THE INFLUENCE OF SOIL, TILLAGE AND OTHER FACTORS ON THE UPTAKE OF NITROGEN BY BARLEY

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DECLARATION

I, Ann Elizabeth Elmes, declare that this thesis was composed by myself. My contribution to this work included all the soil incubation work and much of the field work, crop sample preparation and analysis and statistical analysis. Staff of the Soil Science Department helped with field work and crop and soil analysis. M. F. Franklin of the A.F.R.C. Unit of Statistics organised the statistical analysis of data from Bush.

Signed

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ABSTRACT

Field experiments were conducted, using ^{15}N-labelled nitrogen fertilizer, to measure the absolute and relative uptakes of nitrogen by barley from (a) the fertilizer and (b) other sources. Results from 2 years of parallel experiments on several sites are presented, together with previous years' data from one site.

Interaction between the 2 sources of nitrogen was observed on imperfectly-drained soil at the Bush Estate, Midlothian. There was a general, positive response of unlabelled N uptake to increasing levels of applied, labelled N. There was no evidence of differences in readily-mineralizable N in topsoil due to differential rates of N application over several years. In general, crop yields were greater on the ploughed than on the direct-drilled plots. The exception was in 1979, when the spring was wetter and the summer was drier than in the other years.

The response of unlabelled N uptake to increasing levels of labelled N application seen at Bush was observed occasionally at the other, higher yielding, sites. It was observed more frequently at a site at Balerno (Midlothian), on soil derived from carboniferous till (as at Bush) than at Aberlady, East Lothian, on a raised beach soil. Uptake of unlabelled N generally increased towards the end of the growing season, while uptake of labelled N remained constant or fell. This phenomenon was observed at all sites. Of the various mechanisms possible for the interaction of nitrogen fertilizer with other sources of N, it was concluded that the most likely explanation of the results was a stimulation of crop root growth by the fertilizer, promoting greater exploitation of available N. Significantly higher quantities of N from both sources were taken up by winter barley than by spring barley.

In soil under autumn-sown barley, there was less available N in spring than in similar soil newly sown with spring barley. This highlighted the risk of leaching of available N in the soil before it could be taken up by the spring-sown crop. Laboratory measurements of N mineralization indicated a zero-order relationship with time in topsoil. There was also rough agreement with A-values calculated from crop uptake.

CONTENTS

CONTENTS PAGE

LIST OF FIGURES AND PLATES

LIST OF TABLES

REVIEW OF LITERATURE

CONTENTS

1 INTRODUCTION

1.1 The Nitrogen Cycle

Green plants (autotrophs) are able to trap and store solar energy in the form of organic compounds. When

FIGURE 1

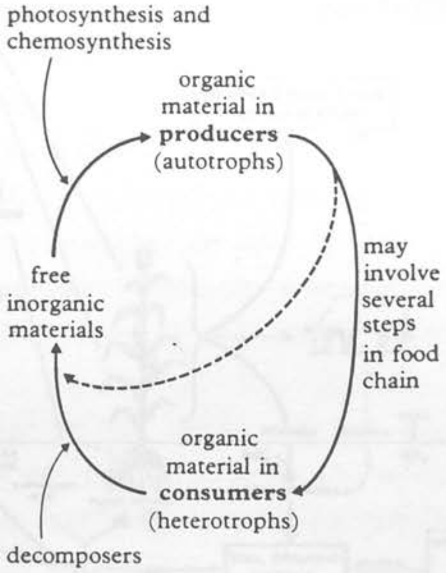


FIGURE 2

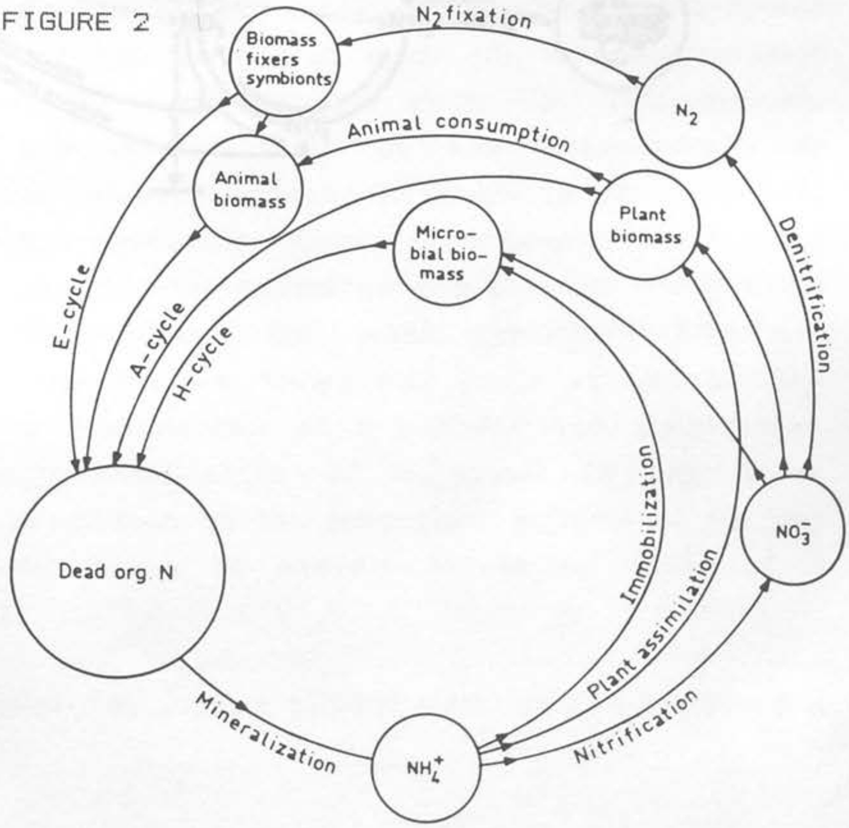
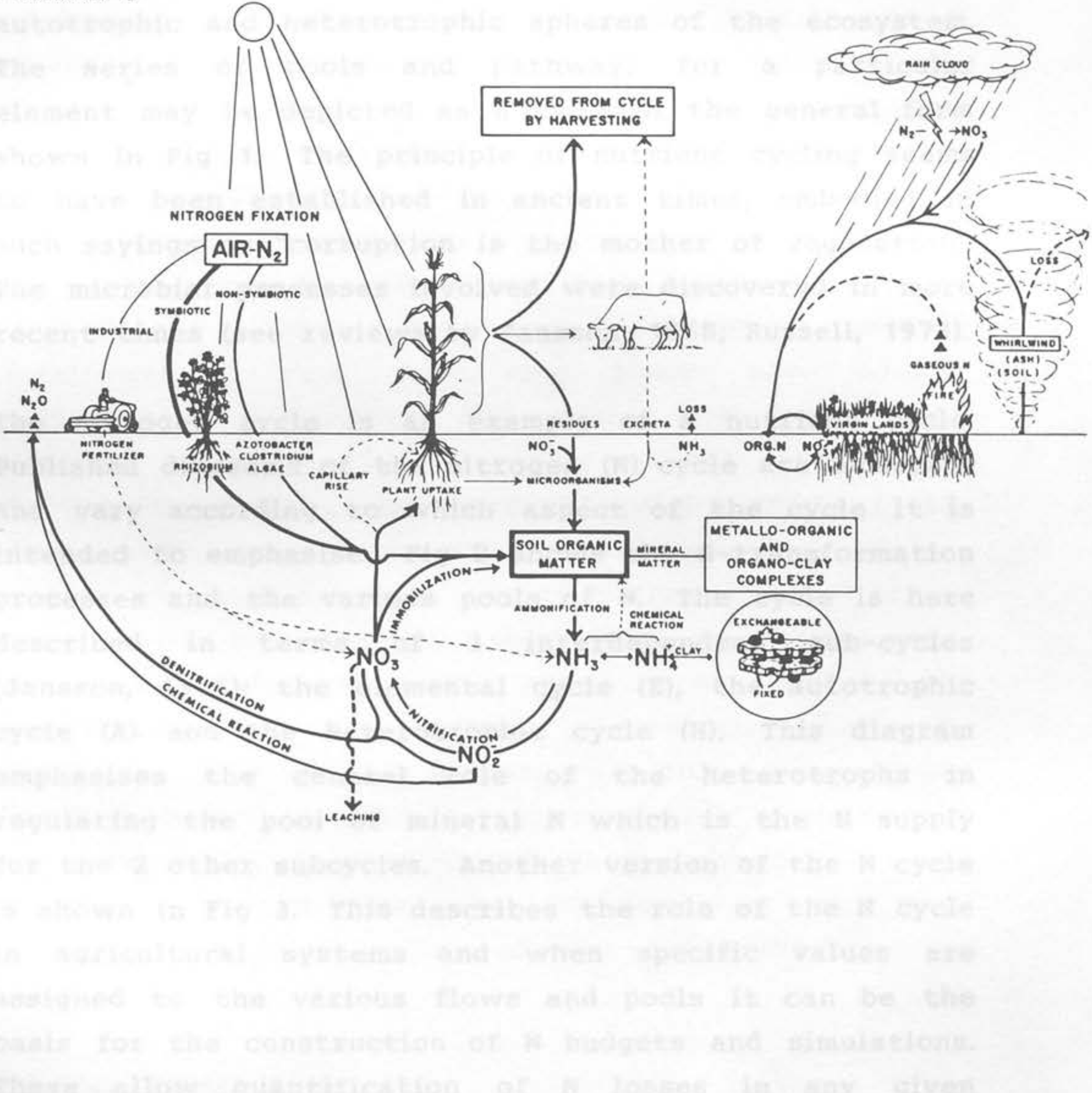


FIGURE 3


REMOVED FROM CYCLE BY HARVESTING
RAIN CLOUD
$N_2 \rightarrow NO_3$
NITROGEN FIXATION
AIR-N_2
NON-SYMBIOTIC
SYMBIOTIC
INDUSTRIAL
LOSS
WHIRLWIND
(ASH)
(SOIL)
GASEOUS N
FIRE
N_2
N_2O
NITROGEN FERTILIZER
RHIZOBIUM
AZOTOBACTER
CLOSTRIDIUM
ALGAE
CAPILLARY RISE
PLANT UPTAKE
RESIDUES
EXCRETA
LOSS
NO_3^-
NH_3
ORG.N
NO_3^-
VIRGIN LANDS
MICROORGANISMS
SOIL ORGANIC MATTER
MINERAL MATTER
METALLO-ORGANIC AND ORGANO-CLAY COMPLEXES
IMMOBILIZATION
AMMONIFICATION
CHEMICAL REACTION
EXCHANGEABLE
FIXED
CLAY
NO_3
NH_3
NH_4^+
DENITRIFICATION
CHEMICAL REACTION
NITRIFICATION
NO_2^-
LEACHING

plants die, these compounds enter the soil and the energy is used by heterotrophic soil organisms, which convert the plant material back into the inorganic compounds originally taken up by the green plants. Thus, although energy flows one way through an ecosystem, the nutrient elements are continuously circulated between the autotrophic and heterotrophic spheres of the ecosystem. The series of pools and pathways for a particular element may be depicted as a cycle of the general form shown in Fig 1. The principle of nutrient cycling seems to have been established in ancient times, embodied in such sayings as "corruption is the mother of vegetation". The microbial processes involved were discovered in more recent times (see reviews by Jansson, 1958; Russell, 1973).

The nitrogen cycle is an example of a nutrient cycle. Published diagrams of the nitrogen (N) cycle are numerous and vary according to which aspect of the cycle it is intended to emphasise. Fig 2 shows the N-transformation processes and the various pools of N. The cycle is here described in terms of 3 interdependent sub-cycles (Jansson, 1971): the elemental cycle (E), the autotrophic cycle (A) and the heterotrophic cycle (H). This diagram emphasises the central role of the heterotrophs in regulating the pool of mineral N which is the N supply for the 2 other subcycles. Another version of the N cycle is shown in Fig 3. This describes the role of the N cycle in agricultural systems and when specific values are assigned to the various flows and pools it can be the basis for the construction of N budgets and simulations. These allow quantification of N losses in any given system and prediction of the long-term effects of various treatments in terms of overall losses or gains of N (Clark, 1981).

Plants and micro-organisms obtain most of the combined N required for growth from the environment by the uptake of simple N compounds, particularly nitrate and ammonium. Soil N is mostly in organic forms which are unavailable for plant uptake. These complex organic compounds are slowly decomposed by the heterotrophic micro-organisms to ammonia (NH_3) which, in all but the most alkaline soils, equilibrates to ammonium (NH_4^+) ions (Schmidt, 1982). Losses of available mineral N that can occur at this stage include volatilization of NH_3, and chemical fixation of both NH_3 and NH_4^+. Some NH_4^+ is assimilated by soil biomass (immobilized) but generally, in the absence of sufficient carbon and energy supplies, most of the NH_4^+ in the rooting zone of well-drained soils is rapidly oxidised to nitrate (NO_3^-) by chemoautotrophic bacteria (nitrification). Thus, most crop plants have evolved mechanisms for handling NO_3^- (Olson and Kurtz, 1982) although there may be a greater energy cost to the plant in using NO_3^- rather than NH_4^+ (Miflin, 1980). In the absence of oxygen some micro-organisms reduce NO_3^-, a process that can result in loss of N from the soil if the product is a gas (denitrification). Nitrate is also easily leached from the soil profile as it is not held by the negatively-charged soil colloids. Leguminous plants, by association with N-fixing bacteria, are able to supplement the N from soil organic matter breakdown with N from the atmosphere. Non-leguminous plants must rely on soil mineral N, which may be supplemented by fixed atmospheric N in the form of man-made fertilizers or legume residues.

1.2 Crop Uptake of N

N is essential to plant growth and relatively large amounts of N, compared with other elements, are required to produce fast-growing, high quality crops. Chlorophyll, enzymes and proteins in general contain N. Ammonium and carbohydrates produced by photosynthesis are converted into proteins mainly in green leaves (Russell, 1973). An increase in N supply, compared with other nutrients, will allow extra protein production. This will increase growth rate and reduce the proportion of carbohydrate incorporated into cell walls. The photosynthetic area of a crop is generally related to N supply (Russell, 1973).

The response of crop yield to increasing rate of applied N has been investigated frequently and attempts made to describe the relationship mathematically. Such work has been reviewed by Viets (1965) and Russell (1973) and recent work in the U.K. is described by Sparrow (1979). The question of a possible negative relationship between the N content of grain and yield has been discussed by many workers, recently by Benzian and Lane (1981). Miflin (1980) considers there to be no good evidence for a necessary yield penalty being paid for increased N metabolism. Studies on the effect of timing of N applications on grain N content and yield have been reviewed by Olson and Kurtz (1982).

In recent years, the overall consumption of inorganic N in the U.K., and the average application rate, have increased steadily (Fertilizer Manufacturer's Association, 1981). This increase has been possible with the development of high-yielding crop varieties capable of responding to large inputs of N and a favourable economic climate (Royal Society, 1983). About half of the N applied is removed in the harvested portion of the crop. The rest is either retained in the soil or lost by leaching or to the atmosphere. As well as being expensive to the farmer such losses can cause problems elsewhere, e.g. NO_3^- in drinking water or NO and N_2O_4 as contributing factors to acid deposition (Royal Society, 1983).

The fate of N applied to soils has been investigated widely (Allison, 1966; Stevenson,1982). This review is limited to those studies in which tracer methods have been used. It also deals critically with field experimental techniques, methods of ^{15}N measurement and problems of interpretation of results.

2. USE OF NITROGEN 15 IN CROP AND SOIL EXPERIMENTS

2.1 Theory of Isotopic Tracer Methods

Isotopes of an element have the same number of protons in the nucleus (i.e. the same atomic number) but differ in the number of neutrons and thus have different mass numbers. An element under investigation may be labelled by substituting one isotope, the tracer, for another. For a brief historical review of this technique see Middleboe (1980). N has 2 stable isotopes, ^{14}N and ^{15}N, which occur naturally in an almost constant ratio; materials in which this ratio has been altered may therefore be used as tracers (Hauck and Bremner, 1976). Tracer studies of soil and fertilizer N generally use the technique of isotope dilution analysis, in which a known amount of tracer is added to a system containing an unknown amount of a test substance. After the tracer has been mixed uniformly with the test substance, the extent to which the tracer has been diluted in any sample taken from the system can be used to determine the amount of the test substance in the system.

The general formula used is:

$$S= s[(a_i/a_f)-1]$$

where:

a_i=initial specific activity of tracer

a_f=final specific activity of tracer

S=amount of test substance
s=amount of test substance associated with tracer

Ideally, a tracer should be chemically and physically indistinguishable, at the tracer concentration used, from the other isotope. The introduction of the tracer must not disturb the system, also, for tracer dilution analysis, both isotopes should be uniformly mixed.

2.2 Measurement of the Isotopic Ratio of N

The isotopic composition of a sample of N is usually expressed in terms of the ^{15}N content, either in absolute terms as a ^{15}N abundance in atom percent ^{15}N:

Atom % ^{15}N
=(number of ^{15}N atoms/total number of N atoms)x100

or, alternatively, with respect to the ^{15}N abundance of atmospheric N_2 which is generally accepted as 0.3663 ± 0.0004 (Junk and Svec, 1958):

[atom % ^{15}N of sample - 0.3663]
= atom % ^{15}N excess or depletion.

Two methods for isotopic ratio analysis are suitable for tracer investigations: mass spectrometry and emission spectrometry (Hauck and Bremner, 1976). The N atoms in gas are paired to form the molecules $^{14}N_2$, $^{14}N^{15}N$ and $^{15}N_2$. Both mass and emission spectrometric methods provide output signals which are proportional to the numbers of the three types of molecules. In optical emission spectrometry, N_2 molecules are separated on the basis of their vibration properties, while in mass spectrometry, charged ions are separated according to their mass to charge ratio (m/e). In any nitrogen gas mixture, the ^{15}N %

abundance can be derived from the equation:

$$A=[(^{30}N + 1/2\ ^{29}N) / (^{28}N + ^{29}N + ^{30}N)]x100$$

where A is the abundance.

If equilibrium exists between the three types of molecule, only the ^{28}N and ^{29}N signals need be measured (Fiedler and Proksch, 1975). The ^{15}N % abundance may then be calculated thus:

$$^{15}N\ \%\ abundance = 100/(2R+1)$$

where R is the ratio of the ^{28}N and ^{29}N signals.

Recent, comprehensive reviews on methods for N isotope ratio analysis, including sample preparation, have been written by Hauck (1982), Haystead (1983) and Middleboe (1983). These include references to the earlier work, e.g. by Rittenberg, upon which modern techniques are based.

2.2.1 Errors

The sampling, sample preparation, sub-sampling and analytical techniques used in ^{15}N work are all prone to error. Precautions must be taken to avoid cross-contamination between samples and loss or non-quantitative conversion of N (Bremner et al., 1966; Hauck and Bremner, 1976; Buresh et al., 1982). Furthermore, it has been established that significant losses of N from plant tops can occur between flowering and maturity, which are not due to systematic errors in methodology (Wetselaar and Farquhar, 1980). Thus fertilizer recovery measurements made at harvest may be underestimates, because they do not include any fertilizer N that was taken up by the plant but then lost before maturity. Explanations for such losses include translocation, leaching and volatilization.

2.3 Field Use of Labelled N Fertilizers

The use of labelled fertilizers enables the N in the plant from a fertilizer application to be distinguished from the N derived from other sources. These other sources include the soil organic matter, residual unlabelled fertilizer etc.. In fact, the measurements made are the proportions of crop N derived from 2 sources: the labelled N fertilizer application and all other sources. Thus, using labelled N fertilizer, fertilizer N uptake may be determined directly. The degree of enrichment required varies with the type of experiment. Analysis of the results of an international programme of maize fertility experiments has shown that the use of fertilizer enriched in ^{15}N by as little as 0.3 atom% would have enabled the same conclusions to have been reached, without appreciably increasing the error, as with the more highly enriched fertilizers actually used (Rennie and Fried, 1971).

Without the use of labelled fertilizers, fertilizer N uptake by a crop may be determined by an indirect method. This method involves subtracting the N uptake of an unfertilized crop from that of a fertilized crop and assumes that the soil N contribution is unaffected by the application of N fertilizers. This assumption may be checked using a tracer and is discussed in a later section (2.4.2). The use of tracers involves the assumption that there will be no isotopic discrimination during chemical or biochemical transformations in crop or soil. This is not always valid (Bremner et al., 1966). Delwiche and Steyn (1970) measured slight discrimination against ^{15}N in nitrification and some other microbial reactions. In the soils investigated, the net result of these and other discriminatory processes was that the abundance of ^{15}N varied between 0.004 and 0.002 atom% excess with reference to the atmospheric value of 0.366 atom% ^{15}N. However, the variability of ^{15}N in soils is not considered to be great enough to introduce serious difficulties into tracer experiments using ^{15}N-enriched or ^{15}N-depleted materials (Broadbent et al., 1980). It was suggested by these authors that the ^{15}N content of the untreated soil be used as a reference value for tracer experiments rather than the theoretical value of 0.366 at% ^{15}N, particularly when ^{15}N-depleted materials are used.

2.4 Interpretation of the Results of Tracer Studies of the N Cycle

2.4.1 Internal N cycle Theory

The data obtained using labelled N fertilizers should be interpreted with caution. This is due to the purported existence of rapid mineralization-immobilization turnover, i.e. the internal N cycle in soil (Jansson, 1958). Although measurement of the proportion of crop N derived from a labelled N application is unambiguous (Broeshart, 1974), information on fertilizer recovery by a crop is not. For example, when ammonium-N is applied to soil, if nitrification is slow, resulting in the applied ammonium remaining for a relatively long period, then a greater proportion of applied N will become included in and equilibrated with, the N in the internal cycle. This will result in a lowered proportion of fertilizer N in the plants, though the indirectly determined effect of the fertilizer application may be the same as that in rapidly nitrifying soil. The pathway of the internal cycle is not considered to include the nitrate pool, thus nitrate will not equilibrate with the cyclic N, but possibly be diluted by mineralization outflow (Jansson, 1958). The role of nitrate in the internal N cycle is discussed further in a later section (2.4.3). In view of the possible effects of the internal N cycle in soil on the results of tracer experiments, the net effect of fertilizers on crop yield and N content should still be measured by the indirect method. However, the processes which bring about these effects can be investigated using tracers in conjunction with the indirect method (Jansson, 1958).

2.4.2 "Priming Effects"

Early experiments using ^{15}N as a tracer showed the apparent stimulation or suppression of the decomposition of soil organic matter on the addition of organic materials (Broadbent and Norman, 1947). This effect of manures on mineralization became known as "priming action", or the "priming effect" (Bingeman et al., 1953). The same terms have also been used for the similar apparent (positive or negative) effects of inorganic N fertilizers on mineralization in the absence or presence of crops (Broadbent, 1965; Hauck and Bremner, 1976). A positive priming effect, i.e. greater unlabelled N uptake by treatments receiving applications of labelled N fertilizers than by those grown on unfertilized soil, has been measured in both field and pot experiments. Both ^{15}N-enriched ammonium (or ammonium-releasing) fertilizers (Legg and Allison, 1960; Aleksic et al., 1968; Westerman and Kurtz, 1973; Yoshida and Padre, 1977; Riga et al., 1980) and nitrate fertilizers (Stewart et al., 1963; Legg and Stanford, 1967; Dowdell and Crees, 1980; Sorensen, 1982) were used in these studies. Results of this nature invalidate the assumption made when fertilizer N uptake is determined by the indirect method described previously. However, some workers have found no effect of labelled N fertilizers on uptake of unlabelled N (Olson et al., 1979; Myers and Paul, 1971; Leitch and Vaidyanathan, 1983).

Also, depression of unlabelled N uptake with increasing applications of labelled N has been observed (Campbell and Paul, 1978).

Where plant uptake of N from labelled soil organic N has been measured, the addition of unlabelled inorganic fertilizers also results in increased uptake of labelled N for the fertilized treatments when compared with the unfertilized control (Stewart et al., 1963; Filiminov and Rudelev, 1977; Sorensen, 1982). Explanations for this real, or apparent, effect of inorganic N fertilizers on the mineralization of soil organic N have been numerous and varied (Hauck and Bremner, 1976). Some are discussed here. Among those who consider a real stimulation of mineralization to take place, Westerman and Kurtz (1973) offer the explanation that addition of inorganic N stimulates microbial activity. This increased activity would then result in an increase in decomposition of organic matter. A similar explanation was proposed by Broadbent (1965). Others (Legg and Stanford, 1967) concluded from pot experiments that, since the major source of energy for the soil microorganisms would be plant roots, if these were low in N the microorganisms would immobilise the N mineralized from the soil organic matter to a greater extent than if the roots were high in N, i.e. if the plants were receiving N fertilizers. This explanation was not considered to be normally applicable to field crops.

Another explanation is an extension of a controversial theory of mineralization. This is that ammonium formation in soil is not caused by microorganisms, but is due to the protolytic action of water, thus priming is due to an increase in the supply of protons when fertilizers are applied (Laura, 1975). Other workers did not consider a real increase in soil N supply to take place, and concluded that priming was simply a more efficient use of that available by the fertilized plants (Aleksic et al., 1968; Fried and Broeshart, 1974; Sorensen, 1982). Using a split root technique, Sapoznikov et al. (1968) demonstrated that uptake of additional amounts of soil N by plants occurred even when there was no contact between the fertilizer and the soil and therefore that plant physiological factors were involved.

The effects of various salts on the mineralization of soil organic N has been investigated by Broadbent (1965) and Westerman and Tucker (1974). They concluded that the suggested salt effects, namely osmotic effects on the cells of microorganisms (Broadbent, 1965), or solubilization of organic matter (Westerman and Tucker, 1974), could only be partly responsible for the priming effects observed.

With reference to the possible involvement of non-biological processes in the mineralization of soil organic N (Laura, 1975) the results of an experiment performed by Jansson (1958) are pertinent. During attempts to differentiate between chemical fixation and biological interchange of ammonium, two sets of soil samples to which labelled ammonium had been added were autoclaved. One set of samples was inoculated with 1ml of a soil/water suspension while the other was kept sterile. Both sets were then incubated for 59 days. The results showed that interchange of ammonium between organic and inorganic forms occurred in the inoculated samples but not in the uninoculated ones, which also showed no carbon mineralization, i.e. were sterile. From this work Jansson (1958) concluded that biological processes are the only ones able to cause ammonium formation in soil.

