9	3	3	3

[1] Supplementation costs including youngstock. [2]Supplementation strategies: GO = grazing only. FR2, FR4, FR6 = flat rate system 2, 4, or 6 kg of concentrates. MC2:1, MC3:1, MC4:1 = milk:concentrate ratios of 2:1, 3:1, 4:1. (i.e. for each 4 kg of milk, 1 kg of concentrates is offered, after accounting for the milk produced from grazing).

Table 7.2. Management scenarios for an increase in milk quota to 1100 kg/d

	Objectives			
Activities	MAX NETR	MAX VALUE	MIN CST	MIN CONC
Economic indicators				
Net revenue (£/d)	69.08	58.17	68.97	33.6
Capital (£)	57341	73003	59379	64820
Variable costs (£/d)	99.00	114.77	99.00	104.2
Labour costs (£/d)	24.20	29.00	24.20	29.00
Supplementation costs (£/d)[1]	58.85	65.15	58.85	59.46
Labour				
Number of farm staff	4	5	4	5
Land use				
Total land use (ha)	45.2	49.6	43.3	48.3
Land for lactating cows (ha)	15.8	19.6	15.8	18.4
Land for youngstock (ha)	29.4	30.0	27.5	29.9
Herd				
Total herd size	132	172	132	156
Number of cows/youngstock	66	86	66	78
Lactating cows	49	64	49	56
Dry cows	17	22	17	22
Milk production				
Milk quota (kg/d)	1100	1100	1100	1100
Excess milk (10% of quota, kg/d)	2.53	110	0	0
Milk production/cow (kg/d)	22.5	18.9	22.4	19.6
Supplementation strategies[2]				
1st stage of lactation	FR6	MC4:1	FR6	MC4:1
2nd stage of lactation	MC4:1	MC4:1	MC4:1	MC4:1
3rd stage of lactation	MC4:1	MC4:1	MC4:1	MC4:1
Mean concentrate use/cow (kg/d)	5.5	4.2	4.7	4.4
Grazing management - cows				
Stocking rate lact.cows (cows/ha)	3.1	3.3	3.1	3.0
Paddock size (ha)	0.75	0.76	0.75	0.51
Rest period (d)	20	25	20	35
Residual herbage mass (t GDM/ha)	3.5	3.5	3.5	3.5
N fertiliser use (kg N/ha)	50	200	0	200
Grazing management - dry cows+ystk				
Paddock size (ha)	0.72	1.03	0.63	1.00
Rest period (d)	25	25	35	25
Residual green DM (t/ha)	3.0	3.5	3.5	3.5
N fertiliser (kg N/ha)	0	300	0	50
Consecutive grazing days	5	3	8	3

[1] Supplementation costs including youngstock. [2]Supplementation strategies: GO = grazing only. FR2, FR4, FR6 = flat rate system 2, 4, or 6 kg of concentrates. MC2:1, MC3:1, MC4:1 = milk:concentrate ratios of 2:1, 3:1, 4:1. (i.e. for each 4 kg of milk, 1 kg of concentrates is offered, after accounting for the milk produced from grazing).

7.3.3 *Market scenario: What if concentrate prices increased 20%?*

In view of the current trends, it is essential to consider to what extent farmers need to change their management strategies to meet their milk quota if grain supplement prices increased. Since there is not a single objective that does not require at least small amounts of concentrates to be fed to meet the quota, any increases in their price should have some effect on the solutions obtained.

An example is given for a 20% increase in the price of concentrates, which if current trends are maintained could happen within the next 2 years. Table 7.3 summarises the results for such scenario.The net result of such a policy is to affect the economic parameters, mainly because the proportion of the variable costs represented by concentrates increase to 56-64% depending on the objectives. In the less intensive scenario, it seems preferable to have the same number of animals, but to decrease the net revenue. These trade-offs are subjective and they depend on the value that a farmer whose objective is to have large herds, assigns to the value of the net revenue. Nevertheless, farms are still profitable under these scenarios.

7.3.4 *Policy scenario: what if the price of milk was decreased by 10%?*

The options for the Costa Rican dairy industry in the face of globalisation, and its impacts on farmers, processors and consumers have been widely discussed (Camacho, 1989; CATIE, 1990; Galetto, 1993; Nuñez and Galetto, 1993; Ruiz et al. 1994; Quirós, 1994; Pomareda, 1992, 1994).

Costa Rica is protecting its dairy farmers from an open market situation by applying a tariff barrier of 111% for milk powder coming from outside the Central American region (Ruiz et al., 1994). Since domestic milk prices are 37% higher than those from the rest of the world, any untaxed competitor entering the market would mean that consumers could buy substantially cheaper milk, and this would have negative implications for the whole dairy sector (Nuñez and Galetto, 1993). Even when the decrease in subsidies in other countries may increase the international price of milk by up to 20%, as a result from the GATT Uruguay round, the domestic milk prices would still be higher (Galetto, 1993; Quirós, 1994; Ruiz et al., 1994).

Therefore, 2 possible scenarios have been suggested (Ruiz et al., 1994) 1) To eliminate the tariff barrier, which would require a 26% decrease in the price of milk to compete with foreign imports.Under these circumstances, a large proportion of dairy farmers would be driven out of business and an internal conflict would be generated. 2) To reduce the tariff barrier to 20%, and accepting free trade only with non-subsidised countries (i.e. New Zealand, Uruguay, Argentina). Under these conditions, the domestic milk price would need to be reduced by 10% to be competitive. This section examines the consequences of a 10% milk price decrease for the medium sized farm presented above, and for a smaller farm (700 kg quota, 35ha grasslands). Results are presented in 7.4.

From a net revenue perspective, this scenario shows that a 50 ha farm with a 915 kg quota could withstand a 10% price reduction without changing its management strategies, but would require the acceptance of a lower profit. Similarly, the 35 ha farm, would make a substantially lower profit, probably requiring alternative activities in the land not used for grazing purposes. Grazing management would be changed from a 20 day to 25 day rotation, and stocking rates would be slightly increased. Labour costs would represent 28% and 33% of the variable costs in the 50 ha and the 35 ha farm, respectively

Table 7.3. Model solutions for a 20% increase in the price of concentrates.

	Objectives			
Activities	MAX NETR	MAX VALUE	MIN CST	MIN CONC
Economic indicators				
Net revenue (£/d)	39.34	23.02	42.84	17.70
Capital (£)	49807	72346	49806	69670
Variable costs (£/d)	91.86	109.23	91.86	98.80
Labour costs (£/d)	24.20	29.00	24.20	29.00
Supplementation costs (£/d)[1]	51.35	70.45	51.35	58.30
Labour				
Number of farm staff	4	5	4	5
Land use				
Total land use (ha)	39.3	49.7	39.2	49.3
Land for lactating cows (ha)	14.9	19.7	14.9	19.4
Land for youngstock (ha)	24.4	30.0	24.3	29.9
Herd size				
Total herd size	118	168	118	168
Number of cows/youngstock	59	84	59	84
Lactating cows	44	63	44	63
Dry cows	15	21	15	21
Milk production				
Milk quota (kg/d)	915	915	915	915
Excess milk (10% of quota, kg/d)	0	63.5	0	0
Milk production/cow (kg/d)	20.8	15.5	20.8	15.5
Supplementation strategies[2]				
1st stage of lactation	MC4:1	MC4:1	MC4:1	FR6
2nd stage of lactation	MC4:1	MC4:1	MC4:1	MC4:1
3rd stage of lactation	MC4:1	FR2	MC4:1	GO
Mean concentrate use/cow (kg/d)	4.7	3.2	4.7	3.0
Grazing management - cows				
Stocking rate lact. cows (cows/ha)	2.9	3.2	2.9	3.2
Paddock size (ha)	0.71	0.64	0.71	0.63
Rest period (d)	20	30	20	30
Residual herbage mass (t GDM/ha)	3.5	3.5	3.5	3.5
N fertiliser use (kg N/ha)	0	100	0	200
Grazing management - dry cows+ystk				
Paddock size (ha)	0.55	0.88	1.01	0.85
Rest period (d)	35	30	20	30
Residual green DM (t/ha)	3.5	3.5	3.5	3.5
N fertiliser (kg N/ha)	0	200	0	100
Consecutive grazing days	8	3	3	4

[1] Supplementation costs including youngstock. [2]Supplementation strategies: GO = grazing only. FR2, FR4, FR6 = flat rate system 2, 4, or 6 kg of concentrates. MC2:1, MC3:1, MC4:1 = milk:concentrate ratios of 2:1, 3:1, 4:1. (i.e. for each 4 kg of milk, 1 kg of concentrates is offered, after accounting for the milk produced from grazing).

Table 7.4. Model solutions for 2 different farm sizes for the maximisation of net revenue, with a 10% decrease in the price of milk.