No measurements of biomass size were made in the above-mentioned experiments in which a priming effect was observed. Where this has been done (on the Broadbalk site at Rothamsted) a possible real priming effect was measured, but only due to the effect of years of N fertilizer applications in increasing residue levels and biomass size relative to unfertilized plots (Shen et al., 1982). An alternative explanation for apparent priming effects is that they are a manifestation of the mineralization-immobilization turnover in soil (Jansson, 1958) mentioned previously. This view is supported by Stewart et al. (1963) and Jenkinson et al. (1981).

Those who object to this biological interchange explanation for priming (Broadbent, 1965; Westerman and Tucker, 1974) claim that the following assumptions are necessary for this theory to apply: that immobilization of fertilizer N results in mineralization of a proportional amount of soil N, and that mineralization must occur first followed by immobilization and that the process is not continuous. However, the original proponent of the biological interchange theory, Jansson (1958), does not consider such assumptions to be required or that they are valid (Jansson and Persson, 1982).

2.4.3 The Role of Nitrate

Attempting to understand the role of nitrate fertilizers in this context is complicated by the observation that the heterotrophic microflora responsible for mineralization-immobilization prefer ammonium- to nitrate-N (Jansson et al., 1955; Broadbent and Tyler, 1965; Novak et al., 1981). These workers found that ammonium was immobilized more rapidly, and to a greater extent than nitrate. This result is supported by the observation that, when the formation of nitrate from ammonical fertilizers is prevented by the use of a nitrification inhibitor (A.T.C.), the amount of labelled N in the microbial biomass, compared to the non-A.T.C. treatment, was almost doubled (Juma and Paul, 1983). Nitrate appeared not to be used extensively by the heterotrophic soil organisms, in slightly alkaline soils, unless considerable energy material is added with it (Jansson, 1958; Broadbent and Tyler, 1965). However, immobilization of nitrate, "regardless of the presence of ammonium" has been reported (Overrein, 1967) in acid soils. Also, Stanford, Legg et al. (1973) grew sorghum in pots containing various soils and fertilized with ^{15}N-enriched $NaNO_3$. They found that recoveries, by the whole plants, of soil- and fertilizer (nitrate)-derived N were similar, which indicated to them that the different mineral N sources comprised a common pool with respect to mineralization-immobilization or other reactions affecting N availability to plants. Thus, although the pathway of the internal N cycle in soil is not considered generally to include nitrate , under certain conditions e.g. net immobilization, nitrate may enter the internal cycle, giving rise to an apparent priming effect (Jansson, 1971).

2.4.4 "A values"

The use of "A values" in the interpretation of tracer data has been discussed by a number of workers (Fried and Broeshart, 1974; Westerman and Kurtz, 1974; Jansson, 1971; Hauck and Bremner, 1976). In the original paper on the concept of the A value, Fried and Dean (1952) mentioned the probability of overestimating the availability of a mobile soil nutrient, due to the applied nutrient "becoming indistinguishable" from the native nutrient. They also discussed the effects of factors such as root growth, multiple nutrient sources and fertilizer availability on the interpretation of A values. It was also pointed out that the A values for sequential sampling are, in terms of the nutrient, equivalent to the nutrient in the standard applied, which has been in the soil for varying periods. Thus Jansson´s (1971) comment that "added standard N in these investigations may have been distributed to several of the pathways and pools of soil N" is relevant to the interpretation of A values calculated on the basis of ^{15}N additions to soil.

2.5 Field Crop Experiments Using Labelled Nitrogen Fertilizers

2.5.1 Introduction

The results have been published of numerous field experiments in which labelled N fertilizers were applied. Some of those relevant to soil N supply are reviewed here, together with a more detailed summary of work on the effects of cultivation methods.

Many experiments, which were designed with a specific aim, such as the comparison of different methods of fertilizer application, do not include an unfertilized control or use a single rate of N. Also, there are very few examples of crop samples being taken before maturity. Thus, the majority of field experiments using labelled N can provide only limited information on the supply of N from the soil. Some data on the effect of rate of N application on soil N uptake have been discussed above (section 2.4.2).

2.5.2 Results of General Interest

Where labelled N fertilizers have been applied at more than one rate, a number of basic relationships have been investigated. For example, the proportion of an N application that is immobilized, and whether this varies with the rate of application. Increasing percentage recoveries of fertilizer by wheat, with increasing rate of application (Hamid, 1972) suggested that a large proportion of the lower rate was made unavailable to the crop. Measurement of total N residues in soil after cereal crops (Yoshida and Padre, 1977; Olson et.al., 1979) indicated that the proportion of a N application made unavailable decreased with increasing application rate. Decreasing fertilizer recovery with increasing rate of applied N is generally associated with a poor yield response to N, also giving a decrease in unlabelled N uptake with increasing N rate (Myers and Paul, 1971; Bigeriego et al., 1979).

The proportion of N in maize derived from fertilizer decreased throughout the season if the fertilizer was all applied at planting (Bigeriego, 1979), but increased with time for later applications. This indicated that delayed application resulted in more active uptake of fertilizer N later in the season. Less of such applications was immobilized in vegetative parts of the plant, resulting in higher proportions of fertilizer N in grain at harvest, a result confirmed by others (I.A.E.A., 1974; Leitch and Vaidyanathan, 1983).

2.5.3 Results of Experiments involving Contrasting Tillage Treatments

The effects of tillage on crop N use have been investigated using labelled N fertilizers. Comparisons have often been made between two extremes: ploughing and minimal tillage (direct drilling), the latter technique having become feasible since the introduction of herbicides. Effects of direct drilling on crops are often related to the fact that the relative lack of soil disturbance affects the bulk density, strength, and drainage characteristics of the soil. These properties in turn influence crop emergence, rooting and water supply (O´Sullivan and Ball, 1982). Effects on rooting have been reviewed by Baeumer and Bakermans (1973). Lower root weights in undisturbed soils are often accompanied by shallower rooting, especially during early vegetative growth. However, different soils respond differently when cultivations cease and rooting may be unaffected (Ellis et.al., 1979).

Many workers have measured the effects of soil disturbance on mineral N levels in soil and have concluded that N mineralization is greater in disturbed than in undisturbed soils (Arnott and Clement, 1966; Dowdell and Cannell, 1975; Powlson, 1980). Organic matter levels under contrasting cultivation systems have been measured (Powlson and Jenkinson, 1981) with precautions taken to avoid errors due to differing bulk densities. The conclusion from this investigation was that a change from traditional ploughing to direct drilling had little effect on levels of soil organic matter. The suggested explanation was that the annual balance of mineralization and immobilization was not influenced by tillage although seasonal differences were indicated. Use of labelled N fertilizers has shown there to be generally no significant differences between the uptake of unlabelled N by crops established following contrasting cultivation methods (Legg et al., 1979; Dowdell and Crees, 1980). However, Leitch and Vaidyanathan (1983) found that direct drilled winter wheat took up on average, less unlabelled N than the crop in the cultivated soil. The greatest effect of lack of cultivation was seen before fertilizer application, when the direct drilled crop showed poor initial growth, attributed to low soil N availability.

Crop response to N fertilizers and the timing of N uptake appear to be different for direct drilled crops. A review of results of determinations of crop N content at various growth stages (Baeumer and Bakermans, 1973), showed higher N concentrations in younger direct drilled plants and indicated greater fertilizer recovery by the direct drilled crop. Results from a long-running experiment in Scotland (Holmes and Lockhart, 1970; Holmes, 1976) show a consistent interaction between the effects of tillage and rate of applied N on the yield of spring barley, with relatively low yields for the direct drilled crop at the zero and low N treatments. The direct drilled crop also showed a delay in N uptake, resulting in high grain N content. The proportion of crop N derived from labelled fertilizer applications was measured at 2 immature stages for maize (Legg et al., 1979). For each rate of N applied, this proportion was similar at both stages for the ploughed treatment but lower at the later stage for the direct drilled crop.

The use of labelled N fertilizers with contrasting cultivation methods often shows greater recovery of applied N by direct drilled crops (Legg et al., 1979; Fredrickson et al., 1982; Leitch and Vaidyanathan, 1983), although sometimes tillage has no significant effect (Vaidyanathan, 1979; Dowdell and Crees, 1980). Greater water storage in undisturbed soils (Fredrickson et al., 1982) can result in a greater crop response to applied N. Other explanations which may be more applicable to U.K. conditions include: reduced biological activity, resulting in less immobilization (Leitch and Vaidyanathan, 1983), and restricted rooting in undisturbed soils (Finney and Knight, 1973).

3. MEASUREMENT AND PREDICTION OF AVAILABLE NITROGEN IN SOIL

3.1 The Present Basis for Fertilizer Recommendations

A known amount of N is required by each crop of given yield. In the present context i.e. Scottish agriculture in the early 1980's, much of a barley crop's N requirement will be met by fertilizer applications. However, in order to use only as much fertilizer as is necessary, an estimate of the N the crop may obtain from other sources is needed. Available N is produced in soil as a result of mineralization, i.e. the release of ammonia as a waste product of the conversion of organic substrates into microbial tissue and energy. Immobilization takes place simultaneously, as some N is incorporated into microbial tissue. The substrates for mineralization are the soil organic matter, crop residues and animal wastes or other microorganisms. Net mineralizable N may be directly measured by biological methods; however, any such measurement is of no practical significance on its own. A number of soil, climatic, management and other factors will affect the release of soil N in the field. Also, all that released may not remain available for plant uptake, because of re-immobilization, leaching etc.. Thus, only when such factors are taken into account, together with the expected crop's response to N, can measurements of net mineralizable N provide a basis for the adjustment of fertilizer recommendations.

The state agricultural advisory services and chemical industries in many countries provide fertilizer recommendations for farmers. In Scotland, the state advisory service is provided by the three agricultural colleges: the East of Scotland College of Agriculture, the North of Scotland College of Agriculture and the West of Scotland Agricultural College. Generally separate fertilizer recommendations are provided in each area (E.S.C.A., 1983; N.S.C.A., 1978; W.S.A.C., 1975). In the south-east (East College area) the first criterion when choosing an appropriate N fertilizer recommendation for a crop is farm type. Three categories are given; intensive cash cropping farms or where rotational grass is conserved, arable farms with approximately 1/4 of the cropping area in grass including grazing livestock, and grass-arable farms with at least one half of the cropping area in rotation grass.

For each farm type:

1. an average annual rainfall is given; this allows for adjustment of N recommendations if a particular farm type happens to be in an area where the rainfall is not typical for the farm type in question.
2. various rates of N application are recommended for a crop, depending on its place in the rotation e.g. high if after cereals, lower if after roots eaten in situ.

Appropriate adjustments to the recommended rates are advised for undersown crops and if the previous crop's straw was ploughed in. In the North College area, an assessment of the soil N status is required in order to use the recommendations provided. Three levels are used: low, moderate and high. These are assigned according to farm type, previous cropping and soil type. The West of Scotland Agricultural College also uses a soil N status system. There are four levels, assigned on the basis of previous crop and system of farming. For all areas information is provided on the N contribution of organic manures to arable crops according to type and time of application; adjustment of mineral N applications to account for this contribution is advised. All areas also recommend extra applications of N to compensate for any loss of residual N during wet winters. However, the advice is confined to dry areas (<750mm annual rainfall) in the west and to sandy soils in dry areas in the north. Only in the north and east is a reduction in N application recommended to allow for residual N after very dry winters.

The current basis for fertilizer recommendations in England and Wales is previous cropping and manuring as quantified by the soil N index. There are three indices, and for each the recommended rate of N application varies with soil type (M.A.F.F., 1982a). In the U.S.A. a similar, more or less subjective approach is used and only 2 out of 50 states use any form of mineralizable N determination (Keeney, 1982).

Direct measurements of net mineralization of soil organic N are, however, useful in the investigation of N transformations in soil and in the development of mathematical models of the processes involved in the supply of N from the soil (Addiscott, 1983). Such models are likely to be the basis of any improvement in the precision of N fertilizer recommendation (Needham, 1982).

Many methods for obtaining a measure of future soil N availability have been described and relationships with crop performance established (Harmsen and Van Schreven, 1955; Bremner, 1965a; Keeney, 1982). It is intended only to review those methods based on the measurement of net N mineralization which have been compared with field crop data, also to mention the role of measurements of profile mineral N and some of the rapid chemical tests that have been developed.

3.2 Measurement of Mineralizable N: Techniques

In general, soils are incubated under conditions which promote the mineralization of soil organic N and the quantity of mineral N in the soil before and after incubation is determined. Thus the NET mineralization is measured (and this is what is implied whenever "mineralization" is mentioned in subsequent discussion). This measure of mineralization is tested by correlation with crop N uptake or response to applied N, preferably obtained from field trials.

A method used extensively in the 1950's and early 1960's (Bremner, 1965a) was apparently based on work aimed at"predicting nitrogen fertilizer needs of Iowa soils" (Fitts et al., 1955; Stanford and Hanway, 1955; Hanway and Dumenil, 1955; Munson and Stanford, 1955). For this method the nitrate-N formed on incubating re-wetted, air-dried soils for 2 weeks at 35°C was measured. The soil sample was first mixed with vermiculite to improve its physical condition and then leached repeatedly with water (to remove any nitrate and thus eliminate the need to determine the initial nitrate content). Excess water was then removed by suction. The relationship between the result of this soil test and the yield response to applied N was established by a large number of field experiments over several years (Hanway and Dumenil, 1955). As a result, this soil test was considered to be a sound basis for the prediction of N needs of maize crops in Iowa. The only exception was for maize crops following a legume crop. A preliminary incubation experiment (method similar to that described above except no pre-leaching or vermiculite) had indicated that the amount of nitrate released in samples taken before the first and second maize crops after a legume crop did not always correlate with the yield reduction in the second crop compared with the first (Andharia et al., 1953).

In England mineralizable N determinations by incubation, with a view to forecasting crop response to applied N, were also being carried out at the same time, by Cooke and Cunningham (1958). They also used samples taken from the top 15cm of arable soils in spring. Fresh and re-wetted air-dried soil was incubated at 18°C for 30 days and increases in nitrate- and ammonium-N were determined. Later work (Gasser, 1961; Eagle, 1961) included correlations with crop yield and response to applied N. Generally, mineralization is stimulated by air-drying, especially in the early stages of incubation (Winsor and Pollard, 1956). Both Eagle (1961) and Gasser (1961) obtained closer correlations between mineralizable N and crop data when air-dried soils were used. The use of air-dried soils has been justified by the observation that the entire surface of an arable soil may be effectively air-dried during dry periods in summer (Cooke and Cunningham, 1958). Also, sample handling is easier than with field-moist samples. The depth to which the soil samples were taken was not mentioned in the above investigations (Eagle, 1961; Gasser, 1961) but were generally taken in spring and all were form arable sites. In later work Eagle (1963) correlated the yield response of winter wheat to applied N, over 4 seasons, with soil N status as assessed by his incubation technique (Eagle, 1961). The correlation was much improved by taking into account the ploughing depth, where this differed between sites. Eagle's (1961) soils were incubated at 35°C for 7 days between layers of vermiculite and Gasser's (1961) for 21 days at 25°C. The latter incubation technique was among the methods used to estimate potentially available N in field experiments with sugar beet (Last and Draycott

, 1971). The estimates obtained by analysis of soil samples, taken both in spring and autumn, were correlated with the sugar yield response to N and the optimum N application. The best correlation was obtained with the results from an anaerobic incubation (Waring and Bremner, 1964) of air-dried spring samples. Keeney (1982) has reviewed other applications of this technique.

A more theoretical approach to the estimation of future N mineralization involves a detailed study of the processes of mineralization and immobilization and the fractions of the soil organic matter involved, with a view to modelling the whole process. Stanford and Smith (1972) conducted a study of the long-term mineralization capabilities of a number of widely differing soil types. Air-dried soils were mixed with vermiculite and leached free of nitrate, an N-free nutrient solution was added and excess removed under suction. The samples were subsequently incubated at 35°C for 30 weeks and leached at 2-week intervals with 0.01M $CaCl_2$ and N-free nutrient solution. The cumulative net nitrate-, nitrite- and ammonium-N mineralization measured was found to be linearly related to the square root of time, throughout the period, for all but a few of the soils. It was also shown that the data could be treated as if the mineralization rate, under this particular set of environmental conditions, was proportional to the quantity of mineralizable substrate in the soil. Thus, the kinetics of N mineralization could be described by the first order equation :

$$\log (N_o - N_t) = \log N_o - k/2.303\ (t)$$

where:

N_t= N mineralized (mg kg^{-1} cumulative) at time t

t= time (weeks)

k= the mineralization rate constant

N_o = N mineralization potential (mg kg^{-1})

N_o represents an "active fraction" of soil organic N.

The estimate of N mineralization potential obtained at 35°C for 11 of the soils was used to calculate k at 5, 15 and 25°C using results for cumulative mineralization over 24 weeks at these temperatures (the incubation conditions were otherwise similar) the slope of log (N_o -Nt) against t being k/2.303 (Stanford, Frere et al., 1973). It was assumed that N_o was unaffected by temperature and that the estimate obtained at 35°C was the most reliable. The relationship between k and temperature did not differ significantly between soils and a Q_{10} for k of approximately 2 was obtained.

Stanford and Epstein (1974) investigated the relationship between soil N mineralization, soil water content and soil matric suction. Increments of distilled water were mixed into air-dry soils, giving a range of soil water contents, while the relationship between matric suction and soil water was determined using the pressure membrane method (Richards, 1965). Thus soil water content could be expressed as a percentage of the optimum for N mineralization (a soil water potential in the region of -30 kPa i.e. field capacity as defined in the U.S.A.). The percentage optimum water content was directly correlated with a reduced rate of N mineralization (mineral N accumulated after 2 weeks at 35°C) between the optimum and the permanent wilting point, for 9 widely-differing soils. Pot experiments using sorghum (Stanford et al., 1973) indicated that N_o offers a basis for reliably estimating amounts of soil N mineralized during selected periods of time under specified temperature regimes. A more rapid method for the determination of N_o was developed (Stanford et al., 1974), involving a pre-incubation to remove any partially decomposed or undecomposed crop residues and overcome any lag in microbial activity. Stanford et al. (1977) used the relationships established between mineralization rate, temperature and moisture to estimate monthly N mineralisation with N_o determined for the soil (to 45 cm) from field experiments with sugar beet in Idaho. Reasonable success in estimating N uptake in the field was achieved when residual nitrate-N was included with N mineralization estimated using N_o and adjusted for moisture and temperature.

The definition of mineralization as a first-order decomposition process has been incorporated into prediction models (Burns, 1980; Richter et al., 1980) which gave encouraging results when tested against experimental data. Addiscott (1983) hoped to apply this approach to the results of incubations of English (Rothamsted) soils, but found that it was not necessarily the most appropriate interpretation. The soils had not been air-dried and were leached prior to incubation. Modelling of N mineralization according to zero-order kinetics has been more successful under English conditions (Addiscott, 1983; Whitmore, 1984).

The results of aerobic incubations are influenced by the treatment of the soil sample before incubation and the type of mineral N determination, thus many incubation procedures have been criticised as leading to errors (Bremner, 1965a; Keeney, 1982). The effect of factors such as the time of sampling (Last and Draycott, 1971), depth to which soils are sampled (Eagle, 1963) and whether or not the soils are air dried (Eagle, 1961; Gasser, 1961) have been mentioned already. Other factors such as time of dry or cold storage (Westfall, 1978; Selmer-Olsen et al., 1971) and grinding and sieving (Craswell and Waring,

1972) have been investigated relatively recently. The method used in rewetting dried soils or in adjustment of soil water content prior to incubation can also influence results. Cassman and Munns (1980) used a pressure membrane equilibration method to obtain a range of soil water contents in air-dried soils for incubation. This method was compared with the mixing method used by others e.g. Stanford and Epstein (1974). The nature of the relationship between soil water content and net N mineralization (during incubation for 2 weeks at 25°C) obtained using pressure membrane equilibrated samples was different to that found using mixed samples. The relationship found using the mixed samples was similar to that obtained by other workers using this method for soil moisture adjustment. The leaching of soil samples either before or during incubation has been severely criticized (Bremner, 1965a). Smith et al. (1980) measured the amounts of organic N removed from incubating soils by the common procedure during which leachates are analysed for mineral N only. They concluded that the consequent removal of mineralizable substrate significantly affected the values for mineralization potential (N_o) and the mineralization rate constant (k) obtained when compared with the values obtained using total N leached. Other objections to leaching, including the possible incomplete removal of ammonium-N and concerning the use of nutrient solutions, have been reviewed by Keeney (1982). Provision of adequate aeration while preventing excess water loss during incubation also presents problems in the design of methods which have not always been successfully overcome (Keeney, 1982).

The methods described for the determination of mineralizable N have all been somewhat restricted in application e.g. to certain cropping systems, or have included pre-treatments to remove the effects of undecomposed residues. This approach ignores the importance of trying to measure the contribution of grass and legume leys to the available N supply. Workers at the Grassland Research Institute, Hurley used a measure of N status based on incubation which correlated well with the N uptake of winter wheat. The wheat uptake results were from 6 seasons' crops following various leys of 3-4 years duration established on arable soil (Williams et al., 1960; Clement and Williams, 1962). The measure of N status used was the mineral N in soil incubated aerobically at 30°C for 20 days. Soil samples to a depth of 15 cm were taken immediately before the leys were ploughed, bulked and screened (7mm); stones and top growth, including stolons, were removed. The samples were stored in polythene bags at -15°C. Frozen portions for incubation were removed and thawed overnight on tension tables to reach -7.4 kPa matric potential. It was noted that varying proportions of grass and clover roots in the soil did not affect the N-status and that mineral N was not limiting microbial activity at Hurley, where severe leaching loss is not likely.

As mentioned previously, the general experience in the U.K. has been that the results of soil analysis are not as useful for soil available N prediction as an assessment of N status based on previous cropping and manuring.

3.3 Use of Chemical Methods

Many rapid chemical tests for potentially available N in soil, based on a single extraction, have been proposed (Keeney, 1982). In many recent methods, the extractant, water or a salt solution, is used hot. Oien and Selmer-Olsen (1980), proposed a method in which soil was heated in 2M KCl for 20 hours at 80°C. The extract (which contained the original N present and that released) was analysed for ammonium- and nitrate-N. This method was evaluated by pot experiment (Selmer-Olsen et al., 1981). A good relationship (r=0.87) was found between the inorganic N content after hydrolysis and N uptake by oats for 36 soils. Independent work by Whitehead (1981) included development of a method in which nitrate- and ammonium-N were determined in an extract obtained by boiling soil with 1M KCl for 1 hour. The N extracted from 36 soils was closely related (r=0.90) to the N uptake of ryegrass grown in pots of the same soils. Jenkinson (1968) evaluated some of the commonly used methods and one based on biomass measurement (barium chloride-extractable polysaccharide). The set of soils used had been analysed previously for net mineralizable N (Gasser, 1961). The results of none of the chemical tests were correlated as closely with uptake of N by grass as was net mineralizable N. The polysaccharide measurement, on spring-sampled soils, correlated well with the yield of unfertilized barley in 36 field experiments. However, it was considered that the dynamic nature of the N cycle in soil invalidates any single chemical measurement. Such significant correlations were thought to indicate that immobilization was not important in the soil samples used.

3.4 Methods based on Mineral Nitrogen in the Soil Profile

In some parts of the world, N fertilizer recommendations take into account the mineral N content of the soil profile before crop establishment. The basis for this adjustment has been established in Colorado (Giles et al., 1975) and Nebraska (Herron et al., 1971) in the United States and also in Europe. In N W Germany, field experiments were conducted on loess soils to establish a relationship between the mineral N content of the soil, and N uptake by cereal crops (Bohmer et al., 1977). Samples were taken in spring to a depth of 1m; the mineral N content of such samples was defined as "N min". These experiments resulted in the use by cereal growers in this area of fertilizer recommendations that take N min into account (Wehrman and Scharpf, 1979). This method has been tried in England and Wales (M.A.F.F., 1982b) but so far no correlation has been found between such profile mineral N measurements and a range of crop response measurements. The greater variability in soil and climate in the U.K. cereal-growing area compared with mainland Europe is a suggested reason for the lack of a relationship (Needham, 1982). Recent work based at Rothamsted has concentrated on predicting profile mineral N in spring under a winter wheat crop from that measured in autumn (Addiscott et al., 1984). The prediction model used incorporates a number of existing leaching, mineralization and crop uptake models (Whitmore, 1984) and successful predictions (86% of variance accounted for) were obtained in 39 field comparisons.

OBJECTIVES

The objectives of this project were as follows:

1. To measure the uptake of N by barley, distinguishing between N from applied fertilizer and that from other sources by using N fertilizers labelled with ^{15}N. At the time this work was started (1978) there was no such information available for barley grown in Scotland, or elsewhere in the U.K.. It was considered that extrapolation from the results available for other crops in other environments was unlikely to give satisfactory prediction of N uptake.

2. To investigate any interaction between the 2 sources of N and the mechanisms involved. The experimental sites were:

(i) On the longest-running contrasting tillage (ploughed and direct-drilled) experiment in the U.K. (Holmes, 1976).

(ii) On other contrasting soil types in different climatic conditions within the east of Scotland.

Both spring- and autumn- sown barley crops were grown and sampled at intervals during the growing season.

3. To investigate whether applied labelled N had any effect on the availability and/or uptake of unlabelled N.

4. To measure soil mineral N concentrations and to measure mineralization of N under laboratory conditions. To compare the results of such measurements with crop uptake.

It was considered that this information would be of potential value in optimising the use of N fertilizer on barley crops under Scottish climatic conditions.

METHODS

Site details, crop sampling and statistical methods.