	Objective: maximise net revenue		
Activities	Land =50 ha Milk quota = 915 kg/d	Land = 35 ha Milk quota = 700 kg/d	
Economic indicators		current	-10% price
Net revenue (£/d)	32.55	23.62	10.89
Capital (£)	49271	41172	40918
Variable costs (£/d)	85.70	73.68	73.68
Labour costs (£/d)	24.20	24.20	24.20
Supplementation costs (£/d)[1]	47.83	38.40	38.40
Labour			
Number of farm staff	4	4	4
Land use			
Total land use (ha)	39.8	30.2	30.9
Land for lactating cows (ha)	14.9	12.2	11.1
Land for youngstock (ha)	24.9	18	19.8
Herd			
Total herd size	118	98	96
Number of cows/youngstock	59	48	48
Lactating cows	44	36	36
Dry cows	15	12	12
Milk production			
Milk quota (kg/d)	915	700	700
Excess milk (10% of quota, kg/d)	0	28	28
Milk production/cow (kg/d)	20.8	20.2	20.2
Supplementation strategies[2]			
1st stage of lactation	MC4:1	MC4:1	MC4:1
2nd stage of lactation	MC4:1	MC4:1	MC4:1
3rd stage of lactation	MC4:1	MC4:1	MC4:1
Mean concentrate use/cow (kg/d)	4.7	4.5	4.5
Grazing management - cows			
Stocking rate lact.cows (cows/ha)	2.9	2.9	3.2
Paddock size (ha)	0.71	0.58	0.43
Rest period (d)	20	20	25
Residual herbage mass (t GDM/ha)	3.5	3.5	3.5
N fertiliser use (kg N/ha)	0	0	0
Grazing management - dry cows+ystk			
Paddock size (ha)	0.55	0.46	0.46
Rest period (d)	35	35	35
Residual green DM (t/ha)	3.5	3.5	3.5
N fertiliser (kg N/ha)	0	0	0
Consecutive grazing days	9	3	7

[1] Supplementation costs including youngstock. [2]Supplementation strategies: GO = grazing only. FR2, FR4, FR6 = flat rate system 2, 4, or 6 kg of concentrates. MC2:1, MC3:1, MC4:1 = milk:concentrate ratios of 2:1, 3:1, 4:1. (i.e. for each 4 kg of milk, 1 kg of concentrates is offered, after accounting for the milk produced from grazing).

7.3.5 *Trade-offs between objectives*

In real life, farmers, and humans in general, want to fullfil more than one objective simultaneously (multiple criteria). Therefore trade-offs have to be made between them. The present example demonstrates the trade-offs between maximising net revenue and capital assets; which lead, as seen in the previous sections to different management and land use scenarios. Maximising net revenue was seen as an intensive system, while maximising capital was seen as a less intensive system.

The compromise between these objectives is a problem that can be explained graphically in Figure 7.1. The graph shows that the X axis represents capital in livestock, while the Y axis represents daily net revenue. The coordinate 0,1 represent the maximum net revenue that can be obtained, while the coordinate 1,0 represents the maximum capital that can be achieved. The scales of the graph are normalised between the values for net revenue and capital obtained from the 2 solutions by maximising each objective separately. These 2 maxima were obtained from the previous sections (see Table 7.1). The coordinate 1,1 represents an ideal solution, where both objectives could be met at the same time, in this case achieving a maximum net revenue, while maximising the asset values of the farm. It is clear that both of these objectives cannot be achieved simultaneouly. Therefore, the best compromise between them would be the point in the graph that was closer to the ideal solution (L1). This point is found by setting 2 deviational variables, one for each objective, and trying to minimise their values in relation to the maximisation of both objectives. For illustrative purposes, the graph also contains other points (▲) representing different calculated values for the deviational variables, but these are not closer to the ideal point, and therefore do not represent the best compromise.

The Linf represents the solution of the model when only one deviational variable is used, and is the minimum maximum deviation from the ideal solution. In this case, since the solutions are integerised, the surface space for searching the optimal solutions is discontinuous. Therefore there is the need for sampling the surface space to find the optimal solution. However, in this case, since the L1 is the same as the Linf, there is certainty that this point represents the overall and only optimal compromise between the two objectives.