The site at Bush has been described by Holmes (1976) and has been used for ^{15}N work since 1978. New sites were selected in 1980 to give a wider range of climatic conditions and soil type (see tables 1-3). Two fields were chosen at Aberlady which had been in cereals for the last 3 years and one at Balerno in the first year of cereals. At both sites the intention was to grow barley for the next 2 years. At Aberlady, 2 adjoining fields were used in which spring and winter cereals were grown in alternate years. The winter cereal was followed by rape which was grazed in situ before establishment of the spring barley. In 1980-81 the winter barley variety Athene and the spring barley Golden Promise were grown, in 1981-82 the same variety of spring barley and the winter barley Igri were used. In 1981, the seed dressing on the spring barley failed and mildew was present. At Balerno Golden Promise was used in both 1981 and 1982.

^{15}N-labelled calcium nitrate containing approximately 0.7 atom % ^{15}N was prepared by mixing, in aqueous solution, calcium nitrate containing 5 atom % ^{15}N (BOC Prochem, London, UK) with the appropriate amount of calcium nitrate of normal isotopic composition. The solution was crystallised, ground to a powder and mixed. Isotopic analysis of sub-samples confirmed the actual enrichment and satisfactory uniformity of the labelled fertilizer used. Annual dressings of P and K were applied to the seedbed in all experiments. Rates (kg/ha of P, K, respectively) were: 33,62 at Bush; 56,56 at Aberlady and 40,40 at Balerno. N fertilizer was applied separately in spring in all experiments. Labelled material was broadcast by hand over 2 x 1.5m microplots located within larger main plots at the appropriate rate. The remainder of each mainplot received a similar application of unlabelled N fertilizer. At Aberlady and Balerno 6 rates of N were replicated 4 times, at Bush (South Road) there were 4 rates of N and the number of replicates sampled varied.

Plant samples were taken from the microplots on several occasions during the season (Tables 48 and 49). Half-metre lengths of 2 rows were cut using shears within a few mm of ground level. Samples were dried (60°C), weighed, milled and mixed. Subsamples were taken for total N and N isotopic ratio determination (see appendix). For some sampling occasions at the Bush (South Road) site replicates were bulked on an equal weight basis and determinations performed on the bulked samples. Larger samples were taken from the main plots on each sampling occasion (from 1981 onwards) to give more accurate values for dry matter yield.

Analysis of variance on the main variables was performed for each sampling date at each site, also on the difference between successive dates in some cases. The Genstat package was used (Lawes Agricultural Trust, Harpenden). This provides estimates for missing values, but does not adjust the standard error of the difference between treatment means (S.E.D.). Adjustment was made by the method described by Cochran and Cox (1957). The S.E.D. adjusted for 1 missing value is used when comparing the treatment with one value missing with other complete treatments. The S.E.D. adjusted for 2 missing values is used when comparing 2 treatments, both of which have a value missing. Examples may be seen in Tables 22 and 23. Values for S.E.D. are not shown for the Bush site as the number of different treatments is too large for a clear presentation. However the results of analysis of variance are fully discussed.

PLATES

PLATE 1. BUSH (SOUTH ROAD) PLOUGHED AND DIRECT-DRILLED AREAS

PLATE 2. A MICROPLOT, COVERED DURING APPLICATION OF
UNLABELLED FERTILIZER TO THE MAIN PLOT

PLATE 3. THE BALERNO SITE, LOOKING SOUTH TOWARDS THE PENTLAND HILLS.

PLATE 4. THE ABERLADY SITE, LOOKING NORTH TOWARDS THE FIRTH OF FORTH

RESULTS

RESULTS

Most of the data are presented in Tables in this section; some figures are also included. Remaining data are presented in the appendix.

BUSH 1978-1980

At this Bush (South Road) site, the effects of different soil and tillage treatments were investigated in addition to the effects of N application. The actual sampling dates are given in Table 40 and rainfall data in Figure 7a. Results for 1981 and 1982 are presented separately. Tables 4, 5 and 6 show the percentage of plant N derived from fertilizer (%NDFF) i.e. the proportion of plant N that is labelled. For date 5, the final harvest, results are presented for the grain (G) and straw (S).

Increasing the amount of labelled N applied always increased the %NDFF, to a maximum of about 75% (Table 6). Towards the end of the growing season values declined and more detailed analysis revealed some interesting trends. In 1978 and 1979 (Tables 4 and 5) there was a gradual decline in %NDFF until the 4th sampling date, (anthesis). In 1980, however, the %NDFF was low on the first date and increased until the third (Table 6). This increase was greater on the ploughed plots than on the direct-drilled. Between the third and fourth cuts in 1980, %NDFF values started to decline, particularly on the direct-drilled plots. There was then a greater drop between the fourth cut and harvest. A similar drop took place in 1978 (Table 4), but not in 1979. In 1979, although there was a drop in %NDFF between anthesis and harvest on the direct-drilled plots, there was an increase on the ploughed plots (Table 5).

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In 1979 and 1980, direct-drilled crops had a higher proportion of labelled N early in the season but later the ploughed crops had greater %NDFF than the direct-drilled. In 1978, tillage effects were not marked.

Any effect of soil type on %NDFF was generally to give higher values on Winton than on Macmerry, although there was a tendency towards higher values on Macmerry late in 1979 (Table 5).

Tables 4 and 6 show soil, tillage interactions in 1978 and 1980. In each case, soil type had little or no effect on direct-drilled crops but influenced the %NDFF of crops on ploughed plots. On the 2nd sampling date in 1978, the %NDFF was higher on Macmerry than on Winton. Conversely, at harvest in 1980, %NDFF was higher on Winton. Tillage, N application rate interactions were only seen in 1979, when the response to N was greater on ploughed plots than on direct-drilled (Table 5). Soil, N application rate interactions showed a greater response on Winton on the 1st date in 1979 and on the 4th in 1978. A greater response on Macmerry was observed on the 4th date in 1978 and for the grain in 1980.

Yield-related data for the same site and years are presented in Tables 7-12. Dry matter yields for the Bush site are given in the appendix (Tables i-iii). Crops to which N fertilizers were applied always yielded more than the unfertilized crops, although unfertilized yield and response to applied N varied according to year. The highest unfertilized and fertilized yields were both in 1979 (Table ii) and the lowest in 1978 (Table i). In 1980, although fertilized and unfertilized yields were greater than in 1978, there was little response to increasing rates of applied N measured at harvest (Table iii). Also, in 1980, yields on dates 2 and 3 (early June) were particularly low. Monthly rainfall data is presented in Fig 7a.

In 1978 and 1980, crops on the ploughed plots yielded more than those on the direct-drilled plots (Tables i and iii). The direct-drilled crop, however, yielded more in 1979 (Table ii).

The only significant effect of soil type, measured at harvest, was in 1978 when yields were greater on Macmerry than on Winton (Table i). On some earlier dates in 1978 yields were higher on Winton. In 1979 and 1980, yields were higher on Macmerry on some pre-harvest dates.

Soil, tillage interactions were seen in early 1979, when direct-drilled crops yielded more on Macmerry soil than on Winton. At the higher rates of applied N, yields were greater on the ploughed plots on Winton (Table ii). Tillage, N application rate interactions were seen in 1978 and 1979. In 1978, crops responded better to applied N on the ploughed plots, while in 1979 direct-drilled crops responded more.

Labelled and unlabelled N uptake (kg/ha) data are presented separately in Tables 7-12, treatment effects are described below. Figures 8-17 compare labelled and unlabelled N uptake. Figure 8 shows accumulation of labelled and unlabelled (soil) N with time for 2 rates of applied N (N_0 and N_2 are omitted for clarity). This Figure shows how increasing unlabelled N uptake with time and the general tailing off of labelled N uptake at harvest gave rise to the trend in %NDFF described above (see Tables 4, 5 and 6). The tillage effect observed in 1979 for %NDFF is also seen in the N uptake data (Figs 12-14). Figures 9-17 show labelled and unlabelled N uptake with rate of applied, labelled N for the 4th date, (anthesis) in the grain and (in the appendix Figs i-vi) for the straw. Generally, at harvest, unlabelled N uptake (mean of all rates of N) was greater than mean labelled N uptake. The exception was in 1979 on the ploughed plots and on Macmerry soil, when mean labelled N uptake was greater than unlabelled N uptake (c.f. %NDFF, Table 5). Increasing the rate of labelled N application always increased the crop uptake of labelled N in 1978, 1979 and 1980 (Tables 7, 9 and 11). The overall labelled N uptake was greatest in 1979 when the fitted slope was 14 kg/ha plant N at harvest for every 30 kg/ha applied N, for the direct-drilled crop and on Winton soil (Figure 14).

At all the pre-harvest sampling dates in 1979, but not at harvest, the direct-drilled crops had taken up more labelled N than those on the ploughed plots (Table 9). At harvest in 1978, labelled N uptake was greater on the ploughed area (Table 7). In 1980, on the first sampling date, labelled N uptake was greater on the direct-drilled plots but on the third and fourth dates it was greater on the ploughed (Table 11).

Table 11 shows that at harvest in 1980, labelled N uptake was greater on Winton soil but for the second and fourth dates it was greater on Macmerry. This was also the case late in 1979 and on one date in 1978 (Tables 9 and 7). Early in 1979, labelled N uptake was greater on Winton than on Macmerry. Soil, tillage interactions were observed in 1978 and 1979. Greater crop uptake of labelled N took place on Macmerry in 1978 and on Winton in 1979, for the ploughed plots. Early in the season there was no effect of soil type on the direct-drilled crops, but later they took up more labelled N on Winton in 1978 and on Macmerry in 1979 (Tables 7 and 9). Tillage, N application rate interaction only occurred in

1979, when there was a greater response of labelled N uptake to applied N for the direct-drilled crop. For some pre-harvest dates in 1978 and 1980 the response to applied N was greater on Macmerry than on Winton (Tables 7 and 11).

Nitrogen uptake from the soil i.e. crop uptake of unlabelled N is shown in Tables 8, 10 and 12. Uptake of unlabelled N, after the first sampling date, always increased with increasing rate of applied, labelled N. The response was greatest in 1979 when, at harvest, unlabelled N uptake increased by about 5 kg/ha for every 30 kg/ha labelled N applied, (Figure 14). At the fourth sampling date, unlabelled N uptake increased by about 7 kg/ha per 30 kg/ha labelled N applied, (Table 10, Fig. 12).

Table 10 shows that in 1979, unlabelled N uptake by direct-drilled crops was greater than by those on the ploughed area. This was also the case late in 1980 (Table 12). In 1978 and early in 1980 however, unlabelled N uptake was greater on the ploughed plots (Tables 8 and 12). Effects of soil type on unlabelled N uptake were observed in 1978 and 1979. On the first date in 1978, uptake was greater on Winton but uptake measured in the grain was greater on Macmerry (Table 8). In 1979, uptake was greater on Macmerry on the second date but that measured in the straw was greater on Winton (Table 10).

Tables 8 and 10 show soil, tillage interactions in 1978 and 1979. Pre-harvest there was no effect of soil type when ploughed but the direct-drilled crops took up more unlabelled N on Winton in 1978 (Table 8) and on Macmerry in 1979 (Table 10). At harvest in 1978 there was no tillage effect on Winton but uptake was greater on the ploughed plots on Macmerry. Tillage, N application rate interactions were also seen in 1978 and 1979. At harvest in 1978 the response to N was greater on the ploughed plots (Figs 10 and 11). Pre-harvest in 1979 the response was greater for the direct-drilled crops (Table 10).

BUSH 1981 AND 1982

Additional data for the Bush (South Road) site from crop samples taken in 1981 (Tables 59-78) and 1982 (Tables 79-85) are presented here. In 1981 the entire site was sampled, however in 1982, labelled fertilizer was applied, at a single rate of 120 kg/ha, only to plots on Macmerry soil. Thus samples were only taken from these plots and the unfertilized plots in the same blocks. Other samples taken in 1982 were from plots to which highly enriched fertilizer was applied in 1980. Some of the data are means of 4 replicates (Tables 71-80 and 82-85) as presented previously; but for some sampling dates, replicates were bulked on an equal weight basis and single sets of determinations were performed on these bulked samples (Tables 59-70 and 81). The limited data available from 1981 and 1982 have not been analysed statistically but will be discussed briefly with reference to the main trends and effects observed in the 1978-1980 data.

The general reduction in the proportion of labelled N in crop as the season progressed, observed previously (Figure 8), did not seem to be as marked in 1981 and 1982. Comparison of mean labelled N uptake at harvest with mean unlabelled N uptake does not always confirm the general observation made in previous years that, at harvest, mean unlabelled N uptake is greater than mean labelled N uptake. The opposite is observed on the ploughed plots on Winton soil in 1981 (Tables 74 and 78) and on the ploughed plots in 1982 (Tables 82 and 84). The other example of this was in 1979, for the ploughed plots on Macmerry soil. An apparent soil, tillage interaction was observed in 1981, for the third, fourth and final sampling occasions, when soil type influenced the proportion of labelled N in the crop on the ploughed plots but not on the direct-drilled. This is similar to the interaction observed in 1980 when the proportion of labelled N was also greater on Winton than on Macmerry. Grain yields in 1981 and 1982 confirmed the tillage effect seen in 1978 and 1980 and were greater on the ploughed area than on the direct-drilled. Yields in 1981 were higher than in 1982, 1978, 1979 and 1980. The highest yielding area was the ploughed plots on Macmerry soil. The response of grain N uptake to applied N was also greatest here. The labelled N uptake increased by about 19 kg/ha for every 30 kg/ha labelled N applied while unlabelled N uptake increased by about 7.5 kg/ha labelled N applied (Table 73). This response of unlabelled N uptake to increasing rate of labelled N application was observed in both 1981 and 1982 and confirms the observations of previous years.

Crop samples taken at harvest in 1982 from both tillage treatments, from the plots to which highly enriched (about 5 atom % ^{15}N) were applied in 1980 contained labelled N. The proportion of labelled N from the 1980 application was just over 1%, demonstrating that some of the application of labelled calcium nitrate must have been immobilized in the soil and subsequently mineralized, becoming available for crop uptake once again. This type of work needs to be extended in order to find what proportion of an inorganic N application (nitrate or ammonium) is involved in this turnover process.

GLENCOURSE 1982

Labelled N fertilizer was applied to a winter barley (Igri) crop at Glencourse, on Winton soil, near Bush, in 1982. A single rate (120 kgN/ha) was applied, in spring, to 4 replicate plots on each of two tillage treatments, ploughed and direct-drilled. The crop had received 25 kgN/ha (unlabelled), 65 kg/ha P and 51 kg/ha K in the seedbed. Crop samples were taken; on 16/4/82 at tillering, on 11/5/82 at stem extension, on 25/5/82 at ear emergence and at maturity on 4/8/82. N uptake data are presented in Tables 86-90, the natural ^{15}N abundance from Bush was used in the calculations. These results confirm the tillage effect observed at Bush i.e. that grain yields were greater on the ploughed plots than on the direct-drilled. Pre-harvest and in the grain, N uptake (both labelled and unlabelled) was greater on the ploughed plots than on the direct-drilled but for the straw, unlabelled N uptake and dry matter yield were greater on the direct-drilled area. Generally tillage differences in the proportion of labelled N in the crop were not great, also the values remained high throughout the season. At harvest the both the grain and the straw contained more labelled than unlabelled N. Similar results were seen at other sites in 1982 but for the grain only.

ABERLADY AND BALERNO, 1981 AND 1982.

For the sites at Aberlady and Balerno, sampling dates and brief growth stage descriptions are given in Table 49. Table 50. presents some rainfall data for the Aberlady area. Rainfall at Balerno may be considered similar to that at Bush (Fig 7b).

Data from the winter barley crop at Aberlady harvested in 1981 are shown in Tables 13-17 and Figures 18-21. In Figure 18, results for only 3 of the 6 levels of applied, labelled N are shown for clarity, also for the final harvest the sum of uptake in grain and straw is shown.

The yield for the first 2 cuts increased with increasing rate of applied N. For harvest and the third cut the overall effect of applied N was not significant due to reduced yield at the highest rates. Total N uptake increased with increasing rate of applied N except in the grain. The mean (of all N rates) total N uptake at harvest was slightly less than for the previous cut. The proportion of labelled N in the plant always increased with increasing rate of applied, labelled N. The mean value decreased as the season progressed. Labelled N uptake always increased with N rate, the maximum response being at the 3rd cut when for every 30kg/ha labelled N applied 22.3 kg/ha labelled N was taken up by the crop (Figure 19). Mean labelled N uptake at harvest was less than for the previous (3rd) cut. Except for the 1st and 2nd cuts, mean unlabelled N uptake was greater than mean labelled N uptake. The only sign of any response of unlabelled N uptake to application of labelled N was in the straw (Figure 21). Mean unlabelled N uptake at harvest was greater than for the 3rd cut.

Data for the spring barley at Aberlady in 1981 are presented in Tables 18-23 and Figures 22-25. Tables 19-23 show that after the 1st cut, yield always increased with increasing rate of applied N. Similarly, after the first cut, total N uptake also increased with increasing applications of N. For the 1st cut yield and N uptake both fell off at the 2 top rates of applied N (Table 18). Total N uptake was slightly less at harvest than for the previous (4th) cut. The proportion of labelled N in the plant also fell off at the top rate of applied, labelled N for the 1st cut but otherwise always increased with increasing rate of applied N. The mean value was low for the 1st cut, high for the second, then decreased for the rest of the season. Labelled N uptake always increased with increasing rate of applied, labelled N, the greatest response being for the 4th cut when the slope of a fitted line was 19.6 kg/ha labelled N uptake for every 30 kg/ha labelled N applied (Figure 23). Mean labelled N uptake at harvest was less than for the 4th cut, the effect of a drop at high rates of applied N, but not at lower rates (Figure 22). For the 1st cut and at harvest mean unlabelled N uptake was greater than mean labelled N uptake, otherwise labelled N uptake was greater. Application of labelled N had no effect on crop uptake of unlabelled N pre-harvest. Figure 22 shows that there was greater uptake of unlabelled N for the fertilized crop than for the unfertilized, when measured in the whole crop at harvest. Mean unlabelled N uptake was greater at harvest than for the previous cut.

Data for the spring barley at Balerno in 1981 are presented in Tables 24-29 and Figures 26-30. The only sampling occasion for which yield increased linearly with applied N rate was the 2nd. Otherwise the response tended to be weaker at the higher rates of N (Tables 24-29). Total N uptake always increased with increasing N applications but with weak responses for the 1st cut and at harvest (Tables 24, 28 and 29). Mean total N uptake was less at harvest than for the previous (4th) cut. The proportion of labelled N in the plant always increased with increasing rate of labelled N application. The mean value declined steadily throughout the season. Labelled N uptake always responded to increasing rates of applied labelled N, the maximum fitted slope being just over 20 kg/ha labelled N in the plant for every 30 kg/ha labelled N applied, at the 4th cut (Figure 28). Labelled N uptake was generally lower than unlabelled N uptake, except at the highest rates of applied N, pre-harvest (Figures 27-30). Mean unlabelled N uptake was always higher than mean labelled N uptake. Labelled N uptake (mean of all N rates) fell between 4th cut and harvest. Unlabelled N uptake did respond to labelled N applications (see Figures 26-30). The response in the 1st cut was negative (Table 24) but in subsequent cuts the response was generally positive. The mean unlabelled N uptake was greater at harvest than for the previous cut. This site gave higher yields particularly of unlabelled N, compared with Aberlady; also, proportions of labelled N in the crops were lower at Balerno.

As discussed in the chapter on methods, the design for for the winter barley experiment at Aberlady, harvested in 1982, was slightly different. As usual, treatment means obtained using all 4 blocks are presented in Tables 30-34, however the means for the 2 highest N treatments combine the effects of 2 different N application strategies. On blocks 1 and 4, the 2 largest applications were split. One third was applied on 23/2/82 and the rest on 30/3/82, together with all the other normal (single) applications. Also on 30/3/82, the first crop samples were taken, but only from the plots to which the early split had been applied and from the unfertilized plots in the same blocks. The individual plot data from

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this first sampling and from all subsequent occasions for the zero-N and 2 highest N treatments are presented in the appendix (Tables iv-ix). Table 35 compares labelled N uptake for the 2 N-application methods for the 2nd, 3rd and 4th sampling occasions. Harvest data are not included because of excessive inter-block variation in yield caused by lodging (Tables viii and ix). For the 2nd cut (15/4/82), labelled N uptake was greater when the N application was split than for a single application (Table 35). In the 3rd cut (7/5/82) the opposite effect was seen i.e. labelled N uptake was greater for a single application. Table 49 shows that this change probably occurred during tiller death, possibly accelerated by the dry weather during April (Table 50). The 4th cut also showed greater labelled N uptake from a single application than from the split application (Table 35). The proportion of labelled N in the plant also reflected this change between cuts 2 and 3 (Tables v and vi). For the split application the proportion of labelled N was higher for the 2nd cut but lower for all subsequent cuts, including harvest (Tables v-ix).

The effects of increasing N application rate are shown in Tables 30-34, ignoring the effects of application methods at the top 2 rates. Harvesting difficulties resulted in yield differences between blocks swamping any treatment effects on yield-related data. However, the pre-harvest data are discussed below. Yield increased with increasing rate of applied N for the 3rd and 4th dates. For the 4th cut the response was not linear, the yield at 90 kg/ha applied N being less than at 60. Total N uptake and the proportion of labelled N increased with increasing rate of labelled N applied. The proportion of labelled N in the 1st cut was very low, probably because dry weather reduced its availability (Table 50). It was much greater in the 2nd cut then decreased for the rest of the season.

Labelled N uptake always responded to N application rate: the maximum response was for the 4th cut. On this occasion the slope of the fitted line was 19.2 kg/ha labelled N uptake for every 30 kg/ha labelled N applied. Unlabelled N uptake was not significantly affected by application of labelled N although, for the third and fourth cuts, mean unlabelled N uptake on the fertilized plots was greater than on the unfertilized. Comparison of the winter barley crops harvested at Aberlady in 1981 and 1982 showed that the proportion of labelled N in the crop at harvest was higher in 1982.

Results from the spring barley at Aberlady in 1982 are presented in Tables 36-41 and Figures 31-34. Yield response to increasing N application rate was generally non-linear and tended to decrease at the higher rates pre-anthesis. Total N uptake responded to applied N for the 2nd cut onwards. Between the 4th cut and harvest, mean total N uptake increased. The proportion of labelled N in the crop increased with increasing rate of applied, labelled N except for the top rates in the first and second cuts. The average proportion of labelled N in the 1st cut was very low, after the dry weather in April (Tables 36 and 50). The mean value increased from the 1st to the 2nd cut, then decreased until harvest. Labelled N uptake also increased with rate of N application. The maximum response of labelled N uptake to applied N was for the 4th cut when the slope of the fitted line was 16.5 kg/ha per 30 kg/ha N applied (Fig. 32). Mean labelled N uptake was less at harvest than for the previous cut (Fig. 31) and was less than mean unlabelled N uptake for all cuts. Unlabelled N uptake was not altered significantly by application of labelled N (Figures 32-34). The unlabelled N uptake at harvest was greater than for the previous cut (Fig. 31). For spring barley at Aberlady, yields at final harvest were greater in 1982 and the proportion of labelled N in the plant was generally higher in 1981.

Results from the spring barley at Balerno in 1982 are presented in Tables 42-47 and Figures 35-38. Yield response to increasing N application rate was linear for the third and fourth cuts and also for the straw. Inter-block variation was high for the first and (to a lesser extent) second cuts, resulting in weak responses to N. Grain yields did not increase with increasing N application rate over the range 30 to 90 kgN/ha (Table 46). Total N uptake reflected some of the trends observed in the yield data. The response to increasing N application rate was linear for the 2nd, 3rd and 4th cuts and for the straw. Mean total N uptake increased between the 4th cut and harvest. The proportion of labelled N in the crop generally increased with increasing N application rate, but differences between the values at the top 2 rates of applied N were generally insignificant pre-harvest. The mean value (of all N rates) increased from the 1st to the 2nd cut then declined for the rest of the season. Crop uptake of labelled N increased with increasing N application rate except for some insignificant differences between N rates in cuts 2 and 3 (Tables 43 and 44). The maximum response of labelled N uptake to applied N was for the 4th cut when the slope of the fitted line was 17.5 kg/ha for every 30 kg/ha N applied (Figure 36). Mean labelled N uptake increased between the 4th cut and harvest (see Figure 35). Unlabelled N uptake decreased with increasing rate of N application for the 1st cut but did not generally respond to N applications (see Figures 36 and 37). Uptake of unlabelled N by the fertilized crop was greater than for the unfertilized crop at cut 3 and there was a positive response in the straw (Figure 38). Pre-harvest, mean (of all N rates) labelled N uptake was greater than unlabelled

N uptake, although the difference was small for the 3rd and 4th cuts. At harvest however, mean unlabelled N uptake was greater than mean labelled N uptake. At Balerno in 1982, the proportion of labelled N in the crop was generally higher pre-harvest than in 1981, although harvest values were similar. Yields at final harvest were lower in 1982 than in 1981.

RESULTS AND DISCUSSION

MINERAL NITROGEN IN SOIL

In this section the results are presented of a number of investigations involving the determination of NH_4^+- and NO_3^--N in soil:

1. Mineral N and N isotopic ratios in soil cores taken from Bush(South Road) during the growing season.
2. Mineral N in soil at Aberlady and Balerno shortly before spring fertilizer applications.
3. Potential N mineralization in soil from Bush (South Road). Determined by short-term laboratory incubation.
4. Long-term laboratory incubation of soils from the Bush (South Road) and Aberlady sites.

Results are discussed with reference to crop uptake data or to soil processes which affect crop uptake.

Soil cores were taken (to 40-50 cm depth) from microplots at the Bush (South Road) site to which labelled N fertilizer had been applied. The amounts of available N present and N isotopic ratios were determined (see appendix). Thus amounts of both labelled and unlabelled available N are known for certain occasions. Tables 51 and 52 show available labelled (NDFF) and unlabelled (NDFS) N in the soil from direct-drilled (DD) and ploughed (SP) plots on 2 occasions in 1979. Results are given for the top 20 cm and for the rest of the profile. A high proportion of the available labelled N was found in the top 20 cm.

Cores were taken on 13/6/79 and 26/6/79 and crop N uptake for this interval was interpolated from a graph of the uptake measured on 5/6/79, 19/6/79 and 27/6/79 plotted against time (see Figure 8). In Table 53 crop recoveries are shown which were calculated using this estimated crop uptake and the available N in the core taken on 13/6/79 (Table 51). Recovery of labelled N was greater than recovery of unlabelled N and recovery of unlabelled N increased with increasing rate of labelled N application. Similar results were obtained using the available N in the cores taken on 26/6/79, the only difference was that lower labelled N levels for the ploughed plots gave greater differences between recovery from the 2 sources of N.

Cores were taken after harvest in 1979; the available N content is shown in Table 52. The available labelled N remaining in the soil after harvest is expressed as a percentage of the initial application in Table 54 and compared with the proportion of the application recovered in the crop at harvest. For the direct-drilled crop, recovery increased with increasing rate of N application. Total recovery in crop and soil was greater for the ploughed plots at all rates of N application. The rest of the application had either been lost to the sampled profile, or was present in organic form.

In 1981, the soils at the Aberlady (winter and spring barley) and Balerno (spring barley) sites were sampled shortly before N fertilizers were applied. Several samples of topsoil and subsoil were taken at each site and the available N content determined (see appendix). Mean values for mineral N are presented in Table 55. At Aberlady, on similar soils, the available N content at the winter barley site was lower than at the spring barley site. The autumn-sown crop had already taken up N when the soil was sampled, while the spring-sown (18/3/81) crop had not yet emerged.

Another short investigation at the Bush (South Road) site was designed to investigate any differences in potential mineralization of N due to differential rates of N application over several years i.e. the possibility of higher mineralization in plots which had received the top N rate from 1968 to 1982 than on those which had received no N over the same period. One approach would be to measure the organic matter levels in the soil. However the soils concerned were developed on till derived essentially from productive coal measures and contain particles of coal and shale. Thus any measure of organic matter will not represent the true soil organic matter (Shaw, 1959). Another complication at this site is the variation in soil bulk density caused by the different tillage techniques and possibly by the different rates of N application. This necessitates careful sampling, ideally on an equal soil weight rather than on an equal soil depth basis (Powlson and Jenkinson, 1981).

The method chosen to estimate potential N mineralization was a N availability index obtained by incubation, similar to that recommended by Bremner (1965a). Plots sampled at Bush (South Road) had received differential rates of applied N from 1968 to 1982 and uniform subsequent treatment. The topsoil was sampled on 8 plots, 4 each from the ploughed and direct-drilled areas and receiving either the top rate or no applied N (2 replicates). Composite samples were made up from each plot on 14/10/83, taken to about 20 cm on the ploughed area and an equivalent weight from the direct-drilled area which was more compact. The general incubation method (appendix) was modified slightly as described below. No storage was necessary, but some of the ploughed soil samples had to be dried slightly before sieving. 3 replicate 20 g samples were incubated from each plot, in conical flasks with 50 g of sand and 10 ml of distilled water, for 2 weeks at 30°C. These and the unincubated samples were then extracted with 100 ml of 1M KCl for

30 min. Mean net mineralized N (mg kg^{-1} dry soil) after 2 weeks is shown in Table 56. The results were analysed using a suitable approximation to the t test (Clarke, 1980). This result gives no evidence for any greater amounts of readily mineralizable N in fertilized topsoil than in unfertilized. In fact, for the direct-drilled plots, the reverse effect is apparent. Where no N was applied, N mineralization was greater for the direct-drilled plots than for the ploughed.

The first of 2 investigations into the mineralization process was a long-term incubation of topsoil from Bush (South Road). The second involved the long-term incubation of topsoil and subsoil from Aberlady.

The aim of the preliminary investigation using topsoil from Bush (South Road) was to simulate the mineralization of soil organic nitrogen over the growing season. This was attempted by determining, at regular intervals, the accumulated mineral N in soil aerobically incubated in the laboratory, at similar temperatures to those ocurring in the field. A 30°C incubation was included for comparison. Samples of topsoil were taken from the ploughed plots, to which 120 kg N/ha had been applied during the previous growing season. Soil was taken from each of the 4 blocks on Macmerry soil, mixed and sieved on 5/12/80. Samples were taken for moisture determination and extraction for immediate analysis. The soil was then stored at 4°C until 10/12/80 when the incubations were set up. The sample for incubation in beakers (see appendix) was 25 g dry weight (approx. 32 g moist) mixed with 75 g sand and distilled water to make the total volume of water up to 15 ml. Sufficient were made up to allow 3 replicates from each treatment to be analysed on each occasion, except at 20 weeks when 6 replicates were analysed. 2 temperature treatments simulating seasonal temperature trends were used: A, the 4-weekly mean soil temperature at 5 cm, derived from measurements made at Bush House meteorological station between April and September from 1963 to 1980 and B, which superimposed a diurnal fluctuation onto A (Table 57). The latter was derived from measurements made at the site from April to September 1973 (Hay, 1976). The pattern of diurnal temperature fluctuation was 8 hours at maximum and minimum with a 4 h transition period. The aim was to get as close as possible to the sine waveform of natural temperature fluctuations. The third temperature treatment C, was a shorter, high temperature (30°C) incubation similar to that described by Bremner (1965a). Samples were removed at intervals and extracted for 30 min with 100 ml of 1M KCl. The extracts were analysed as described in the appendix.

During the incubations at simulated field temperatures (A and B) no appreciable quantities of ammonium were found (< 0.2 mg/kg). Figure 40 shows the increase in nitrate-N over the 20 weeks of incubation. Differences between the 2 seasonal temperature treatments were not always significant but the one in which the temperature was constant over the 4-week period (A) always gave higher nitrate contents than that with diurnal fluctuations (B). After the first month of incubation at 30°C the soil had dried out to about one third of the original field moisture content in spite of the covers on the beakers. The lost moisture was replaced and maintained over the next 3 weeks. During this time the samples were extracted weekly, as the rate of increase in mineralized N was expected to be much higher than in the incubations at lower tempetature. Appreciable levels of ammonium-N were found after 4 weeks, but not on subsequent occasions when the soil had been kept moist. The nitrate-N accumulation at 30°C is shown in Figure 41; the rate of increase fell off during the sixth week. The nitrate-N concentration at the end of this week was 53.5 mg/kg dry soil. This compares with the maximum nitrate-N concentration of 49 mg/kg dry soil reached after 20 weeks of a lower temperature treatment (A). Figure 40 shows that the rate of increase in nitrate-N concentration in treatments A and B had not started to decline. Comparison of Figure 40 with crop uptake of unlabelled N (Figure 8) shows that the shape of the relationship with time is similar.

The main incubation experiment was conducted at 15°C and continued for a longer period (28 weeks). Topsoil and subsoil samples were included to give estimates for N available for crop uptake. The constant temperature allowed investigation of the kinetics of N mineralization (see review chapter, section 3.2).

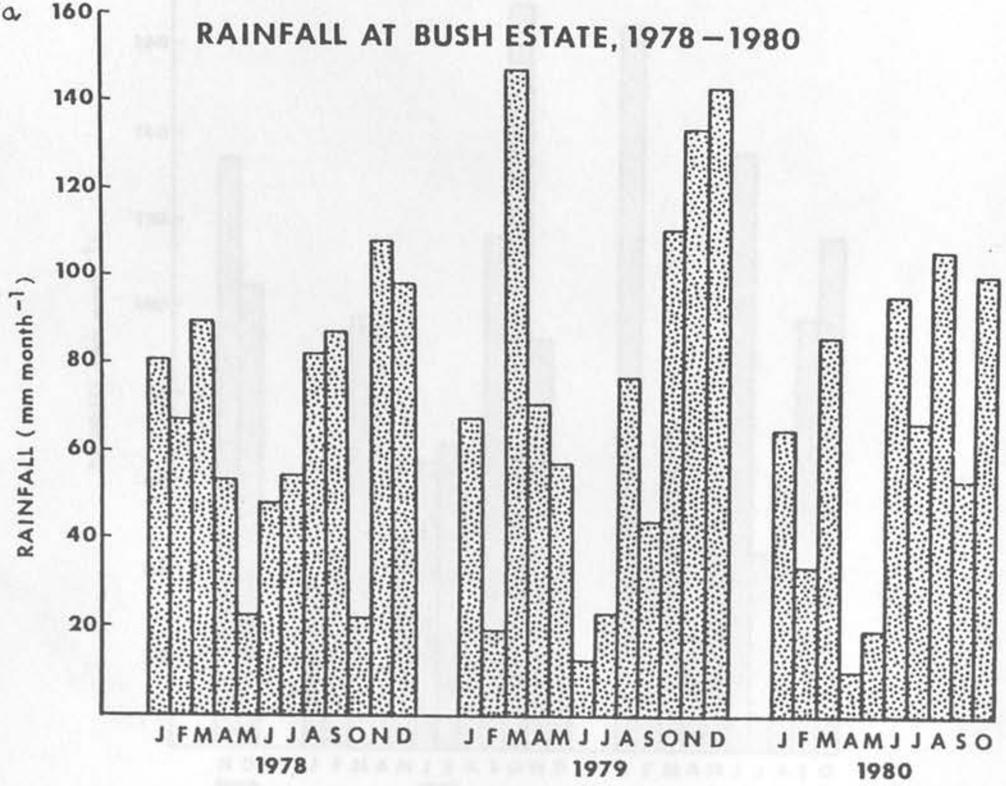
Composite soil samples were taken from the site at Aberlady, which was in winter barley in 1980-1981 and spring barley in 1982, on 21/1/82. Topsoil samples were taken to 20 cm and subsoil samples from 20 to 80 cm depth. Incubations were set up as described in the appendix, without added sand or water, 3 replicates were provided for each sampling date. Samples were extracted at 4 week intervals for mineral N determination (see appendix). Nitrate-N was the main form of mineral N during incubation. The pH values (in 0.01M $CaCl_2$) before and after incubation were 7.8 and 7.4 respectively. Net nitrate-N mineralization in the topsoil and subsoil samples during incubation is shown in Figure 39. The results were examined using analysis of variance which showed that the slopes of the relationship between mineralization and time were significantly different for topsoil and subsoil. Further investigation of this relationship, taking the 2 depths separately, involved regression of log mineralization (y) on log time (x) to give an estimate for b in:

$$y = ax^b$$

also, 5% confidence limits were calculated for b. The estimate for b for nitrate-N mineralization in topsoil was 0.767±0.02 and for subsoil was 0.601±0.196. Thus the estimate for b for subsoil includes 0.5 which would give a first-order relationship between mineralization and time. While the estimate for topsoil could indicate a zero-order relationship (when b=1).

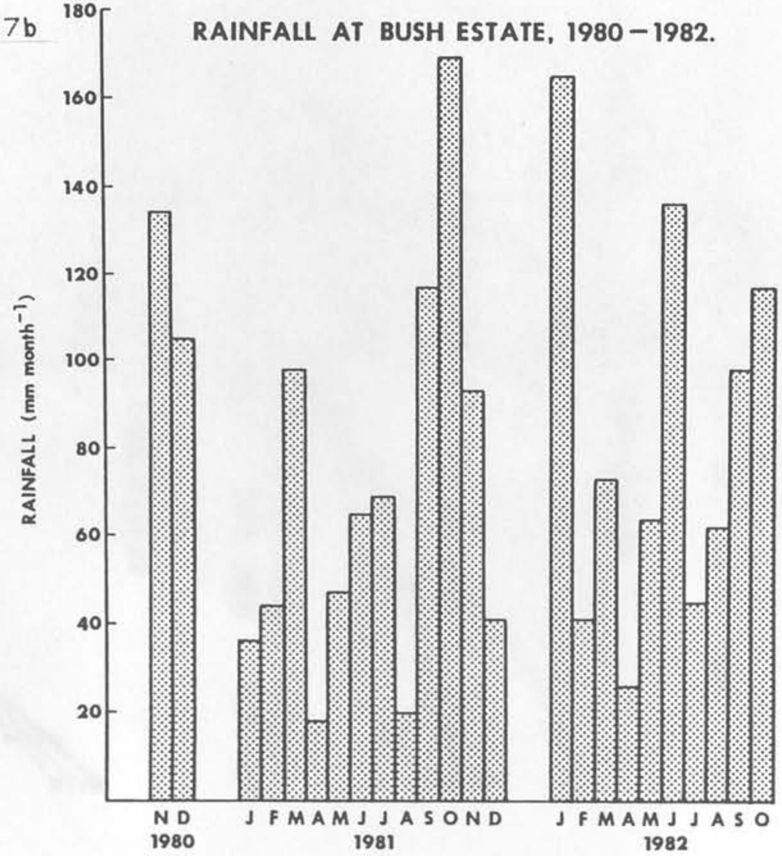
Estimates of the available N in soil, the "A-value" (Fried and Dean, 1952) were calculated for the Aberlady sites using the data on the proportion of labelled N in the crop (means of all rates of applied N). These are presented in Table 58; the values generally increased with the increasing length of time elapsed since fertilizer application. The A-values compare well with the mineralization data in Figure 39, bearing in mind the previous discussion on the interpretation of A-values (Review chapter, section 2.4.4).

FIGURE 7a



RAINFALL AT BUSH ESTATE, 1978 – 1980

FIGURE 7b



RAINFALL AT BUSH ESTATE, 1980 – 1982.

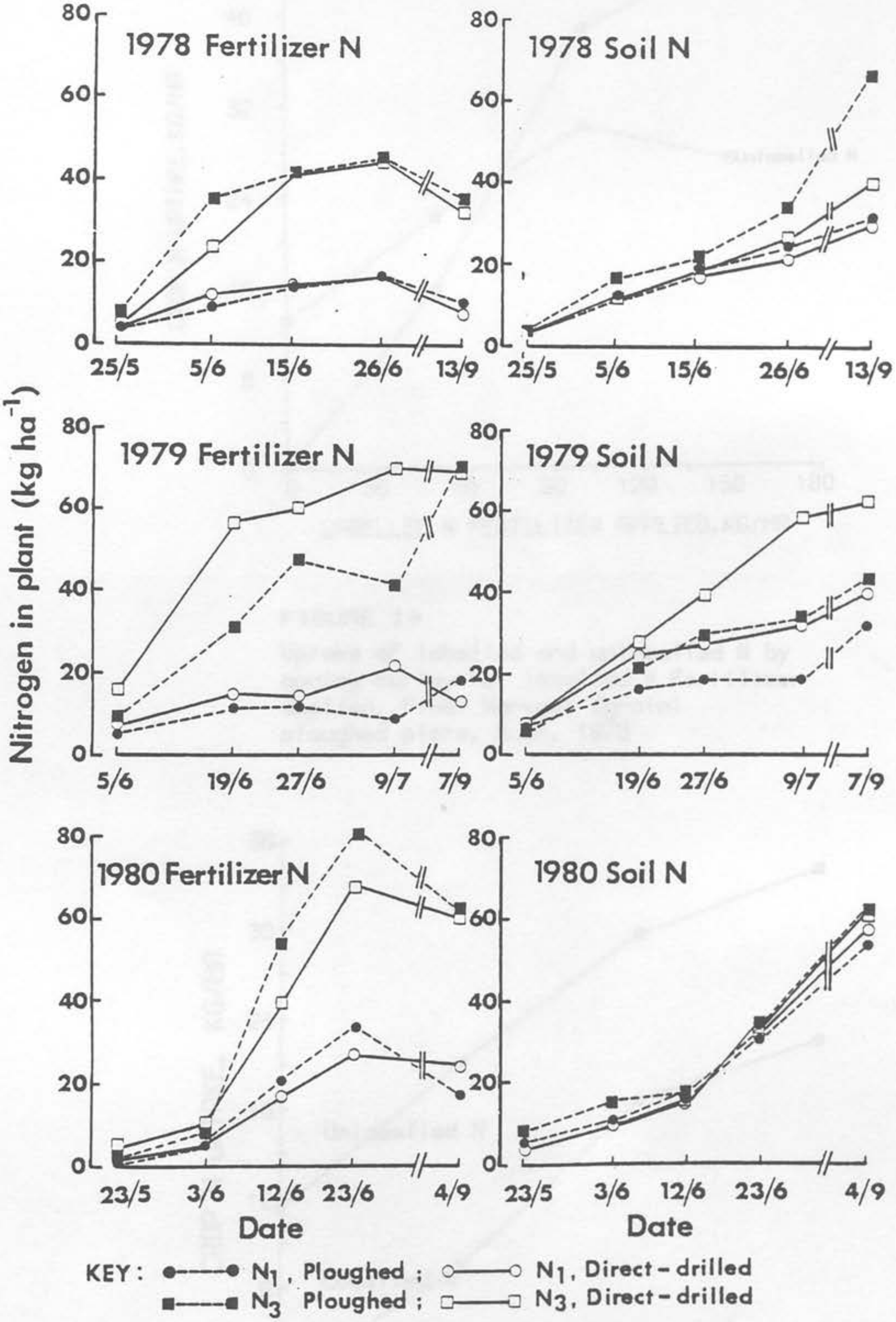


FIGURE 8
Accumulation of N in plant shoot during growth at 2 levels of applied N, Bush 1978-1980

FIGURE 9

Uptake of labelled and unlabelled N vs. labelled N fertilizer applied, spring barley, **Bush,** South Road 1978 4th Cut.

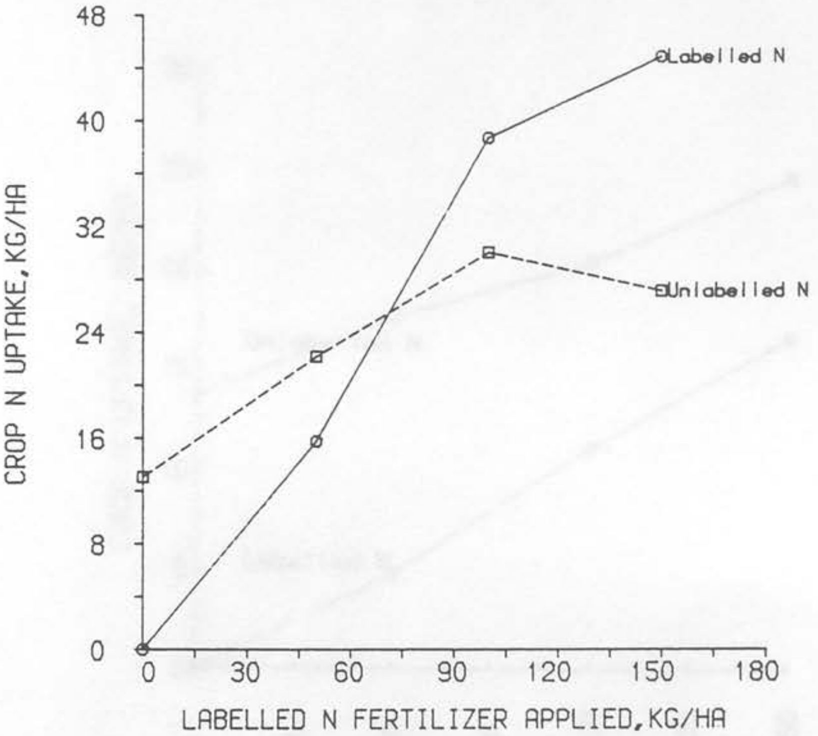


FIGURE 10

Uptake of labelled and unlabelled N by spring barley vs. labelled N fertilizer applied, final harvest (grain) ploughed plots, Bush, 1978

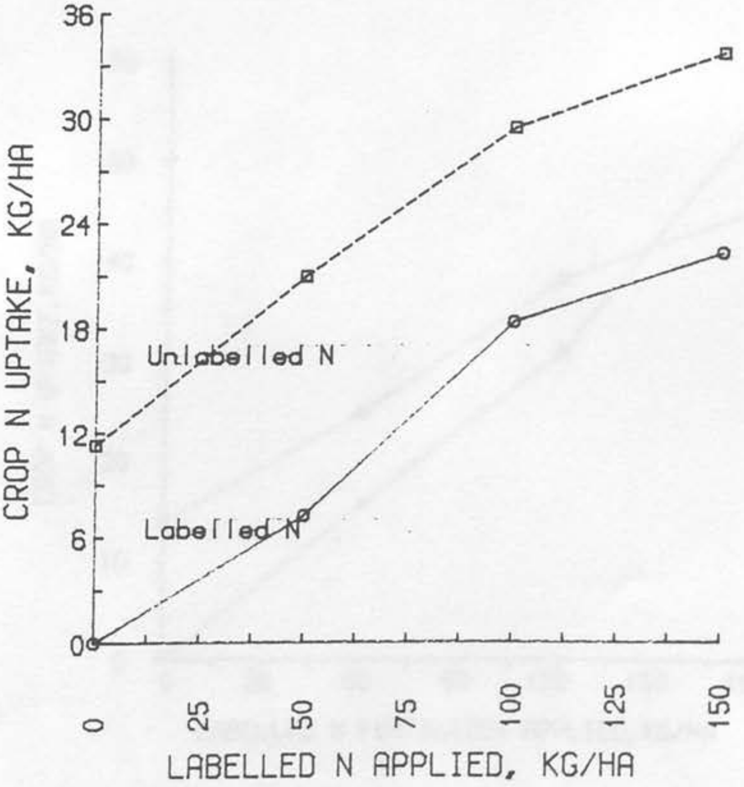


FIGURE 11

Uptake of labelled and unlabelled N by spring barley vs. labelled N fertilizer applied, final harvest (grain) direct-drilled plots, Bush, 1978

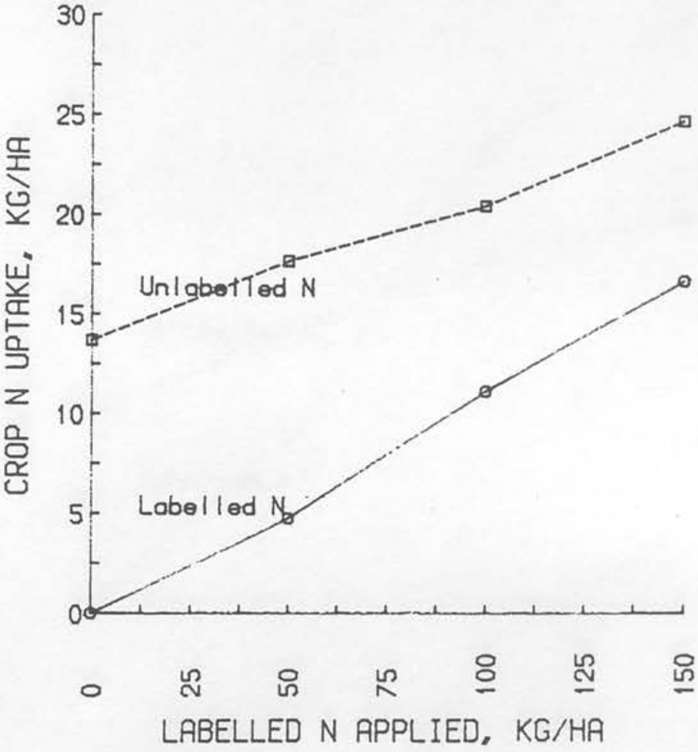


FIGURE 12

Uptake of labelled and unlabelled N vs. labelled N fertilizer applied, spring barley, Bush, South Road 1979 4th Cut.