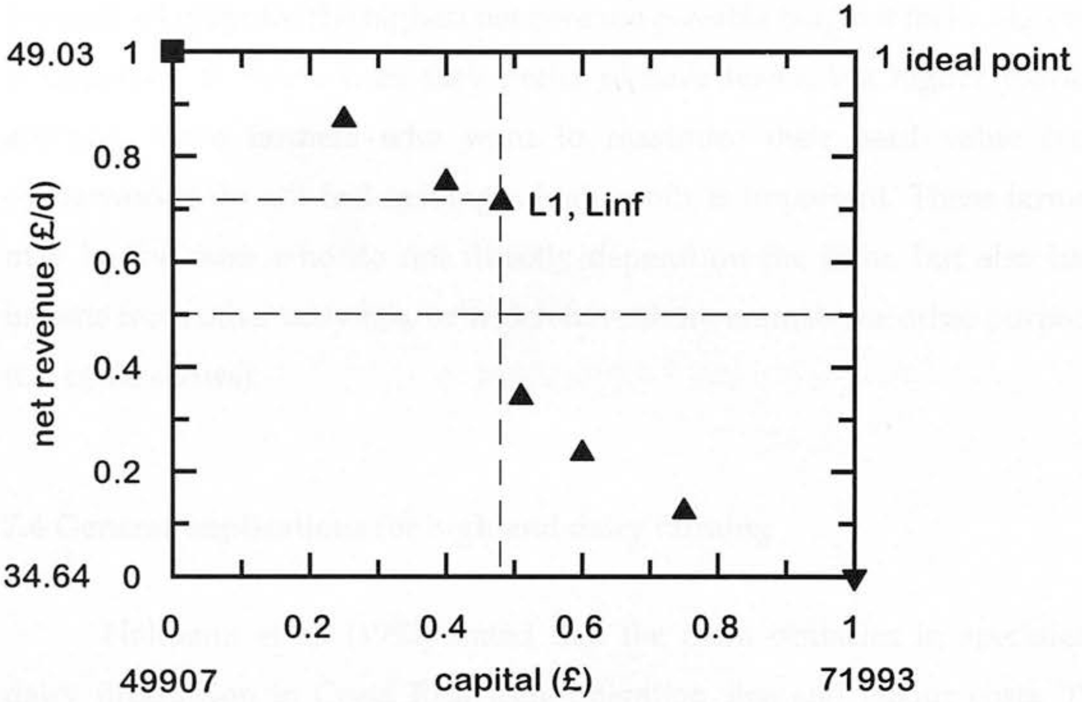

Figure 7.1. Optimal compromise between the maximisation of net revenue and capital in a medium-sized specialised dairy farm.

This type of analysis has important management implications. For the farm described above (50 ha, 915 kd/d quota), the compromise generates a net revenue of £44/d at a capital asset value in livestock of £60507. This is obtained by having a total herd size of 138 animals, with 51 lactating cows producing on average 19.7 kg milk/d; and consuming on average 4.5 kg concentrate/d. The method of concentrate allocation used in this strategy would be a 4:1 milk:concentrate ratio. Cows would need to graze at stocking rates of 3.2 cows/ha, under a 100 kg N/ha/yr fertilised, 25-day rotational grazing system, in 0.60 ha paddocks. Total land use would be 44.8 ha, thus leaving 5.2 ha for alternative enterprises.

This analysis has the advantage that it can also represent a variety of management styles. For example, farmers who would be in the compromise scenario would tend to be relatively risk-averse farmers, since they have a high value for profit, while at the same time knowing the importance of having enough animals, which in a worst-case situation could be sold. Farmers who opt for the highest net revenue possible may not feel a high risk is important to them, since they prefer to have fewer, but higher yielding animals; while farmers who want to maximise their herd value (very conservative) do not feel making a high profit is important. These farmers may be the ones who do not directly depend on the farm, but also have income from other activities, or which have dairy animals for other purposes (i.e. cattle shows).

7.4 General implications for highland dairy farming

Holmann et al. (1992) stated that the main obstacles in specialised dairy production in Costa Rica were operation size and labour costs. The results of the present study confirm their findings. For a herd with 30 cows, Ruiz et al. (1994) estimated that labour costs represented 33% of the variable, which is exactly the model outcome for a herd size of 36 cows. Since men are integers, there is a range in the number of cows before an extra person is employed. This range explains the small difference in the number of cows obtained between the two studies. Nevertheless, the present study suggests that labour costs do not represent a constant proportion of the variable costs. Labour costs are diluted as operation size is increased, simply because cow:men ratios are not constant, and increase with herd size. Therefore, labour costs represent a larger burden in smaller farms than in medium sized or big farms (33% vs. 26-28% of variable costs, depending on the objective).