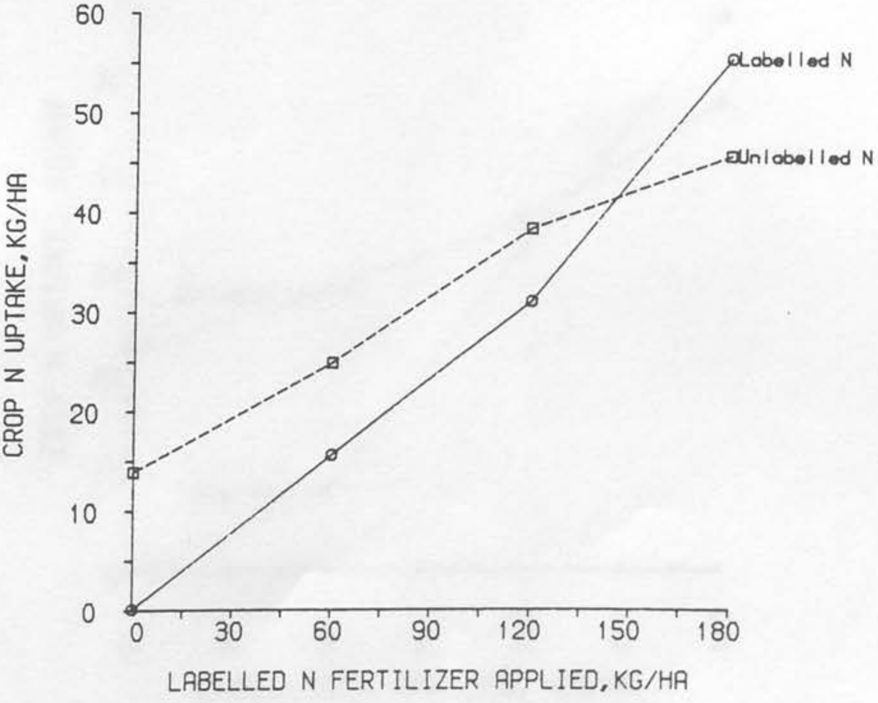


FIGURE 13

Uptake of labelled and unlabelled N by spring barley vs. labelled N fertilizer applied, final harvest (grain) ploughed plots, Bush, 1979

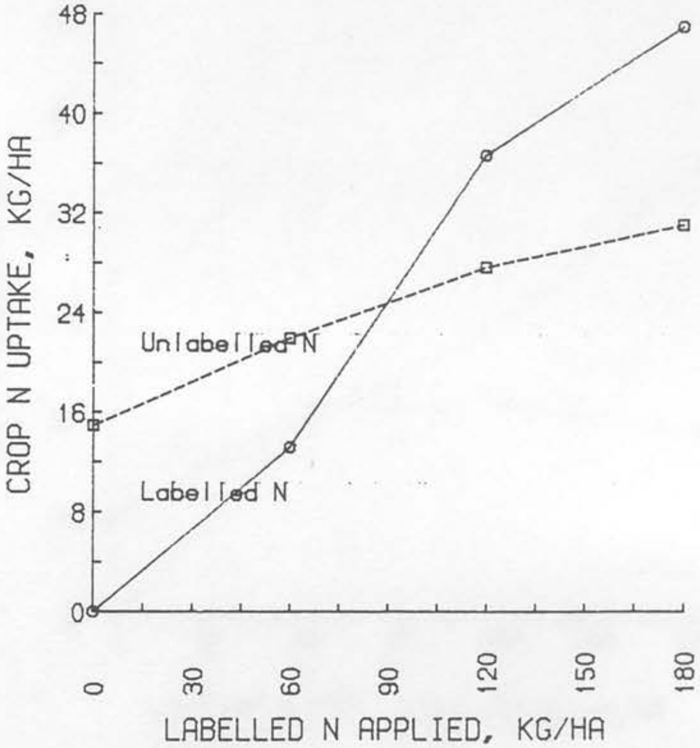


FIGURE 14

Uptake of labelled and unlabelled N by spring barley vs. labelled N fertilizer applied, final harvest (grain) direct-drilled plots, Bush, 1979

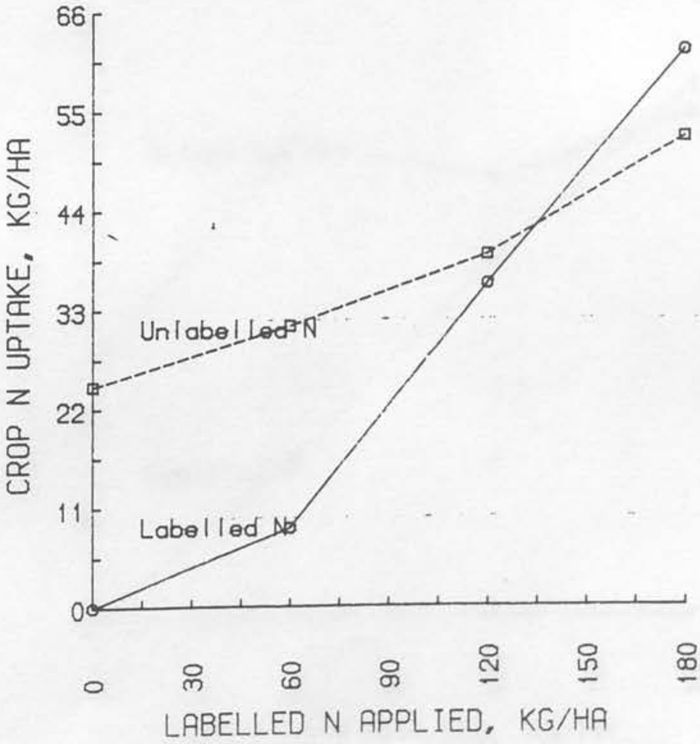


FIGURE 15

Uptake of labelled and unlabelled N vs. labelled N fertilizer applied, spring barley, Bush, South Road 1980 4th Cut.

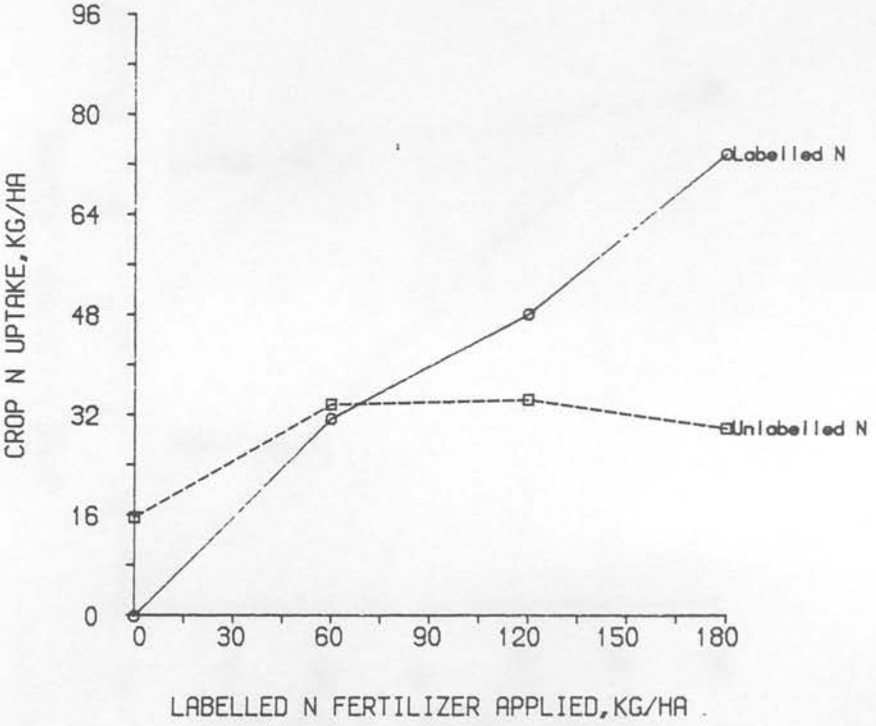


FIGURE 16

Uptake of labelled and unlabelled N by spring barley vs. labelled N fertilizer applied, final harvest (grain) ploughed plots, Bush, 1980

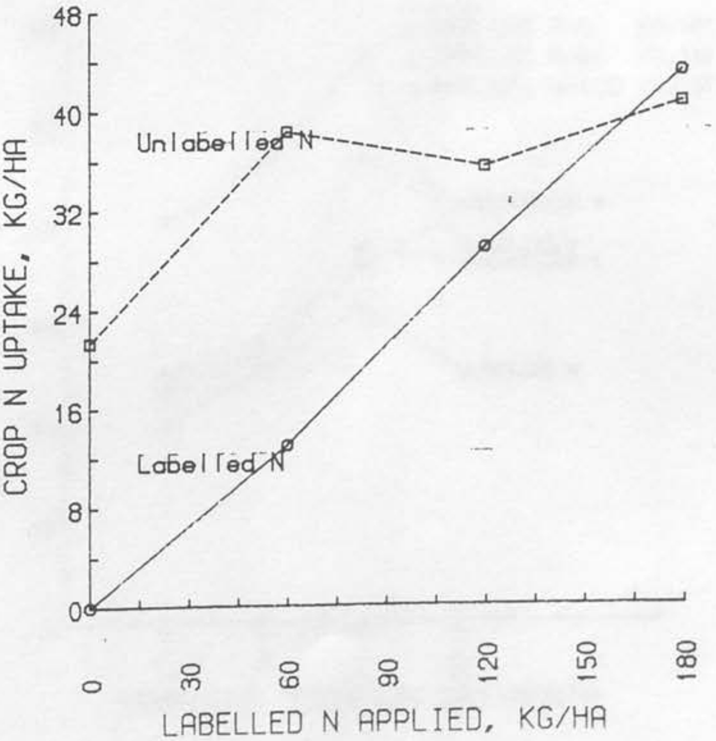


FIGURE 17
Uptake of labelled and unlabelled N by spring barley vs. labelled N fertilizer applied, final harvest (grain) direct-drilled plots, Bush, 1980

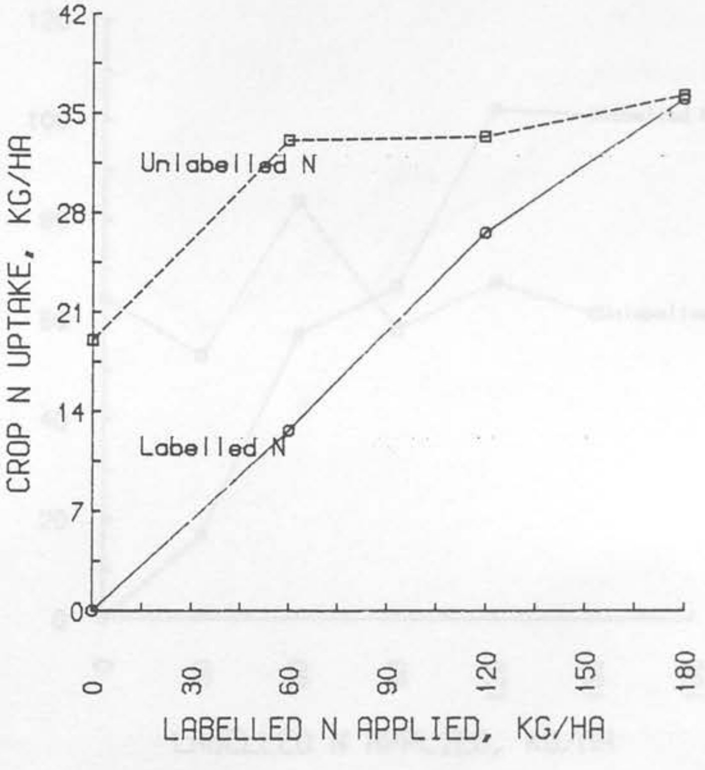


FIGURE 18
Accumulation of N in winter barley shoot during growth at 3 levels of applied, labelled N, Aberlady, 1981

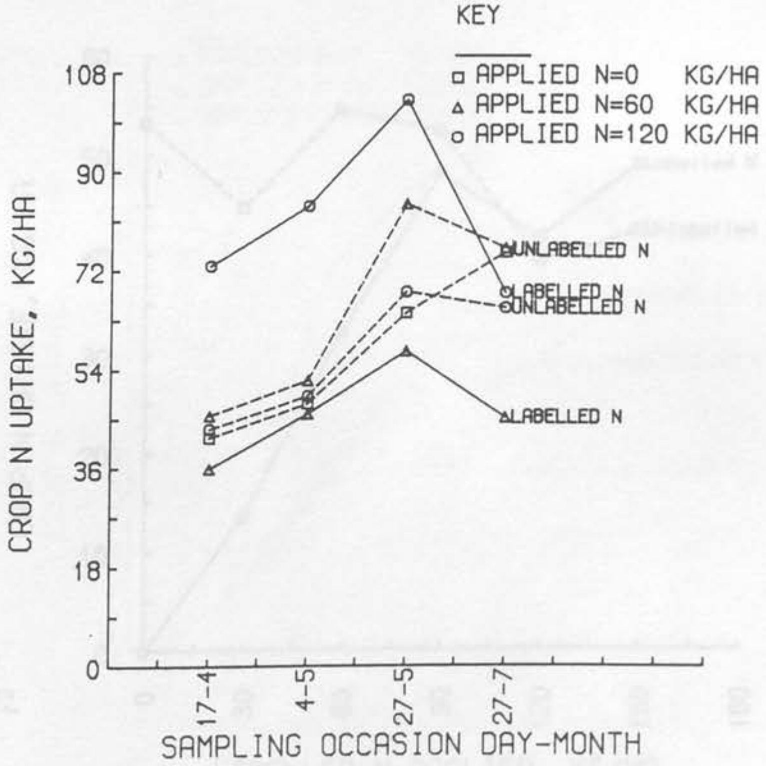


FIGURE 19

Uptake of labelled and unlabelled N by winter barley vs. labelled N fertilizer applied, 3rd Cut (anthesis) Aberlady, 1981

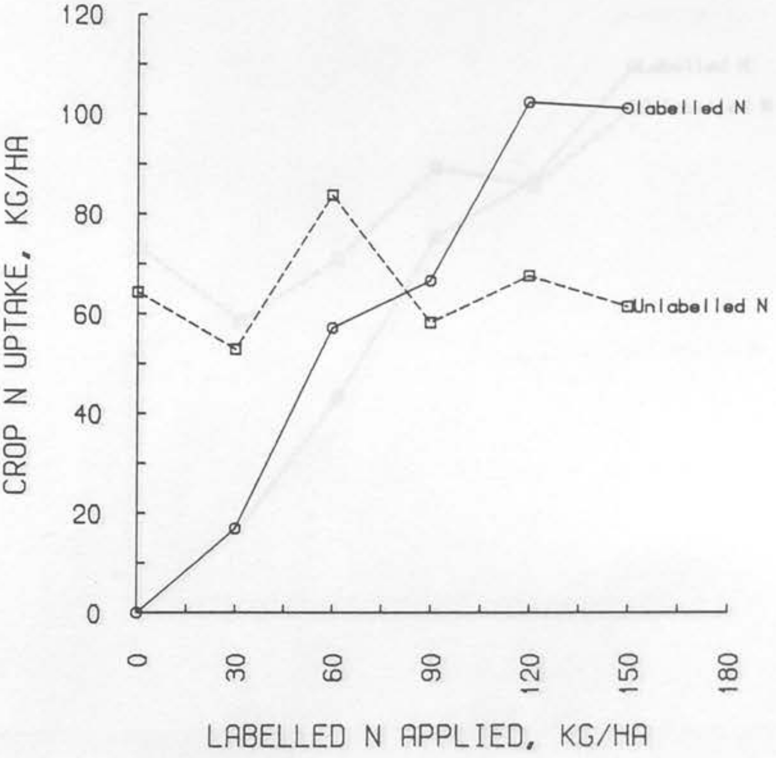


FIGURE 20

Uptake of labelled and unlabelled N by winter barley vs. labelled N fertilizer applied, final harvest (grain) Aberlady, 1981

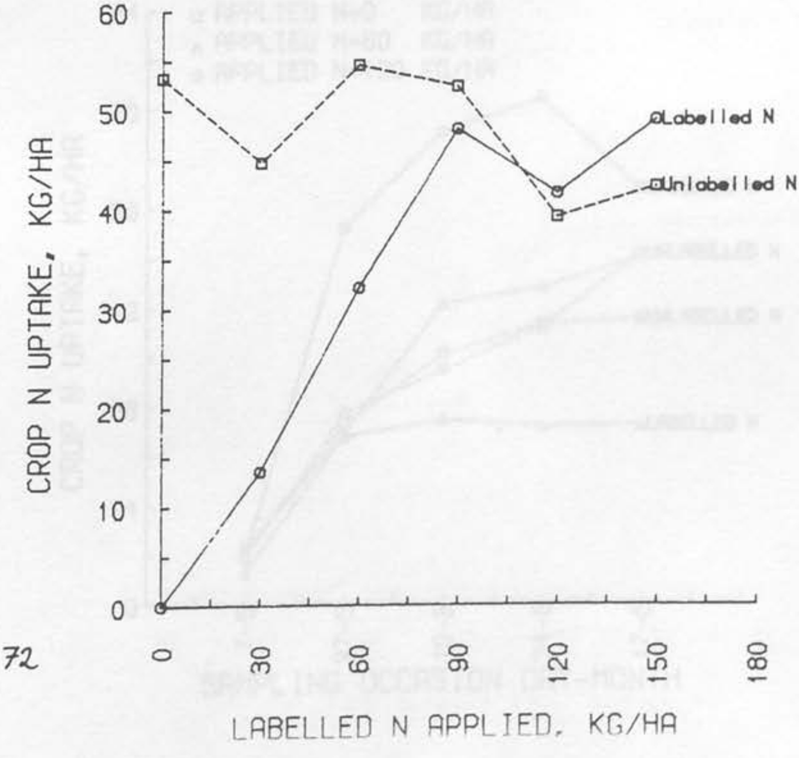


FIGURE 21
Uptake of labelled and unlabelled N by winter barley vs. labelled N fertilizer applied, final harvest (straw)
Aberlady, 1981

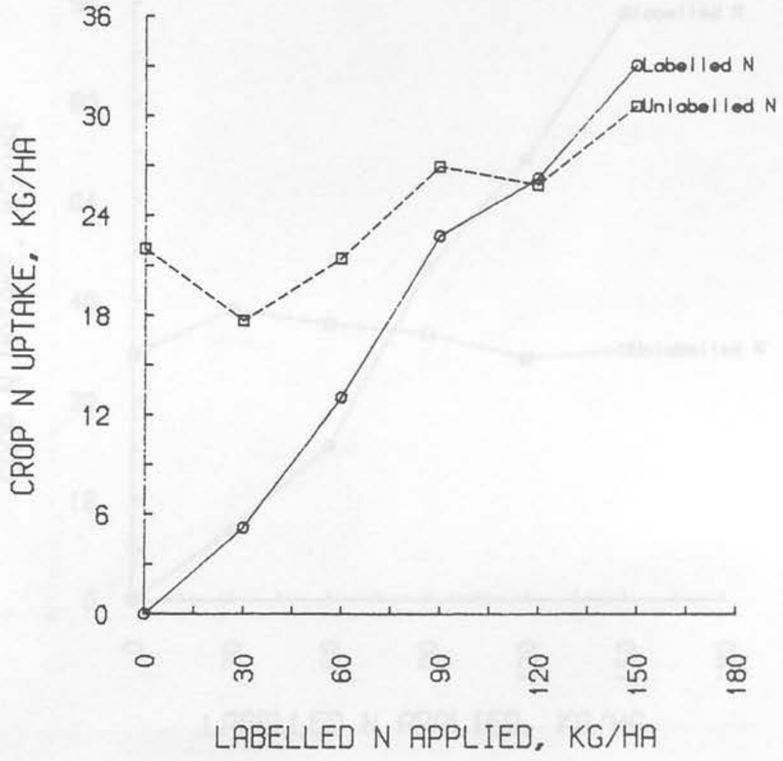


FIGURE 22
Accumulation of N in spring barley shoot during growth at 3 levels of applied, labelled N,
Aberlady, 1981

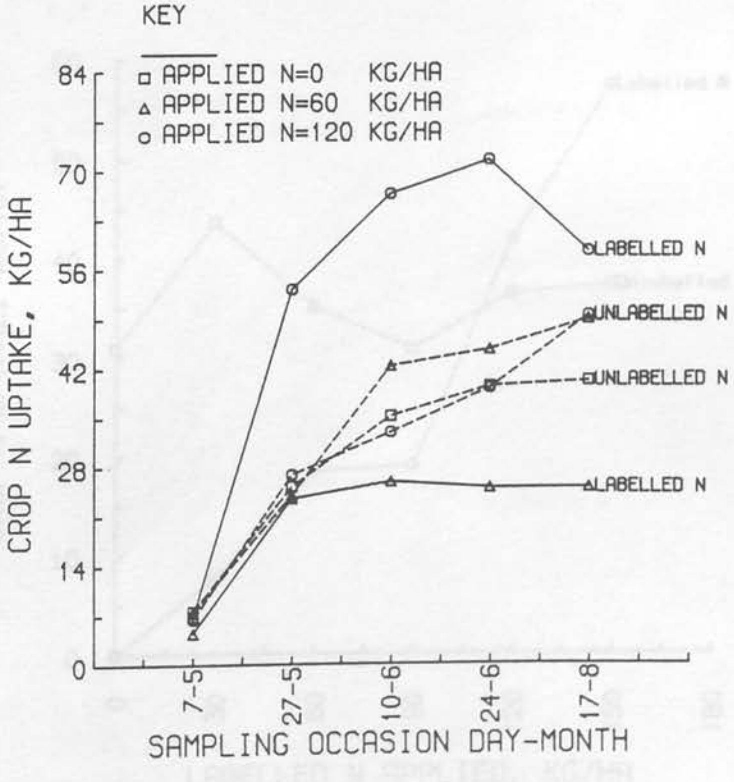


FIGURE 23
Uptake of labelled and unlabelled N by spring barley vs. labelled N fertilizer applied, 4th Cut (anthesis)
Aberlady, 1981

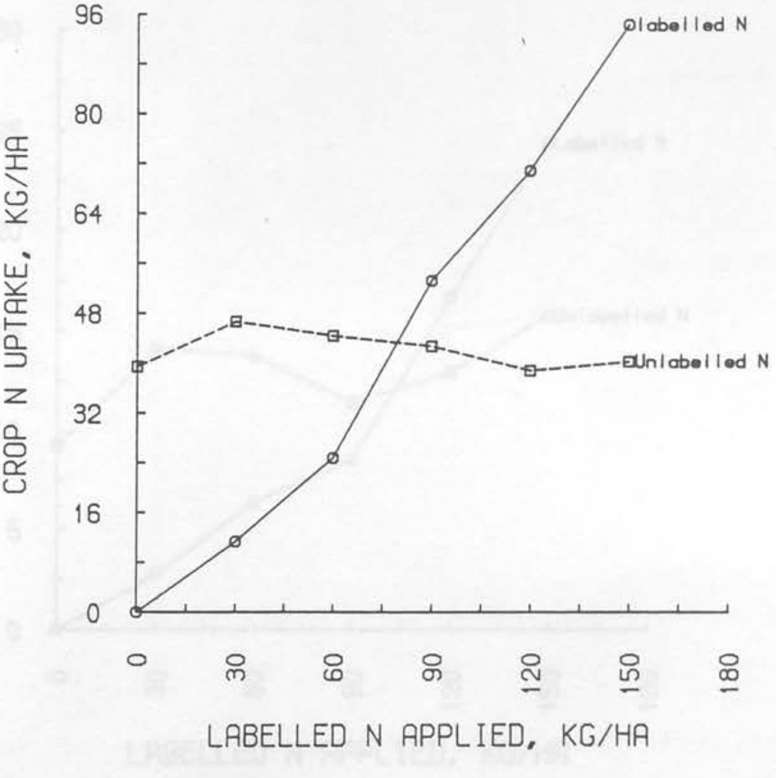


FIGURE 24
Uptake of labelled and unlabelled N by spring barley vs. labelled N fertilizer applied, final harvest (grain)
Aberlady, 1981

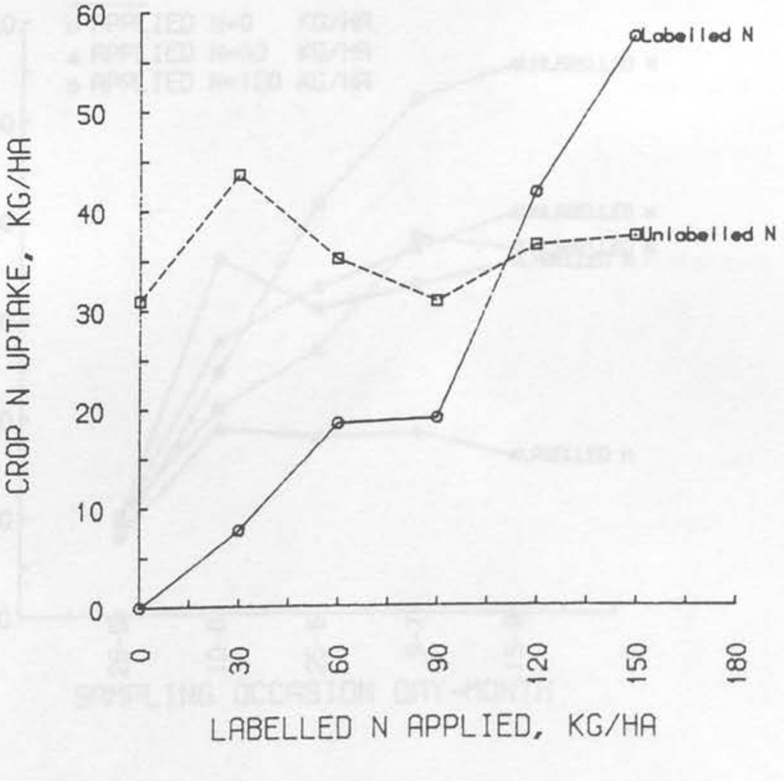


FIGURE 25

Uptake of labelled and unlabelled N by spring barley vs. labelled N fertilizer applied, final harvest (straw)
Aberlady, 1981

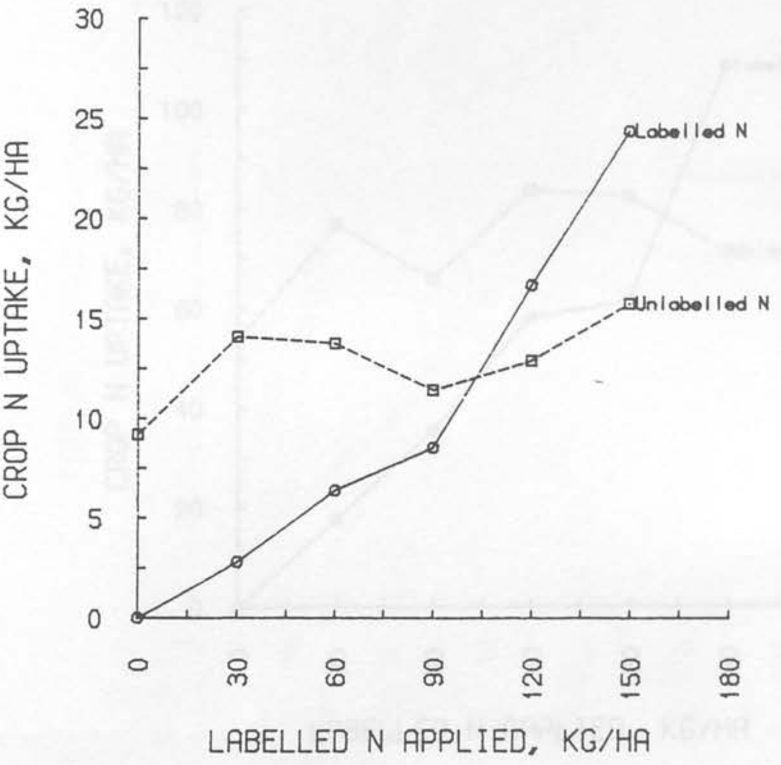


FIGURE 26

Accumulation of N in spring barley shoot during growth at 3 levels of applied, labelled N,
Balerno, 1981

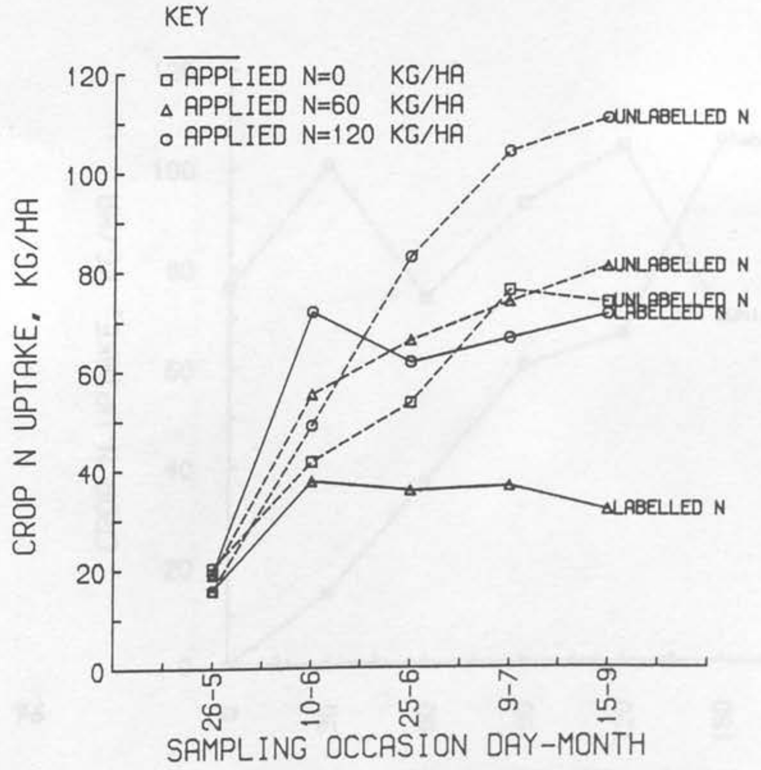


FIGURE 27
Uptake of labelled and unlabelled N by spring barley vs. labelled N fertilizer applied, 3rd Cut
Balerno, 1981

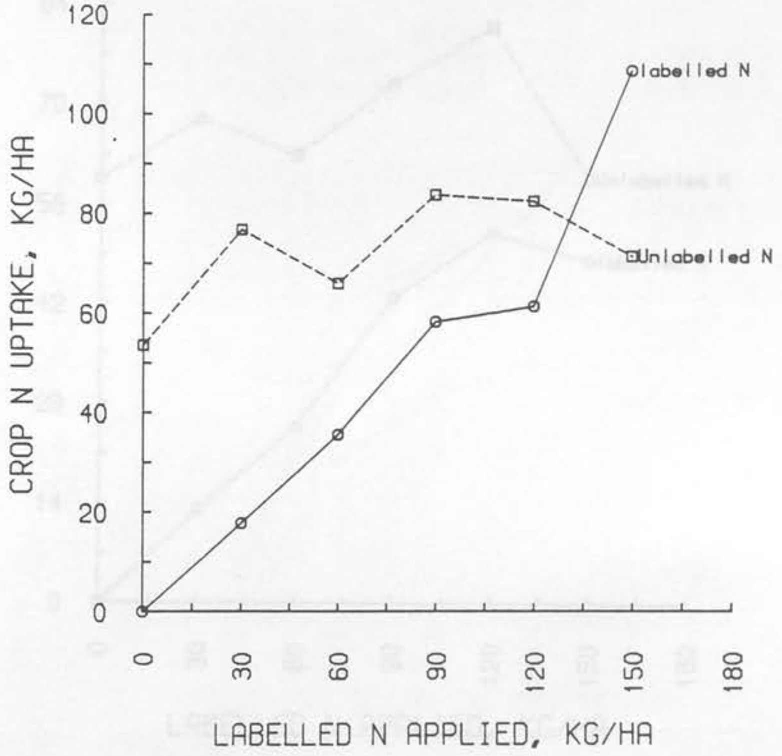


FIGURE 28
Uptake of labelled and unlabelled N by spring barley vs. labelled N fertilizer applied, 4th Cut (anthesis)
Balerno, 1981

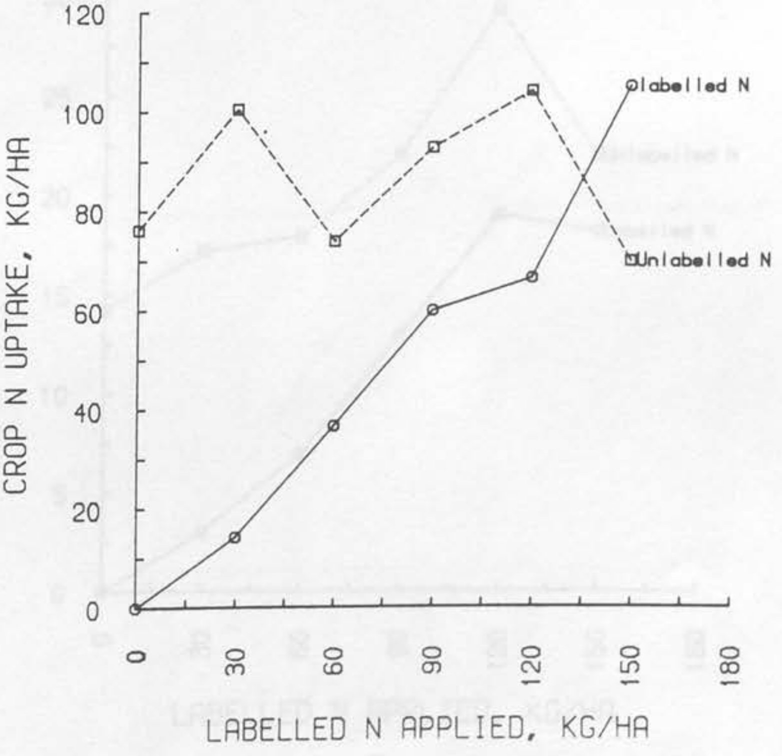


FIGURE 29
Uptake of labelled and unlabelled N by spring barley vs. labelled N fertilizer applied, final harvest (grain)
Balerno, 1981

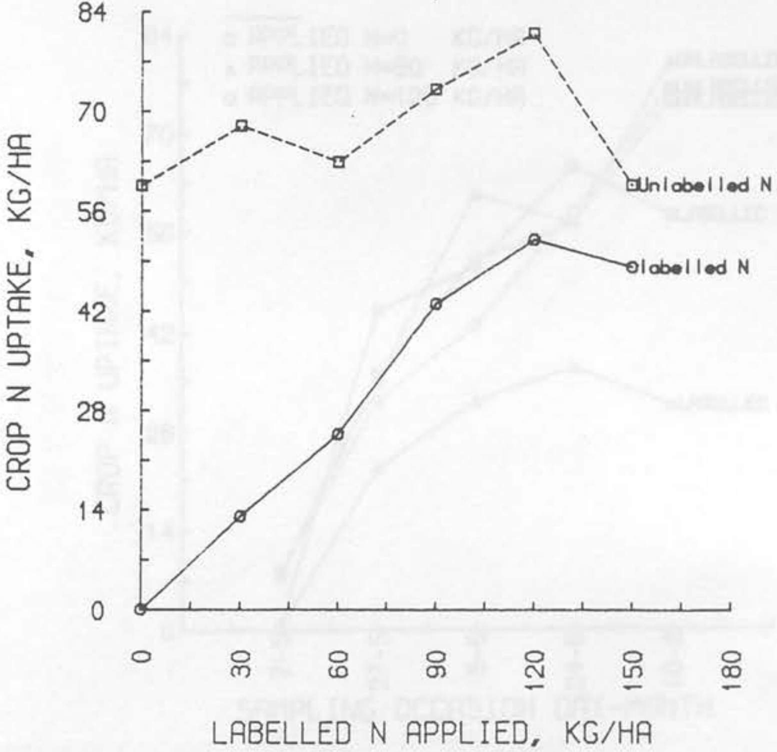


FIGURE 30
Uptake of labelled and unlabelled N by spring barley vs. labelled N fertilizer applied, final harvest (straw)
Balerno, 1981

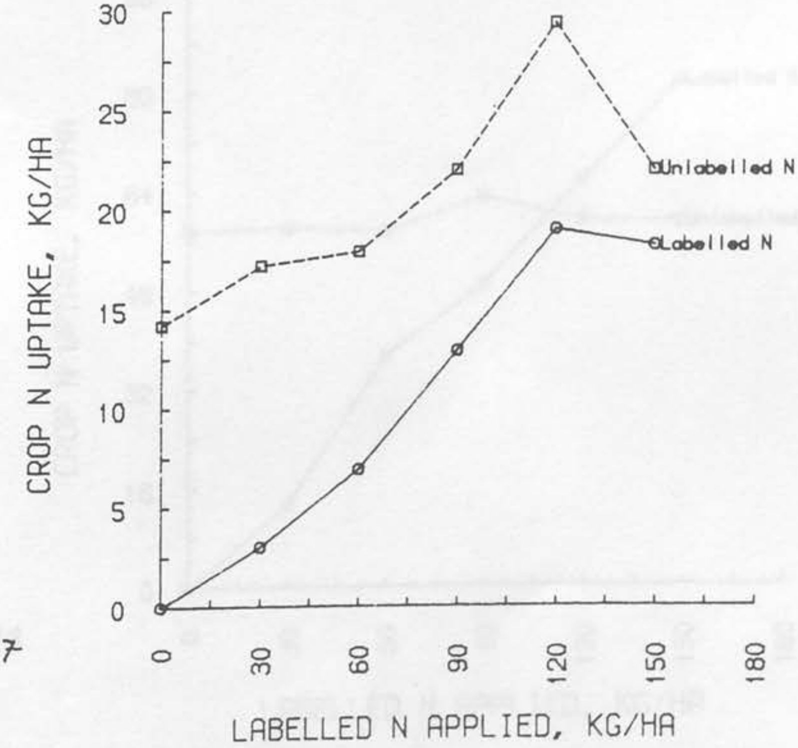


FIGURE 31
Accumulation of N in spring barley shoot during growth at 3 levels of applied, labelled N, Aberlady, 1982

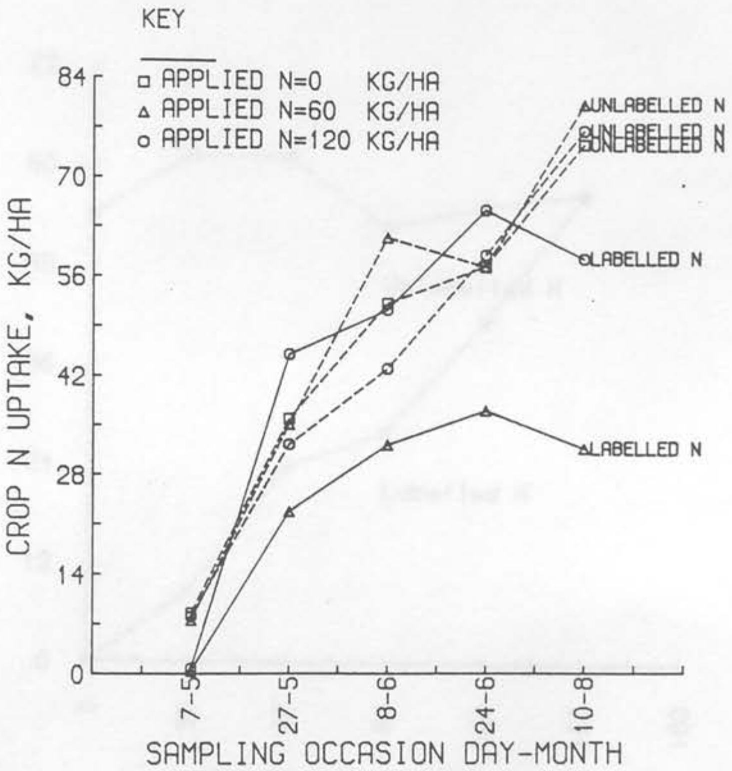


FIGURE 32
Uptake of labelled and unlabelled N by spring barley vs. labelled N fertilizer applied, 4th Cut (anthesis)
Aberlady, 1982

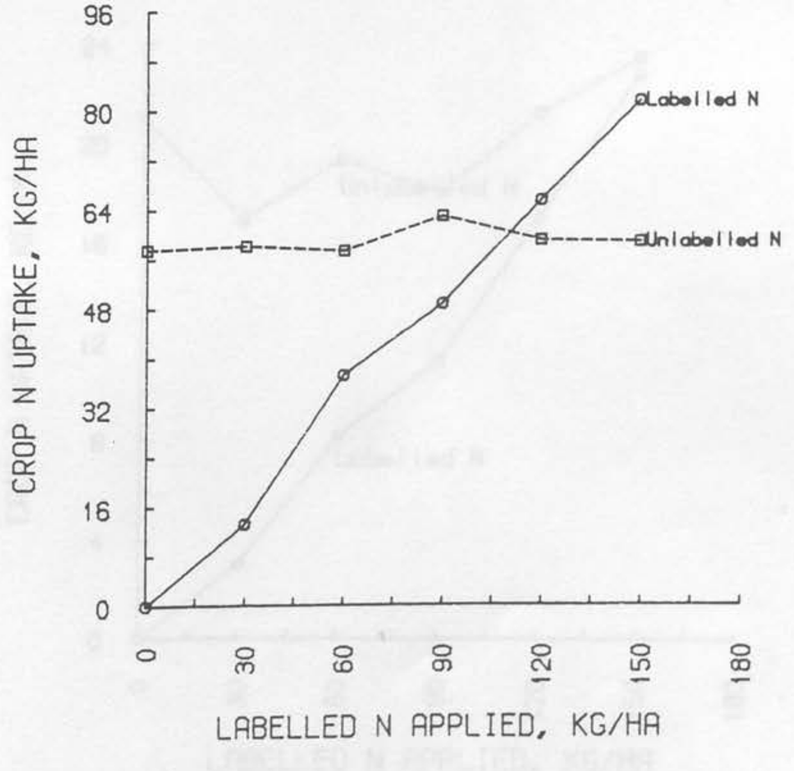


FIGURE 33

Uptake of labelled and unlabelled N by spring barley vs. labelled N fertilizer applied, final harvest (grain)
Aberlady, 1982

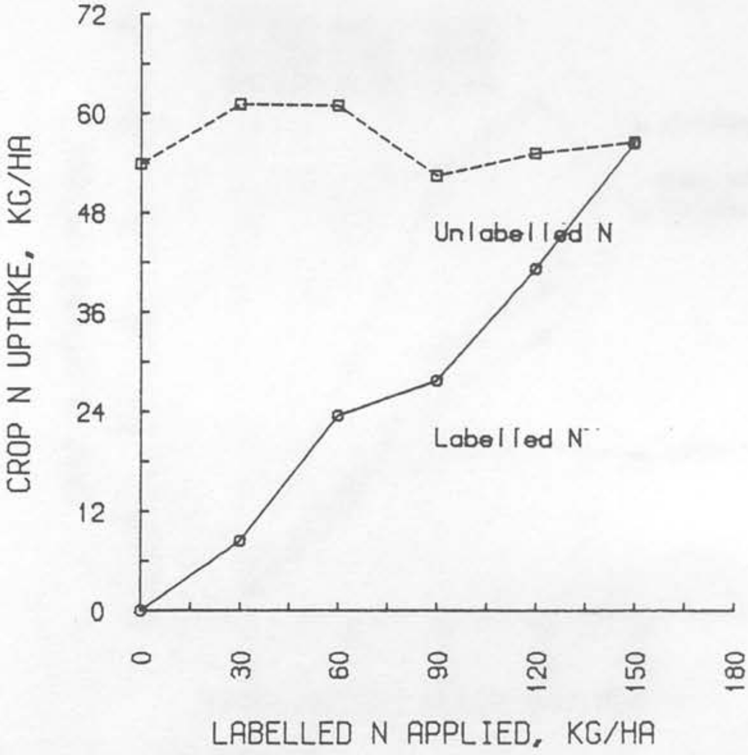


FIGURE 34

Uptake of labelled and unlabelled N by spring barley vs. labelled N fertilizer applied, final harvest (straw)
Aberlady, 1982

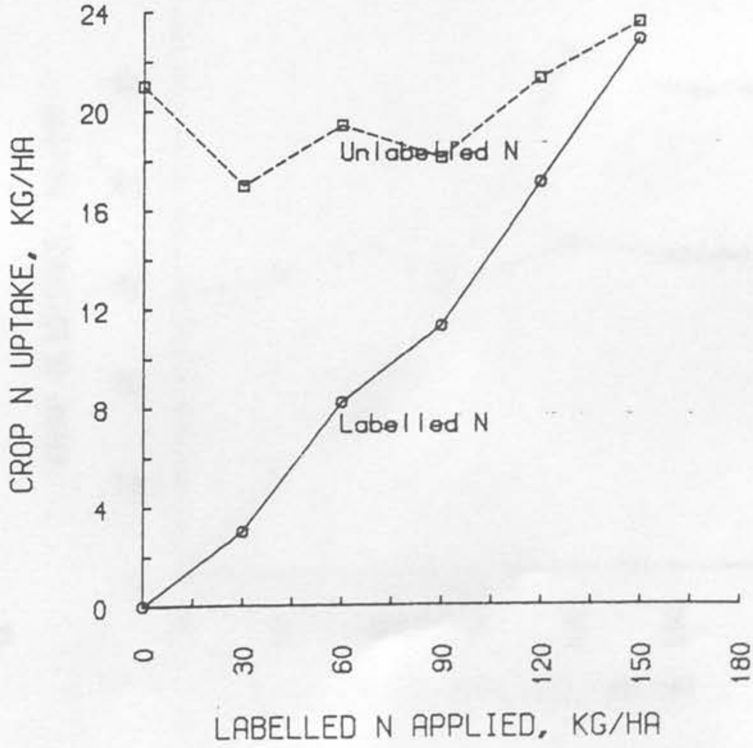


FIGURE 35

Accumulation of N in spring barley shoot during growth at 3 levels of applied, labelled N, Balerno, 1982

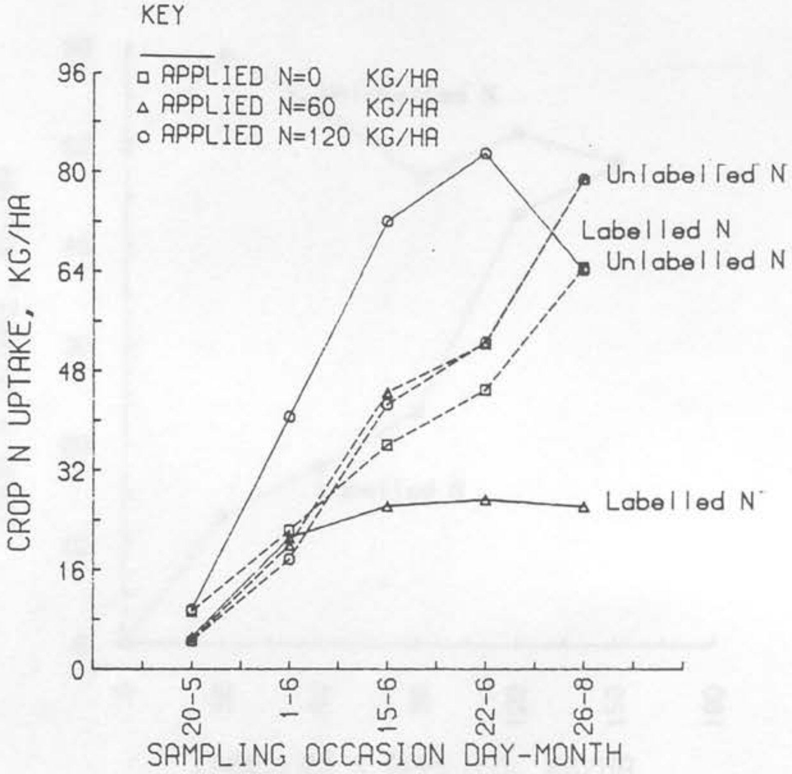


FIGURE 36

Uptake of labelled and unlabelled N by spring barley vs. labelled N fertilizer applied, 4th Cut (anthesis) Balerno, 1982

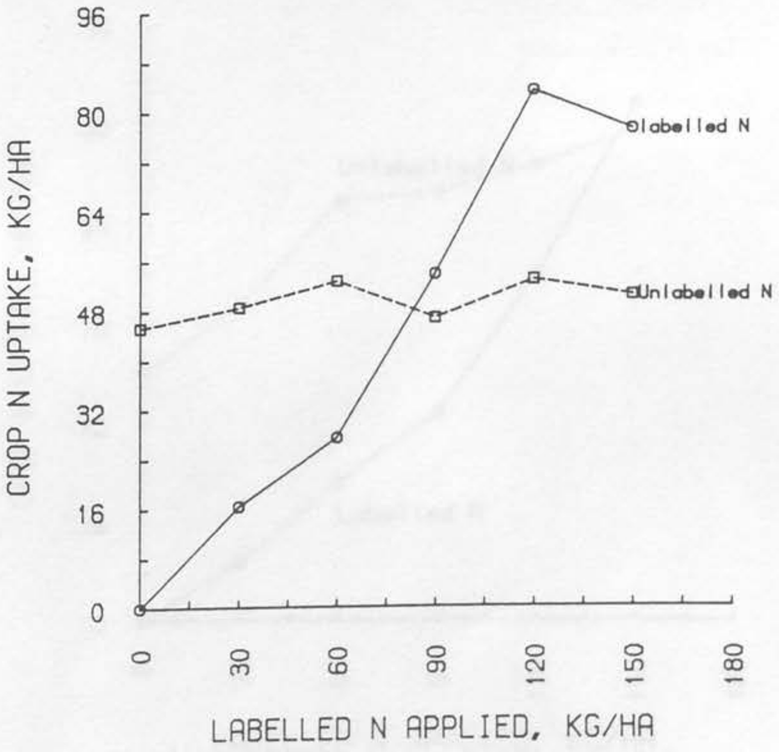


FIGURE 37
Uptake of labelled and unlabelled N by spring barley vs. labelled N fertilizer applied, final harvest (grain)
Balerno, 1982

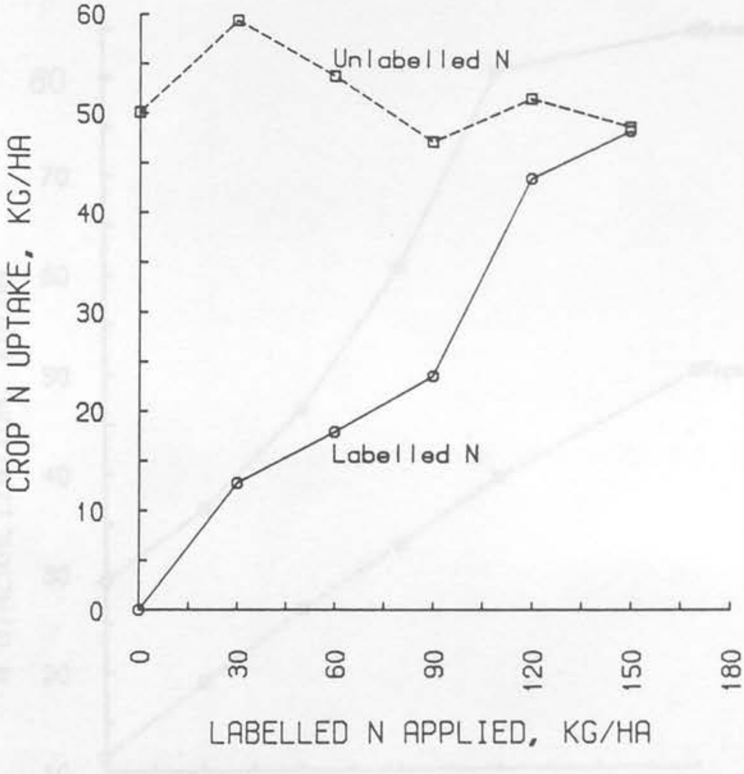


FIGURE 38
Uptake of labelled and unlabelled N by spring barley vs. labelled N fertilizer applied, final harvest (straw)
Balerno, 1982

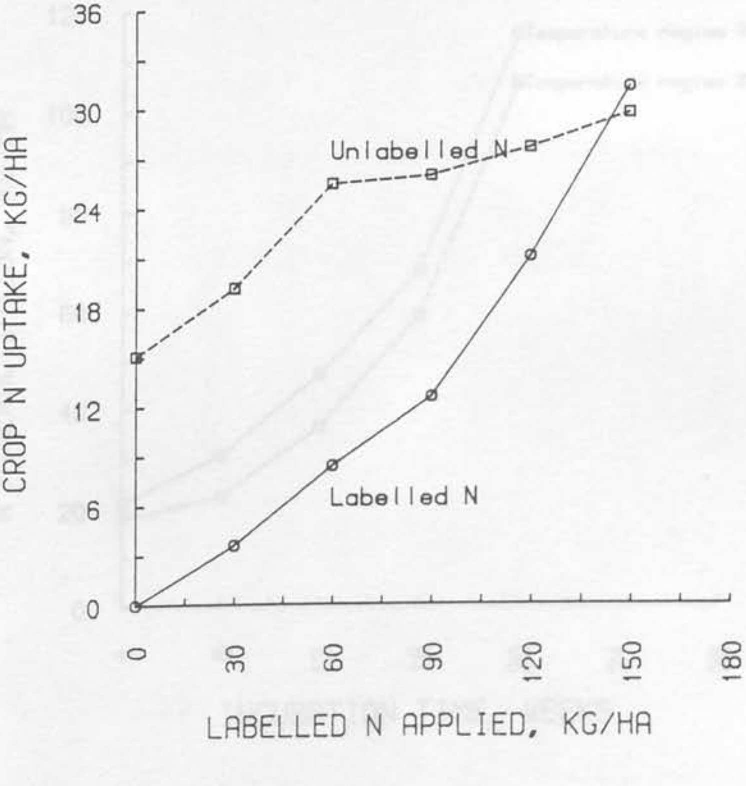


FIGURE 39
NITRATE-N MINERALIZATION IN SOIL FROM ABERLADY
INCUBATED AT 15°C

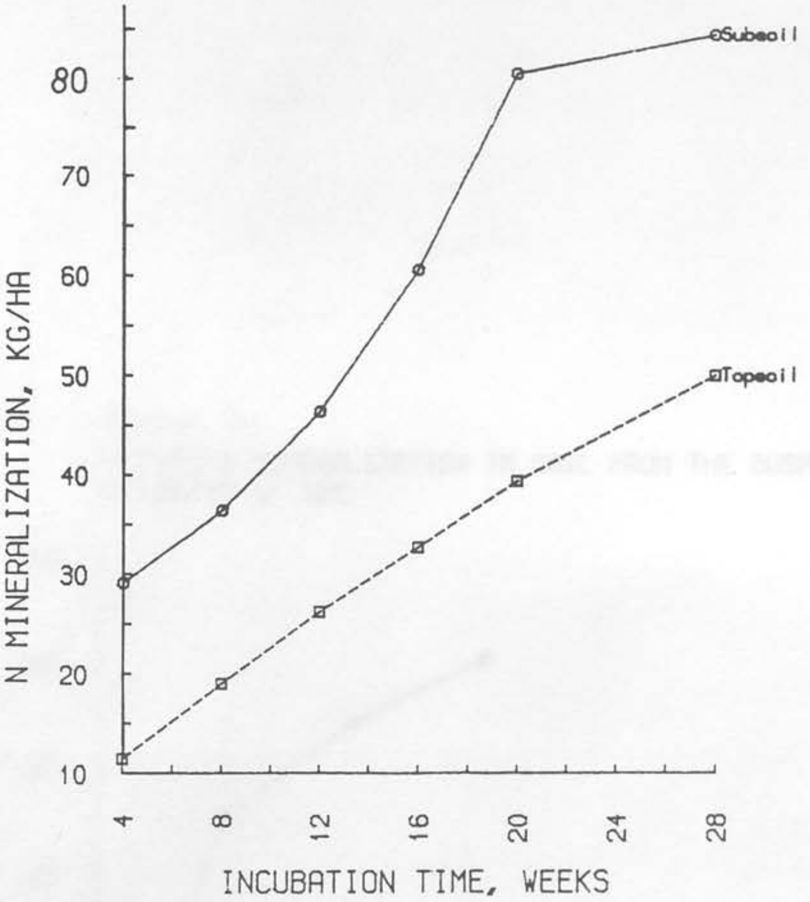


FIGURE 40
NITRATE-N MINERALIZATION IN SOIL FROM THE BUSH ESTATE
INCUBATED UNDER TWO TEMPERATURE REGIMES.