The effects of operation size are important considering the current trends in prices and policies, since they are likely to determine the feasibility for farmers to continue dairying. Although the concept of an appropriate salary for a farm household [represented here by the net revenue, cautiously assuming little or no additional re-investment on the farm] is subjective, a pausible threshold net revenue for comparative purposes could be set around £300/month (£10/d or approx. $500/month). Under the present scenarios, dairying is still a profitable activity with herd sizes above 30 lactating cows plus progeny, 650-700 kg of daily milk quota, a grasslands area of about 30 ha, and concentrate supplementation at a 4:1 milk:concentrate ratio. This broadly reflects the results of other authors (Pomareda, 1994; Ruiz et al., 1994). Under the 20% concentrate price increase scenario, these farms are still above the net revenue threshold level (£15.36/d), but if the milk price is reduced by 10%, households with smaller farms than this would not survive by dairying alone. In this size of farm, trade-offs between dairying objectives are more difficult, since maximising net revenue only produced the threshold net revenue. Farmers wanting to compromise profit for capital assets (livestock) may not be able to achieve the threshold net revenue, since results from the compromise will always be lower that the results from the maximisation of single objectives. This suggests that these farms would require the degree of intensification associated with maximising net revenues to achieve the desired profit. However, in the example shown above for a 35 ha farm, not all the land was required for dairying by adopting the management strategies chosen, about 5 ha could be left for alternative uses. This would suggest that diversification is the long term option for smaller farmers to supplement their incomes from dairying, and that there are trade-offs and opportunity costs of using land for other purposes. These should be considered for smaller or agriculture/dairying mixed farms. From an environmental policy perspective, it would be ideal if farmers were given an economic premium by the government to reforest areas not required for grazing, rather than embark on activities not linked to conservation of natural resources and biodiversity. This could be seen as an opportunity cost for protecting biodiversity.

From a managerial perspective, it is clear that the systems could be improved. For example, van der Grinten et al. (1992) found that average stocking rates and concentrate use in the Poás region were 2.0 cows/ha and 6.1 kg/cow, respectively, while Ruiz et al. (1994) report stocking rates of 2.6 cows/ha, as a general figure for specialised dairy cattle farming. The results of the present work suggests that, in general terms, stocking rates could be increased to approximately 3.0 cows/ha, while decreasing average concentrates use between 1.3 - 3.0 kg/cow/d, depending on herd size and land use. Current practice is to give concentrates on a 2.5:1 milk:concentrate ratio, while the single best supplementation strategy appears to increase this ratio to 4:1. Nevertheless, it is important to notice that there is not a single strategy that does not use concentrates to achieve the milk production levels to fulfil the quota, which is a reflection on the limited nutritive quality of kikuyu grass. Also, the strategies that minimised concentrates use always produced the lowest net revenue, thus demonstrating the importance of concentrates in economic terms. According to CATIE (1990) and Pomareda (1994), supplementation costs account for 55-63% of the variable costs, which confirms the results of this study (52-64% of variable costs, depending on objectives). However, if concentrate prices continue increasing, this would mean that profits will tend to decrease, and that the systems have a limit. Under these circumstances, the need for using alternative feed resources instead of concentrates is imperative.

A promising output of this study is that management alternatives that do not compromise forest areas <u>do exist</u>, independent of production objectives. Although current average paddock sizes (approx. 0.75 ha) are similar to those predicted, the rotation cycles are different. Current rotation cycles are of 30 days approximately, while predicted ones seem to depend on production objectives. If maximisation of net revenue or cost minimisation are used, these could be reduced to 20-25 days; while they could be maintained at 30 days if the objectives were to have bigger herd sizes (i.e. maximisation of capital value or minimisation of concentrates use). Clearly, these strategies should improve land use.

This suggests that flexible management is the key issue for the sustainability and success of these systems and the households depending from them.

Chapter 8

General conclusions and future areas of research

Chapter 8

General conclusions and future areas of research

This study has demonstrated that integrating biological simulation and multiple-criteria decision making models is a suitable framework for the development of decision-support systems for pastoral enterprises. It has also shown suitable mechanisms for integrating biological, economic, social and environmental aspects to analyse farming systems from different perspectives and at different levels of aggregation.

It would be arrogant to believe that the models and the framework are complete. Systems research has often had the reputation for being oversimplistic, with dubious biological background and too aggregated. Although, a balance between theory, biological understanding and applicability was sought in the development of these tools, in the eyes of single discipline researchers, this work might have compromised some depth for breadth. However, these tools are a major step forward in the way existing models can be integrated into logical frameworks to solve real problems at the farm, regional and policy level.