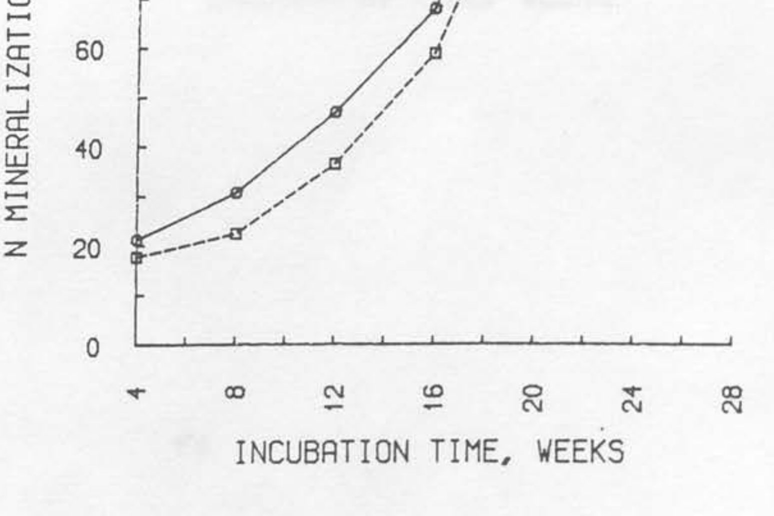


FIGURE 41

NITRATE-N MINERALIZATION IN SOIL FROM THE BUSH ESTATE INCUBATED AT 30°C

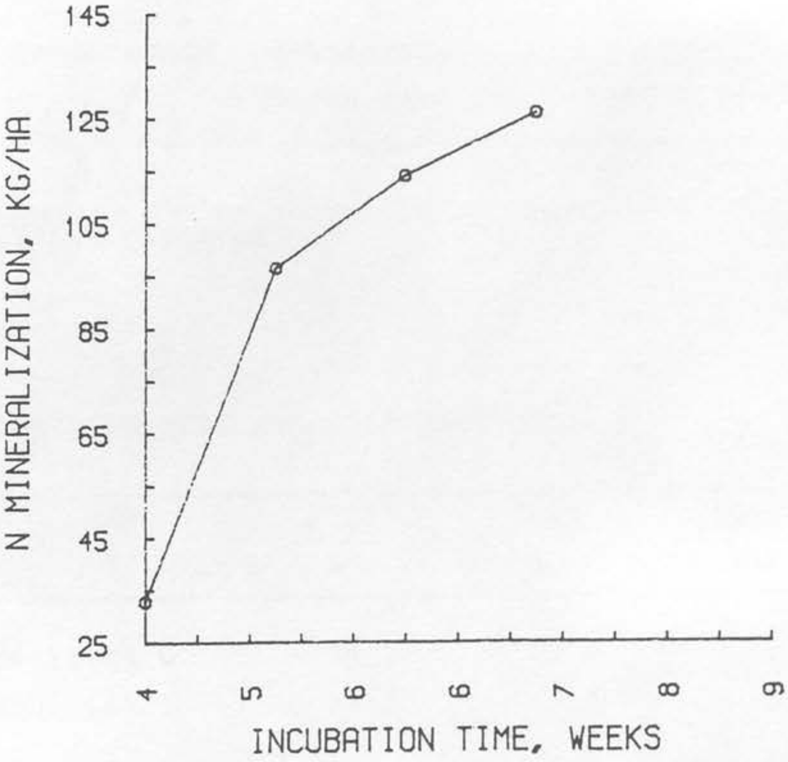


TABLE 1. SITE DETAILS

SITE	GRID REF.	ALTITUDE m	AV. ANNUAL RAINFALL mm
BUSH	NT 261633	170	866
BALERNO	NT 137657	183	905
ABERLADY	NT 452797	12	589

TABLE 2. DETAILS OF SOILS ON WHICH SITES WERE LOCATED

SITE	SOIL SERIES	CLASSIFICATION[a]	%C	%N	pH[b]
BUSH	MACMERRY	Stagnogleyic brown earth	3.1	0.22	6.6
	WINTON	Cambic stagnogley	2.2	0.16	6.5
BALERNO	ROWANHILL	Cambic stagnogley	3.2	0.23	6.1
ABERLADY	FRASERBURGH	Calcareous brown sand	1.4	0.14	7.8

[a] According to Avery, 1980

[b] 0.01M Calcium Chloride

TABLE 3. PARTICLE SIZE ANALYSIS (TOPSOIL)

SITE	SAND %	SILT %	CLAY %	TEXTURAL CLASS
BUSH(MACMERRY)	49.5	35.2	15.2	L
BUSH(WINTON)	47.5	35.3	17.4	L
BALERNO	65	15	20	SCL
ABERLADY	85	7	8	LS

TABLE 4. %NDFF, MEANS FOR EACH SOIL AND TILLAGE TREATMENT, APPLIED N LEVEL AND SAMPLING OCCASION, BUSH 1978

TREATMENT	N RATE	DATE 1	DATE 2	DATE 3	DATE 4	DATE 5(G)	DATE 5(S)
PLOUGHED	50	47.07	39.93	40.44	40.49	25.74	23.95
	100	62.20	55.87	60.54	55.66	37.74	36.65
	150	64.85	64.85	65.02	61.30	39.85	32.25
DIRECT	50	44.84	46.43	41.04	43.51	20.74	22.39
DRILLED	100	65.28	60.00	59.00	57.16	35.88	39.35
	150	64.38	66.88	69.05	63.68	41.31	44.00
MACMERRY	50	47.39	45.38	38.35	40.44	21.10	24.25
SOIL	100	64.88	56.20	61.29	57.00	35.22	39.03
	150	66.77	71.24	67.12	66.99	35.49	36.33
WINTON	50	44.16	40.86	43.13	46.62	25.38	22.09
SOIL	100	62.59	59.67	58.24	55.82	38.39	36.89
	150	62.47	60.49	66.95	57.99	45.67	39.92

TABLE 5. %NDFF, MEANS FOR EACH SOIL AND TILLAGE TREATMENT, APPLIED N LEVEL AND SAMPLING OCCASION, BUSH 1979

TREATMENT	N RATE	DATE 1	DATE 2	DATE 3	DATE 4	DATE 5(G)	DATE 5(S)
PLOUGHED	60	44.48	41.58	40.35	32.48	34.96	36.44
	120	50.93	58.04	49.98	42.29	56.70	59.72
	180	60.33	59.22	60.22	55.53	59.76	60.65
DIRECT	60	49.24	37.52	34.07	40.04	21.69	27.73
DRILLED	120	60.20	52.86	54.54	45.85	46.41	45.17
	180	67.23	67.60	59.66	54.46	54.07	53.96
MACMERRY	60	46.23	37.99	38.06	37.54	26.61	33.99
SOIL	120	45.37	48.65	51.93	46.23	54.56	56.49
	180	58.17	61.60	58.55	58.05	59.25	62.25
WINTON	60	47.49	41.10	36.35	34.98	30.05	30.18
SOIL	120	65.75	62.26	52.59	41.91	48.54	48.40
	180	69.39	65.22	61.33	51.94	54.58	52.36

TABLE 6. %NDFF, MEANS FOR EACH SOIL AND TILLAGE TREATMENT, APPLIED N LEVEL AND SAMPLING OCCASION, BUSH 1980

TREATMENT	N RATE	DATE 1	DATE 2	DATE 3	DATE 4	DATE 5(G)	DATE 5(S)
PLOUGHED	60	7.62	28.19	52.23	51.85	25.97	28.00
	120	13.02	36.16	75.61	68.53	43.61	41.88
	180	18.47	33.86	75.97	75.05	51.04	53.56
DIRECT DRILLED	60	28.28	36.81	48.77	44.84	30.24	30.77
	120	40.72	46.96	71.05	46.16	43.84	42.30
	180	52.51	50.79	72.93	66.50	48.80	44.44
MACMERRY SOIL	60	17.58	32.78	47.13	44.44	24.94	25.43
	120	27.99	49.75	76.45	60.27	37.97	34.80
	180	37.55	50.22	74.51	71.51	43.72	41.77
WINTON SOIL	60	18.32	32.22	53.87	52.25	31.28	33.34
	120	25.76	33.37	70.21	54.41	49.49	49.37
	180	33.43	34.43	74.39	70.04	56.12	56.23

TABLE 7. NITROGEN UPTAKE FROM FERTILIZER (KG/HA), MEANS FOR EACH SOIL AND TILLAGE TREATMENT, APPLIED N LEVEL AND SAMPLING OCCASION, BUSH 1978

TREATMENT	N RATE	DATE 1	DATE 2	DATE 3	DATE 4	DATE 5(G)	DATE 5(S)
PLOUGHED	50	3.46	8.87	12.74	17.09	7.23	3.41
	100	6.36	22.18	36.81	39.52	18.44	12.03
	150	7.46	36.05	42.09	45.57	22.41	14.60
DIRECT DRILLED	50	3.33	11.70	12.73	17.18	4.77	2.50
	100	4.27	20.29	26.45	38.55	11.22	5.99
	150	5.56	23.72	42.09	45.01	16.80	13.40
WINTON SOIL	50	3.83	10.21	13.77	19.42	5.66	2.86
	100	6.20	23.97	31.21	44.44	15.54	8.84
	150	7.47	22.28	34.58	44.26	20.72	14.43
MACMERRY SOIL	50	3.00	10.17	11.70	16.02	6.34	3.04
	100	4.44	18.51	32.05	33.62	14.12	10.24
	150	5.54	37.49	49.61	46.33	18.49	13.56

TABLE 8. NITROGEN UPTAKE FROM SOIL (KG/HA), MEANS FOR EACH SOIL AND TILLAGE TREATMENT, APPLIED N LEVEL AND SAMPLING OCCASION, BUSH 1978

TREATMENT	N RATE	DATE 1	DATE 2	DATE 3	DATE 4	DATE 5(G)	DATE 5(S)
PLOUGHED	0	4.54	7.38	10.90	12.73	11.31	5.34
	50	4.09	11.77	18.69	25.12	21.03	10.33
	100	3.83	17.37	23.76	31.48	29.61	20.49
	150	4.14	17.21	22.61	28.59	33.92	30.28
DIRECT DRILLED	0	2.79	6.44	9.66	13.37	13.69	5.56
	50	4.07	12.34	17.84	22.14	17.74	8.64
	100	2.24	14.22	17.71	29.06	20.57	9.24
	150	3.20	11.65	18.87	26.20	24.87	17.26
WINTON SOIL	0	3.41	5.64	9.16	13.24	10.53	4.32
	50	5.01	13.03	17.98	22.24	16.53	9.57
	100	3.68	16.01	21.24	35.05	24.50	15.74
	150	4.58	14.39	17.01	31.92	24.07	21.36
MACMERRY SOIL	0	3.79	8.18	11.41	12.86	14.37	6.58
	50	3.27	10.91	18.55	23.59	22.24	9.41
	100	2.39	15.57	20.23	25.49	25.69	15.57
	150	2.76	14.47	24.47	22.87	34.72	26.17

TABLE 9. NITROGEN UPTAKE FROM FERTILIZER (KG/HA), MEANS FOR EACH SOIL AND TILLAGE TREATMENT, APPLIED N LEVEL AND SAMPLING OCCASION, BUSH 1979

TREATMENT	N RATE	DATE 1	DATE 2	DATE 3	DATE 4	DATE 5(G)	DATE 5(S)
PLOUGHED	60	6.02	11.41	12.45	8.99	13.24	4.2
	120	7.43	23.25	24.67	20.26	36.91	17.05
	180	9.00	31.26	47.64	40.87	47.36	22.06
DIRECT DRILLED	60	7.68	14.99	14.05	22.15	8.76	2.82
	120	13.84	37.53	35.32	42.03	35.92	13.04
	180	16.24	56.88	60.39	70.21	61.87	20.50
WINTON SOIL	60	6.58	11.69	11.79	11.87	11.22	2.87
	120	12.79	33.80	26.85	29.15	34.88	12.77
	180	14.10	42.21	52.95	51.25	56.29	20.23
MACMERRY SOIL	60	7.12	14.70	14.71	19.27	10.79	4.15
	120	8.49	26.98	33.15	33.14	37.95	17.32
	180	11.14	45.92	55.09	59.84	52.94	22.34

TABLE 10. NITROGEN UPTAKE FROM SOIL (KG/HA), MEANS FOR EACH SOIL AND TILLAGE TREATMENT, APPLIED N LEVEL AND SAMPLING OCCASION, BUSH 1979

TREATMENT	N RATE	DATE 1	DATE 2	DATE 3	DATE 4	DATE 5(G)	DATE 5(S)
PLOUGHED	0	4.79	7.26	8.62	12.50	14.91	4.03
	60	7.06	16.08	18.41	18.63	22.07	6.73
	120	6.01	15.15	24.62	27.04	27.86	11.69
	180	5.27	21.47	28.84	32.73	31.29	14.35
DIRECT DRILLED	0	4.25	9.04	14.04	15.32	24.53	5.74
	60	7.98	25.32	26.92	31.19	31.25	7.12
	120	9.28	34.87	29.33	49.66	39.15	14.70
	180	8.02	27.80	38.72	58.71	52.19	17.78
WINTON SOIL	0	4.2	6.74	10.37	12.52	18.25	5.28
	60	7.09	16.88	21.06	22.21	25.32	6.48
	120	6.4	20.76	24.25	38.09	35.59	12.88
	180	6.17	21.07	32.06	49.37	48.12	18.57
MACMERRY SOIL	0	4.84	9.55	12.30	15.30	21.19	4.49
	60	7.95	24.52	24.27	27.60	28.00	7.37
	120	8.90	29.25	29.70	38.61	31.41	13.52
	180	7.12	28.20	35.50	42.07	35.36	13.56

TABLE 11. NITROGEN UPTAKE FROM FERTILIZER (KG/HA), MEANS FOR EACH SOIL AND TILLAGE TREATMENT, APPLIED N LEVEL AND SAMPLING OCCASION, BUSH 1980

TREATMENT	N RATE	DATE 1	DATE 2	DATE 3	DATE 4	DATE 5(G)	DATE 5(S)
PLOUGHED	60	0.56	4.42	20.01	36.30	12.98	4.63
	120	1.11	6.97	39.86	59.28	28.92	12.39
	180	1.64	8.12	53.91	83.69	43.20	18.90
DIRECT DRILLED	60	1.36	5.21	15.75	26.76	12.73	10.83
	120	2.71	9.33	34.85	37.68	26.82	14.70
	180	4.28	10.15	39.59	64.81	36.35	21.31
WINTON SOIL	60	1.03	4.47	19.11	30.78	15.24	7.98
	120	1.69	6.41	38.15	46.47	34.30	16.30
	180	2.71	5.66	44.28	66.73	48.32	27.36
MACMERRY SOIL	60	0.89	5.16	16.65	32.27	10.47	7.48
	120	2.14	9.89	36.56	50.49	21.45	10.79
	180	3.21	12.61	49.22	81.77	31.23	12.86

TABLE 12. NITROGEN UPTAKE FROM SOIL KG/HA, MEANS FOR EACH SOIL AND TILLAGE TREATMENT, APPLIED N LEVEL AND SAMPLING OCCASION, BUSH 1980

TREATMENT	N RATE	DATE 1	DATE 2	DATE 3	DATE 4	DATE 5(G)	DATE 5(S)
PLOUGHED	0	3.63	5.36	10.78	15.85	21.38	6.14
	60	6.26	11.24	18.29	34.10	38.34	12.57
	120	7.05	11.47	13.04	26.88	35.48	16.72
	180	7.58	15.59	17.11	27.58	40.70	15.64
DIRECT DRILLED	0	2.3	4.96	10.25	15.35	19.04	9.44
	60	3.39	8.94	16.63	33.52	33.27	24.26
	120	3.6	10.92	14.25	42.53	33.66	20.77
	180	3.73	8.84	14.70	32.67	36.63	23.15
MACMERRY SOIL	0	2.98	5.37	10.40	15.80	21.26	8.70
	60	5.05	10.65	18.50	40.25	37.96	19.68
	120	5.77	10.21	11.27	33.40	35.17	20.68
	180	5.46	12.48	16.71	31.97	40.64	18.08
WINTON SOIL	0	2.95	4.95	10.64	15.40	19.15	6.88
	60	4.60	9.54	16.43	27.37	33.65	17.14
	120	4.89	12.18	16.02	36.01	33.97	16.81
	180	5.85	11.94	15.10	28.29	36.68	20.71

TABLE 13. YIELD AND N UPTAKE OF WINTER BARLEY,
FIRST CUT ABERLADY, 1981

LABELLED N APPLIED KG/HA	DRY YIELD KG/HA	TOTAL N KG/HA	LABELLED N %	LABELLED N KG/HA	UNLABELLED N KG/HA
0	1781	41.6	-0.01	0.0	41.6
30	2405	67.5	32.81	22.1	45.3
60	2438	81.6	43.84	35.9	45.7
90	2543	98.4	58.91	57.6	40.8
120	2787	116.1	62.53	72.9	43.2
150	2921	127.4	65.77	83.5	43.9
SED	210.9	7.2	2.7	4.9	4.9

TABLE 14. YIELD AND N UPTAKE OF WINTER BARLEY,
SECOND CUT ABERLADY, 1981

LABELLED N APPLIED KG/HA	DRY YIELD KG/HA	TOTAL N KG/HA	LABELLED N %	LABELLED N KG/HA	UNLABELLED N KG/HA
0	2755	47.9	0.00	0.0	47.9
30	3418	69.2	22.44	15.5	53.6
60	4245	98.2	47.24	46.0	52.1
90	5625	130.7	49.35	64.4	66.3
120	4869	133.2	63.47	83.8	49.3
150	4907	156.6	67.74	105.9	50.7
SED	419.9	11.8	3.1	7.9	7.2

TABLE 15. YIELD AND N UPTAKE OF WINTER BARLEY, THIRD CUT ABERLADY, 1981

LABELLED N APPLIED KG/HA	DRY YIELD KG/HA	TOTAL N KG/HA	LABELLED N %	LABELLED N KG/HA	UNLABELLED N KG/HA
0	5583	64.2	0.01	0.0	64.3
30	5219	69.9	24.26	16.9	53.0
60*	8915	141.5	41.46	57.4	84.1
90	8301	125.6	55.70	67.0	58.6
120	9496	171.2	59.64	103.1	68.1
150	8265	163.7	61.54	101.9	61.9
SED	1293.7	20.8	4.7	14.3	12.7
1MV			5.1	15.6	13.9

* ONE MISSING VALUE IN THIS TREATMENT

TABLE 16. YIELD AND N UPTAKE OF WINTER BARLEY, FINAL HARVEST (GRAIN) ABERLADY, 1981

LABELLED N APPLIED KG/HA	DRY YIELD KG/HA	TOTAL N KG/HA	LABELLED N %	LABELLED N KG/HA	UNLABELLED N KG/HA
0	4386	53.3	0.01	0.0	53.3
30	4693	58.2	22.31	13.5	44.7
60	6219	86.7	36.60	32.1	54.6
90	6813	100.5	47.96	48.1	52.4
120	4786	80.8	50.94	41.6	39.2
150	4843	91.2	54.07	49.0	42.3
SED	942.9	15.6	3.74	8.6	8.0

TABLE 17. YIELD AND N UPTAKE OF WINTER BARLEY, FINAL HARVEST (STRAW) ABERLADY, 1981

LABELLED N APPLIED KG/HA	DRY YIELD KG/HA	TOTAL N KG/HA	LABELLED N %	LABELLED N KG/HA	UNLABELLED N KG/HA
0	5649	22.0	-0.01	0.0	22.0
30	6118	22.9	22.00	5.2	17.7
60	7974	34.6	37.71	13.1	21.5
90	10253	50.0	45.76	22.9	27.1
120	8665	52.4	49.28	26.4	26.0
150	9008	64.1	51.76	33.3	30.8
SED	1180.7	6.6	3.7	4.2	3.3

TABLE 18. YIELD AND N UPTAKE OF SPRING BARLEY, FIRST CUT ABERLADY, 1981

LABELLED N APPLIED KG/HA	DRY YIELD KG/HA	TOTAL N KG/HA	LABELLED N %	LABELLED N KG/HA	UNLABELLED N KG/HA
0	144	7.6	0.01	0.0	7.6
30	186	10.4	18.94	2.1	8.3
60	206	11.9	37.82	4.5	7.4
90	251	14.7	42.63	6.3	8.4
120	228	13.2	51.35	6.8	6.4
150	186	10.5	39.69	4.3	6.2
SED	3.6	1.79	5.13	1.05	1.3

TABLE 19. YIELD AND N UPTAKE OF SPRING BARLEY, SECOND CUT ABERLADY, 1981

LABELLED N APPLIED KG/HA	DRY YIELD KG/HA	TOTAL N KG/HA	LABELLED N %	LABELLED N KG/HA	UNLABELLED N KG/HA
0	790	25.2	-0.01	0.0	25.2
30	752	28.2	28.66	8.5	19.8
60	1104	47.5	48.76	23.5	24.0
90	1457	71.4	64.54	46.0	25.4
120	1655	80.1	66.65	53.2	26.9
150	1734	91.1	67.66	61.6	29.5
SED	133.5	6.5	5.64	4.42	3.32

TABLE 20. YIELD AND N UPTAKE OF SPRING BARLEY, THIRD CUT ABERLADY, 1981

LABELLED N APPLIED KG/HA	DRY YIELD KG/HA	TOTAL N KG/HA	LABELLED N %	LABELLED N KG/HA	UNLABELLED N KG/HA
0	1696	35.3	-0.01	0.0	35.2
30	2383	53.2	31.87	17.3	35.9
60	2516	68.1	37.84	25.8	42.3
90	2828	78.7	50.67	40.5	38.1
120	2957	99.5	66.44	66.6	32.9
150	2991	112.4	70.66	80.2	32.1
SED	242.5	10.5	3.9	8.5	5.4

TABLE 21. YIELD AND N UPTAKE OF SPRING BARLEY, FOURTH CUT ABERLADY, 1981

LABELLED N APPLIED KG/HA	DRY YIELD KG/HA	TOTAL N KG/HA	LABELLED N %	LABELLED N KG/HA	UNLABELLED N KG/HA
0	2640	39.3	-0.01	-0.1	39.4
30	3491	58.2	20.61	11.4	46.8
60	3873	69.6	35.85	24.9	44.6
90	4188	96.6	55.24	53.6	43.0
120	4637	110.5	63.81	71.4	39.1
150	4988	135.7	69.51	95.1	40.6
SED	351.7	10.0	5.3	8.5	7.69

TABLE 22. YIELD AND N UPTAKE OF SPRING BARLEY, FINAL HARVEST (GRAIN) ABERLADY, 1981

LABELLED N APPLIED KG/HA	DRY YIELD KG/HA	TOTAL N KG/HA	LABELLED N %	LABELLED N KG/HA	UNLABELLED N KG/HA
0	2272	31.0	0.00	-0.1	31.0
30*	3578	51.3	17.11	7.7	43.6
60*	3780	53.6	35.20	18.5	35.1
90	3293	49.9	39.38	19.0	30.8
120	4279	78.1	52.94	41.7	36.4
150	4584	94.7	59.94	57.4	37.3
SED	551	10.1	4.3	6.4	7.9
1MV			4.7	7.0	8.6
2MV			5.2	7.6	9.4

TABLE 23. YIELD AND N UPTAKE OF SPRING BARLEY, FINAL HARVEST (STRAW) ABERLADY, 1981

LABELLED N APPLIED KG/HA	DRY YIELD KG/HA	TOTAL N KG/HA	LABELLED N %	LABELLED N KG/HA	UNLABELLED N KG/HA
0	1718	9.2	0.00	0.0	9.2
30*	3003	16.9	19.62	2.8	14.1
60*	3242	20.2	31.98	6.4	13.8
90	2995	20.2	43.87	8.6	11.5
120	3618	29.9	55.54	16.8	13.0
150	4311	40.5	60.18	24.6	15.9
SED	370	3.7	4.7	2.7	2.9
1MV			5.1	2.9	3.2
2MV			5.6	3.2	3.5