The next sections will focus on areas of research which are believed to be required to improve and extend this framework to other production systems, in different agro-ecoregional zones.

In terms of grassland modelling, adaptation of the models to other pasture species, grass/legume associations and rangelands is required. This needs the incorporation of plant / water relations, a phenological submodel and a substantial amount of research on the ecophysiology of tropical pastures to parameterise these models. Studies on competition for above (C) and below (N) ground resources by plants are required, especially to develop management guidelines for maintaining sustainable grass/legume pasture and rangelands, and to prevent the common scenarios of pasture degradation presented in Chapter 1. A better understanding of plant competition and pasture degradation might also be obtained by incorporating aspects of population dynamics into these models. This would provide an important link into the study of grazing dynamics and the effect of vegetation structure and density on intake of tropical pastures.

From the animal standpoint there is a need to improve the knowledge and understanding about the interactions between the behavioural, ingestive and digestive constraints mentioned recently by Illius (1997) for predicting intake more accurately. It is not a trivial task to build models covering these aspects simultaneously, and even less to design experiments to prove the theories developed. However, intake studies with grazing animals supplemented at different levels, and with different nutrient ratios could provide a wider range of treatments than if these constraints were studied in unsupplemented grazing animals. These studies would also provide better descriptions of the incomplete and inconclusive data of supplementation on the grazing behaviour of ruminants available in the literature. There is also substantial work to be done on the factors controlling passage rates in grazing ruminants, especially on the effects of nutritive value and buoyancy on them. It is also necessary to develop simple methods to predict them for enabling their use in decision-support models. All these aspects might lead to improved predictions of the diets consumed by grazing animals and their performance.

The biological aspects of a grazing system are not complete without mentioning the soil, which is perhaps the most crucial element determining the biological sustainabilty of the system in the long term. There is a need for developing soil models that are easy to parameterise to be able to develop efficient nutrient cycling strategies for grazing systems. This is especially true in systems that rely on little or no fertiliser to sustain crop growth and subsequent animal production, and for the development of strategies for smallholder mixed systems, where the role of livestock as fertiliser providers is of crucial importance.

As a general trend, modelling biological systems is now a well established discipline in research programmes. Unfortunately, mathematical programming techniques are not as widely used, and they offer unlimited potential for designing and selecting holistic management strategies in grazing systems that cannot be attained by simulation alone. The MCDM models could be extended in several ways. The analysis could be applied to other objectives and farm sizes and could be expanded substantially to include other activities, if farms were mixed, or if seasonal resource compromises needed to be studied. For advisory purposes, if a wide span of farms was covered, then target values for the management variables could be set depending on quota size, land available, herd structures and other resources. Results could be monitored with the livestock information system and use the DSS for replanning as necessary. A variety of alternative nutritional management strategies based on other foodstuffs or combinations of them could be tested, as well as grazing management practices (i.e. leader/follower systems, use of other ruminants). Another interesting proposition would be to link a dynamic model of digestion with a linear programming diet formulation programme to work iteratively. This could be a major step in designing feeds and feeding programmes for ruminants, since feed descriptions could be dynamic and linked to the availability and use of farm resources. As a regional tool, spatial scales could be incorporated via GIS interfaces to study alternative land use management scenarios. The only limitation would be the time required to simulate the wide range of strategies and their combinations, but this is a decreasing problem due to the rapid development of computing technology.

From a herd management perspective, the decision support system needs to be expanded to study changes in reproductive policies and replacement decisions which are important in regions with marked seasonal differences in resource availability. At the same time, epidemiological models could be used to scale the productive responses and to calculate the costs and effects of certain diseases on the economic performance of the farms.

The development options for the DSS are multiple. However, the final test for any DSS is adoption of the strategies selected. With the current understanding of grazing systems, biologically feasible alternatives are easier to find than generating adoption. The problem does not lie in the theory, the problem is knowing what is attainable within the social and economic organisation of a region or country. What is feasible is largely determined by an understanding of the production systems and the farm households managing them. Unless greater efforts are made to increase understanding about the management of systems, and to educate the people managing them, the fate of DSS lies solely within the academic circles. The only way to break this trend is by using the DSS, going to the fields, observe, talk to farmers and see what their problems are with an open, unbiased mind. The time gap between science and the solutions to farmers' problems, needs to be shortened. At the end of the day the truth is out there!

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