* ONE MISSING VALUE IN THIS TREATMENT

TABLE 24. YIELD AND N UPTAKE OF SPRING BARLEY, FIRST CUT BALERNO, 1981

LABELLED N APPLIED KG/HA	DRY YIELD KG/HA	TOTAL N KG/HA	LABELLED N %	LABELLED N KG/HA	UNLABELLED N KG/HA
0	377	20.2	0.01	0.0	20.2
30*	509	29.3	28.24	8.2	21.1
60*	567	34.6	45.32	15.7	18.9
90	427	25.5	48.67	12.5	13.0
120	551	34.9	55.77	19.2	15.7
150	562	35.2	59.73	21.0	14.2
SED	56.8	3.7	3.3	1.9	3.0
1MV			3.6	2.1	3.3
2MV			4.0	2.3	3.6

TABLE 25. YIELD AND N UPTAKE OF SPRING BARLEY, SECOND CUT BALERNO, 1981

LABELLED N APPLIED KG/HA	DRY YIELD KG/HA	TOTAL N KG/HA	LABELLED N %	LABELLED N KG/HA	UNLABELLED N KG/HA
0	1136	41.7	0.00	0.0	41.7
30	1716	71.6	22.00	15.8	55.8
60	1924	93.1	40.42	37.7	55.4
90	2262	107.2	37.14	39.4	67.9
120	2268	121.1	60.07	72.0	49.1
150	2284	138.8	67.08	93.1	45.7
SED	190.9	11.2	2.5	4.9	8.2

* ONE MISSING VALUE IN THIS TREATMENT

TABLE 26. YIELD AND N UPTAKE OF SPRING BARLEY, THIRD CUT BALERNO, 1981

LABELLED N APPLIED KG/HA	DRY YIELD KG/HA	TOTAL N KG/HA	LABELLED N %	LABELLED N KG/HA	UNLABELLED N KG/HA
0	2680	53.6	-0.01	0.0	53.6
30	3913	94.7	18.90	17.8	76.9
60	4226	101.9	35.16	35.7	66.2
90	4507	142.8	40.98	58.6	84.2
120	3903	144.8	42.06	61.8	83.0
150	4784	181.4	59.66	109.5	71.9
SED	459.7	14.6	4.8	12.6	7.7

TABLE 27. YIELD AND N UPTAKE OF SPRING BARLEY, FOURTH CUT BALERNO, 1981

LABELLED N APPLIED KG/HA	DRY YIELD KG/HA	TOTAL N KG/HA	LABELLED N %	LABELLED N KG/HA	UNLABELLED N KG/HA
0	5556	76.2	0.01	-0.1	76.2
30*	6001	114.7	13.34	14.2	100.5
60	6709	110.5	32.85	36.6	73.9
90	6868	152.6	39.52	59.9	92.7
120	7946	170.6	37.90	66.5	104.2
150	6682	175.0	59.43	105.1	69.9
SED	585.8	19.8	5.9	12.0	9.9
1MV			6.4	13.1	10.8

* ONE MISSING VALUE IN THIS TREATMENT

TABLE 28. YIELD AND N UPTAKE OF SPRING BARLEY, FINAL HARVEST (GRAIN) BALERNO, 1981

LABELLED N APPLIED KG/HA	DRY YIELD KG/HA	TOTAL N KG/HA	LABELLED N %	LABELLED N KG/HA	UNLABELLED N KG/HA
0	4103	59.6	0.01	0.1	59.6
30	5348	81.2	15.97	13.1	68.1
60	5686	87.9	29.08	24.8	63.1
90	6646	117.0	38.16	43.3	73.6
120	7206	134.0	38.73	52.4	81.6
150	5577	108.8	44.79	48.6	60.2
SED	928	16.4	4.8	7.4	13.0

TABLE 29. YIELD AND N UPTAKE OF SPRING BARLEY, FINAL HARVEST (STRAW) BALERNO, 1981

LABELLED N APPLIED KG/HA	DRY YIELD KG/HA	TOTAL N KG/HA	LABELLED N %	LABELLED N KG/HA	UNLABELLED N KG/HA
0	3998	14.2	-0.01	0.0	14.2
30	5330	20.2	14.71	3.0	17.2
60	5847	24.8	28.45	6.9	17.9
90	6656	34.9	37.47	12.9	22.0
120	7697	48.3	39.06	19.0	29.4
150	6147	40.2	44.23	18.2	22.0
SED	980.7	6.4	4.7	3.3	4.3

TABLE 30. YIELD AND N UPTAKE OF WINTER BARLEY, SECOND CUT ABERLADY, 1982

LABELLED N APPLIED KG/HA	DRY YIELD KG/HA	TOTAL N KG/HA	LABELLED N %	LABELLED N KG/HA	UNLABELLED N KG/HA
0	791	24.8	0.00	0.0	24.8
30	813	33.6	32.50	10.9	22.7
60	847	39.6	43.26	17.3	22.4
90	895	43.0	46.55	20.0	23.0
120	1011	51.1	56.81	29.3	21.8
150	958	51.3	55.83	28.6	22.7
SED	98	5.1	3.8	3.6	2.3

TABLE 31. YIELD AND N UPTAKE OF WINTER BARLEY, THIRD CUT ABERLADY, 1982

LABELLED N APPLIED KG/HA	DRY YIELD KG/HA	TOTAL N KG/HA	LABELLED N %	LABELLED N KG/HA	UNLABELLED N KG/HA
0	1325	24.1	0.00	0.0	24.1
30	2197	45.4	31.56	13.9	31.5
60	2517	63.5	50.71	32.3	31.1
90	2772	79.2	62.06	49.3	29.9
120	3089	97.1	65.60	64.8	32.3
150	3389	113.9	70.01	80.3	33.6
SED	298	10.0	5.02	8.5	4.6

TABLE 32. YIELD AND N UPTAKE OF WINTER BARLEY, FOURTH CUT (ANTHESIS) ABERLADY, 1982

LABELLED N APPLIED KG/HA	DRY YIELD KG/HA	TOTAL N KG/HA	LABELLED N %	LABELLED N KG/HA	UNLABELLED N KG/HA
0	3379	35.7	0.00	0.0	35.7
30	5138	53.7	29.42	15.7	38.0
60	7561	92.9	51.81	48.3	44.6
90	6943	101.5	58.10	58.9	42.6
120	8002	125.7	60.90	77.8	47.9
150	7349	135.8	70.05	94.9	40.9
SED	465	8.2	4.25	7.9	5.3

TABLE 33. YIELD AND N UPTAKE OF WINTER BARLEY, FINAL HARVEST (GRAIN) ABERLADY, 1982

LABELLED N APPLIED KG/HA	DRY YIELD KG/HA	TOTAL N KG/HA	LABELLED N %	LABELLED N KG/HA	UNLABELLED N KG/HA
0	3257	30.8	0.00	0.0	30.8
30	3383	33.2	25.34	8.2	25.0
60	5354	56.3	41.81	23.1	33.2
90	3418	42.0	53.36	22.3	19.7
120	4687	60.2	53.73	32.0	28.3
150	5099	78.1	60.88	47.4	30.6
SED	792	10.8	3.25	6.8	5.1

TABLE 34. YIELD AND N UPTAKE OF WINTER BARLEY, FINAL HARVEST (STRAW) ABERLADY, 1982

LABELLED N APPLIED KG/HA	DRY YIELD KG/HA	TOTAL N KG/HA	LABELLED N %	LABELLED N KG/HA	UNLABELLED N KG/HA
0	2783	10.2	0.00	0.0	10.2
30	3448	23.5	22.13	5.4	18.1
60	5827	47.2	39.77	18.9	28.3
90	3577	30.3	49.84	14.9	15.4
120	5043	51.4	52.44	26.6	24.7
150	5817	71.4	61.94	44.3	27.1
SED	1170	11.0	3.53	6.1	5.8

TABLE 35. THE EFFECT OF SPLITTING* THE LABELLED N APPLICATION TO WINTER BARLEY ON LABELLED N UPTAKE (KG/HA) MEASURED ON 3 DATES, ABERLADY, 1982.

DATE	APPLIC.	TOTAL LABELLED N APPLIED, KG/HA				
DAY/MONTH	TYPE	30	60	90	120	150
15/4	SINGLE	10.9	17.3	20.0	22.3	24.5
	SPLIT	–	–	–	37.2	32.5
7/5	SINGLE	13.9	32.5	49.3	81.8	97.1
	SPLIT	–	–	–	47.8	63.4
27/5	SINGLE	15.7	48.3	58.9	89.0	101.9
	SPLIT	–	–	–	71.3	87.8

*ON HALF THE BLOCKS, THE TOP 2 APPLICATION RATES WERE SPLIT. ONE THIRD WAS APPLIED ON 23/2/82, THE REST, ALSO ALL THE SINGLE APPLICATIONS, WERE MADE ON 30/3/82.

TABLE 36. YIELD AND N UPTAKE OF SPRING BARLEY, FIRST CUT ABERLADY, 1982

LABELLED N APPLIED KG/HA	DRY YIELD KG/HA	TOTAL N KG/HA	LABELLED N %	LABELLED N KG/HA	UNLABELLED N KG/HA
0	155	8.5	-0.02	0.0	8.5
30*	160	8.2	3.43	0.3	8.0
60*	152	7.8	4.46	0.3	7.5
90	204	10.4	7.61	0.8	9.6
120	172	8.7	7.55	0.7	8.0
150	173	8.6	7.05	0.6	8.0
SED	22	1.2	1.1	0.15	1.2
1MV			1.2	0.16	1.3
2MV			1.4	0.18	1.4

* ONE MISSING VALUE IN THIS TREATMENT

TABLE 37. YIELD AND N UPTAKE OF SPRING BARLEY, SECOND CUT ABERLADY, 1982

LABELLED N APPLIED KG/HA	DRY YIELD KG/HA	TOTAL N KG/HA	LABELLED N %	LABELLED N KG/HA	UNLABELLED N KG/HA
0	1162	36.0	-0.01	0.0	36.0
30	1326	46.8	29.05	13.5	33.3
60	1385	58.0	39.10	22.8	35.2
90	1658	73.9	50.59	37.1	36.8
120	1672	77.4	58.41	45.1	32.3
150	1428	68.2	56.21	38.1	30.1
SED	138	7.3	3.5	3.7	4.7

TABLE 38. YIELD AND N UPTAKE OF SPRING BARLEY, THIRD CUT (ANTHESIS) ABERLADY, 1982

LABELLED N APPLIED KG/HA	DRY YIELD KG/HA	TOTAL N KG/HA	LABELLED N %	LABELLED N KG/HA	UNLABELLED N KG/HA
0	3020	52.3	0.00	0.0	52.3
30	3440	61.6	21.07	12.9	48.7
60	4355	93.9	34.56	32.3	61.6
90	3822	91.3	49.86	44.1	47.2
120	3751	94.5	54.93	51.4	43.1
150	3854	107.9	58.62	62.9	45.0
SED	283	6.3	4.3	3.6	5.7

TABLE 39. YIELD AND N UPTAKE OF SPRING BARLEY, FOURTH CUT ABERLADY, 1982

LABELLED N APPLIED KG/HA	DRY YIELD KG/HA	TOTAL N KG/HA	LABELLED N %	LABELLED N KG/HA	UNLABELLED N KG/HA
0	4814	57.6	-0.01	0.0	57.6
30	5662	71.4	18.39	13.2	58.2
60	5921	94.8	39.75	37.2	57.5
90	6097	111.8	43.77	48.9	63.0
120	6087	124.8	53.04	65.6	59.2
150	6395	140.6	58.41	81.7	59.0
SED	568	8.2	4.3	3.8	6.9

TABLE 40. YIELD AND N UPTAKE OF SPRING BARLEY, FINAL HARVEST (GRAIN) ABERLADY, 1982

LABELLED N APPLIED KG/HA	DRY YIELD KG/HA	TOTAL N KG/HA	LABELLED N %	LABELLED N KG/HA	UNLABELLED N KG/HA
0	3919	53.9	-0.01	0.0	53.9
30	4988	69.6	12.35	8.4	61.2
60	5334	84.8	27.76	23.6	61.2
90	4730	80.8	34.68	27.9	52.8
120	5241	97.3	42.39	41.6	55.6
150	5673	113.8	50.05	56.8	57.0
SED	349	8.0	3.1	5.5	4.3

TABLE 41. YIELD AND N UPTAKE OF SPRING BARLEY, FINAL HARVEST (STRAW) ABERLADY, 1982

LABELLED N APPLIED KG/HA	DRY YIELD KG/HA	TOTAL N KG/HA	LABELLED N %	LABELLED N KG/HA	UNLABELLED N KG/HA
0	3533	21.2	0.68	0.2	21.0
30	3891	20.0	15.53	3.0	17.0
60	4378	27.7	29.75	8.2	19.4
90	4103	29.4	38.64	11.3	18.1
120	4558	38.4	43.83	17.1	21.3
150	5077	46.5	49.55	22.9	23.6
SED	213	3.7	2.7	2.2	2.3

TABLE 42. YIELD AND N UPTAKE OF SPRING BARLEY, FIRST CUT BALERNO, 1982

LABELLED N APPLIED KG/HA	DRY YIELD KG/HA	TOTAL N KG/HA	LABELLED N %	LABELLED N KG/HA	UNLABELLED N KG/HA
0	228	9.3	-0.01	0.0	9.3
30	267	12.1	35.87	4.3	7.8
60	198	9.9	52.60	5.2	4.7
90	236	12.4	60.30	7.6	4.9
120*	248	13.2	65.55	8.9	4.6
150	265	14.4	66.30	9.6	4.9
SED	35.2	1.6	1.7	1.0	0.9
1MV			1.9	1.1	1.0

* ONE MISSING VALUE IN THIS TREATMENT

TABLE 43. YIELD AND N UPTAKE OF SPRING BARLEY, SECOND CUT BALERNO, 1982

LABELLED N APPLIED KG/HA	DRY YIELD KG/HA	TOTAL N KG/HA	LABELLED N %	LABELLED N KG/HA	UNLABELLED N KG/HA
0	745	22.5	0.01	0.0	22.5
30	770	30.0	45.97	13.7	16.3
60	947	41.3	50.57	21.3	20.1
90	1144	55.8	66.50	36.9	18.9
120	1124	58.6	69.89	40.8	17.8
150	1043	55.8	72.82	40.5	15.3
SED	132	5.7	3.9	4.2	3.1

TABLE 44. YIELD AND N UPTAKE OF SPRING BARLEY, THIRD CUT BALERNO, 1982

LABELLED N APPLIED KG/HA	DRY YIELD KG/HA	TOTAL N KG/HA	LABELLED N %	LABELLED N KG/HA	UNLABELLED N KG/HA
0	2011	36.3	-0.01	0.0	36.3
30	2927	64.4	26.58	16.9	47.5
60	3020	71.3	36.72	26.4	44.9
90	2240	60.7	49.30	29.8	30.9
120	3507	115.4	62.88	72.5	42.9
150	3673	125.0	63.44	79.2	45.8
SED	249	6.8	2.9	4.7	4.4

TABLE 45. YIELD AND N UPTAKE OF SPRING BARLEY, FOURTH CUT BALERNO, 1982

LABELLED N APPLIED KG/HA	DRY YIELD KG/HA	TOTAL N KG/HA	LABELLED N %	LABELLED N KG/HA	UNLABELLED N KG/HA
0	2719	45.3	-0.01	0.0	45.3
30	3202	65.0	26.29	16.4	48.6
60	3945	80.3	34.00	27.5	52.8
90	4022	100.7	53.46	53.9	46.8
120	4770	136.6	61.16	83.6	53.0
150	4427	127.9	60.32	77.3	50.5
SED	364.2	6.84	3.26	5.02	5.01

TABLE 46. YIELD AND N UPTAKE OF SPRING BARLEY, FINAL HARVEST (GRAIN) BALERNO, 1982

LABELLED N APPLIED KG/HA	DRY YIELD KG/HA	TOTAL N KG/HA	LABELLED N %	LABELLED N KG/HA	UNLABELLED N KG/HA
0	3442	50.1	-0.01	0.0	50.1
30	4495	72.3	17.40	12.8	59.5
60	4441	72.0	24.70	18.0	54.0
90	4016	71.1	33.06	23.7	47.4
120	5122	95.5	44.79	43.7	51.8
150	4849	97.3	49.98	48.5	48.9
SED	742.4	14.43	3.44	7.85	7.6

TABLE 47. YIELD AND N UPTAKE OF SPRING BARLEY, FINAL HARVEST (STRAW) BALERNO, 1982

LABELLED N APPLIED KG/HA	DRY YIELD KG/HA	TOTAL N KG/HA	LABELLED N %	LABELLED N KG/HA	UNLABELLED N KG/HA
0	2619	15.1	0.00	0.0	15.1
30	3772	22.8	15.96	3.6	19.2
60	4663	33.9	24.73	8.4	25.5
90	4457	38.6	33.13	12.6	26.0
120	5524	48.8	43.14	21.1	27.7
150	5670	61.2	50.47	31.4	29.8
SED	714.3	7.4	3.54	4.31	4.11

TABLE 48. SAMPLING DATES, DAY/MONTH BUSH, 1978-1982

CUT	YEAR 1978	1979	1980	1981	1982
1	25/5	5/6	23/5	22/5	11/5
2	5/6	19/6	3/6	4/6	25/5
3	15/6	27/6	12/6	18/6	8/6
4	26/6	9/7	23/6	2/7	
HARVEST	13/9	7/9	4/9	1/9	25/8

TABLE 50. RAINFALL DISTRIBUTION, MARCH-MAY, 1981 AND 1982, DUNBAR, EAST LOTHIAN.

INTERVAL DAY/MONTH	RAINFALL, MM 1981	1982
20/3 -26/3	16.0	0.1
27/3 - 2/4	3.7	4.1
3/4 - 9/4	1.5	15.4
10/4 -16/4	3.5	0.0
17/4 -23/4	3.2	0.0
24/4 -30/4	6.5	0.3
1/5 - 7/5	11.7	28.5

TABLE 49. SAMPLING DATES, DAY/MONTH AND GROWTH STAGE ASSESSMENT, ABERLADY AND BALERNO, 1981 AND 1982

ABERLADY WINTER BARLEY 1981

CUT	DATE	DESCRIPTION
1	17/4	1st node detectable
2	4/5	2nd node detectable
3	27/5	ears emerged
4	27/7	harvest

ABERLADY WINTER BARLEY 1982

CUT	DATE	DESCRIPTION
1	30/3	main shoot + 6-7 tillers
2	15/4	start of stem erection
3	7/5*	1st node dectectable
4	27/5	ears emerged
5	23/7	harvest

ABERLADY SPRING BARLEY 1981

CUT	DATE	DESCRIPTION
1	7/5	3-4 leaves, 1-3 tillers
2	27/5	1st node detectable
3	10/6	awns visible
4	24/6	ears emerged
5	17/8	harvest

ABERLADY SPRING BARLEY 1982

CUT	DATE	DESCRIPTION
1	7/5*	2-3 leaves, 1 tiller
2	27/5	1-2 nodes detectable
3	8/6	awns visible
4	24/6	ears emerged
5	10/8	harvest

* sampling shortly after the first rain after a dry spell

BALERNO SPRING BARLEY 1981

CUT	DATE	DESCRIPTION
1	26/5	4 leaves, 2-3 tillers
2	10/6	2nd node detectable
3	25/6	boots swollen
4	9/7	ears emerged
5	15/9	harvest

BALERNO SPRING BARLEY 1982

CUT	DATE	DESCRIPTION
1	20/5	3-4 leaves, 1-2 tillers
2	1/6	1-2 nodes detectable
3	15/6	flag leaves emerged
4	22/6	ears emerged
5	26/8	harvest

TABLE 51. AVAILABLE N (KG/HA) IN SOIL, BUSH, 2ND CORING 13/6/79

APPLIED LABELLED N, KG/HA	DEPTH CM	TILLAGE DD NDFF	DD NDFS	SP NDFF	SP NDFS
0	0-20	-	84	-	69
	20+	-	28	-	42
60	0-20	7	103	15	95
	20+	-	54	-	57
120	0-20	31	97	75	82
	20+	3	40	1	23
180	0-20	60	102	55	82
	20+	4	52	1	30

TABLE 52. AVAILABLE N (KG/HA) IN SOIL, BUSH, 4TH CORING 19/9/79

APPLIED LABELLED N, KG/HA	DEPTH CM	TILLAGE DD NDFF	DD NDFS	SP NDFF	SP NDFS
0	0-20	-	94	-	93
	20+	-	47	-	69
60	0-20	5	119	5	144
	20+	-	41	3	16
120	0-20	15	112	9	106
	20+	1	39	4	39
180	0-20	4	33	18	161
	20+	9	118	5	59

TABLE 53. PERCENTAGE OF AVAILABLE N IN SOIL TAKEN UP BY CROP DURING 2 WEEKS IN JUNE, BUSH, 1979

APPLIED		TILLAGE			
LABELLED	SOIL	DD		SP	
N, KG/HA	DEPTH	NDFF	NDFS	NDFF	NDFS
0	WHOLE		5.8		2.0
60	PROFILE	32.9	4.5	20.7	3.6
120		20.2	8.0	9.9	11.8
180		25.5	11.7	43.9	11.9
0	0-20 CM		7.7		3.2
60		32.9	6.8	20.5	5.8
120		22.1	11.3	10.0	15.1
180		27.3	17.6	44.7	16.2

TABLE 54. PERCENTAGE RECOVERY OF LABELLED FERTILIZER IN CROP AND SOIL, BUSH, 1979

APPLIED N, KG/HA	TILLAGE	SOIL*	HARVESTED CROP**	TOTAL
60	DD	9.07	22.13	31.2
	SP	13.75	31.95	45.7
120	DD	14.10	34.50	48.6
	SP	11.44	45.18	56.6
180	DD	7.22	38.49	45.7
	SP	12.78	39.05	51.8

*CORES TAKEN 19/9/79 ** HARVEST 7/9/79

TABLE 55. AVAILABLE N IN SOIL AT TIME OF FERTILIZER APPLICATION, 1981

		AVAILABLE N KG/HA *		
SITE	DATE	TOPSOIL	SUBSOIL	TOTAL
ABERLADY WINTER	19/3	9.4	17.5	26.9
ABERLADY SPRING	27/3	27.3	32.0	59.3
BALERNO	14/4	33.2	32.8	66.0

*MOSTLY AS NITRATE (85% MINIMUM)

TABLE 56. NET N MINERALIZED AFTER 2 WEEKS AT 30°C IN SOIL FROM 2 NITROGEN AND 2 TILLAGE TREATMENTS, BUSH, 1983

	N MINERALIZED mg kg^{-1}	
TILLAGE	N_0	N_3
DD	17.4	12.0
SP	11.2	10.7

DD- direct-drilled SP- ploughed

Table 57. Temperature régimes used in soil incubation studies simulating field conditions

Time interval (weeks)	4-week mean temp (°C) (Régimes A and B)	Diurnal range (°C) (Régime B)
0-4	6.5	2.5-10.5
4-8	11.0	7-15
8-12	14.5	10.5-18.5
12-16	14.0	10-18
16-20	14.0	10-18

TABLE 58. AVAILABLE N IN SOIL (A-VALUES) FROM CROP N UPTAKE DATA, ABERLADY

	1981		1982	
CUT	WINTER BARLEY	SPRING BARLEY	WINTER BARLEY	SPRING BARLEY
1	79.8	-	-	-
2	90.0	72.9	101.5	102.8
3	97.5	84.8	70.8	115.4
4	-	93.7	76.5	120.9
G	124.3	130.0	101.4	179.0
S	127.9	123.1	109.0	163.0

TABLE 59. YIELD AND N UPTAKE OF SPRING BARLEY, PLOUGHED PLOTS, MACMERRY SOIL SECOND (BULKED) CUT, BUSH, 1981

LABELLED N APPLIED KG/HA	DRY YIELD KG/HA	TOTAL N KG/HA	LABELLED N %	LABELLED N KG/HA	UNLABELLED N KG/HA
0	202	8.5	0.00	0.0	8.5
60	475	25.9	40.79	10.6	15.4
120	614	37.0	60.01	22.2	14.8
180	1152	68.5	60.35	41.3	27.2

TABLE 60. YIELD AND N UPTAKE OF SPRING BARLEY, PLOUGHED PLOTS, WINTON SOIL SECOND (BULKED) CUT, BUSH, 1981

LABELLED N APPLIED KG/HA	DRY YIELD KG/HA	TOTAL N KG/HA	LABELLED N %	LABELLED N KG/HA	UNLABELLED N KG/HA
0	191	7.5	0.00	0.0	7.5
60	431	21.8	38.45	8.4	13.4
120	982	57.4	60.97	35.0	22.4
180	756	47.5	68.71	32.6	14.9

TABLE 61. YIELD AND N UPTAKE OF SPRING BARLEY, DIRECT-DRILLED PLOTS, MACMERRY SOIL SECOND (BULKED) CUT, BUSH, 1981

LABELLED N APPLIED KG/HA	DRY YIELD KG/HA	TOTAL N KG/HA	LABELLED N %	LABELLED N KG/HA	UNLABELLED N KG/HA
0	164	7.5	0.00	0.0	7.5
60	526	28.4	55.76	15.9	12.6
120	707	42.4	61.29	26.0	16.4
180	730	43.3	58.07	25.2	18.2

TABLE 62. YIELD AND N UPTAKE OF SPRING BARLEY, DIRECT-DRILLED PLOTS, WINTON SOIL SECOND (BULKED) CUT, BUSH, 1981

LABELLED N APPLIED KG/HA	DRY YIELD KG/HA	TOTAL N KG/HA	LABELLED N %	LABELLED N KG/HA	UNLABELLED N KG/HA
0	198	7.9	0.00	0.0	7.9
60	324	16.4	42.95	7.0	9.3
120	746	43.7	65.74	28.7	15.0
180	764	46.7	72.13	33.7	13.0

TABLE 63. YIELD AND N UPTAKE OF SPRING BARLEY, PLOUGHED PLOTS, MACMERRY SOIL THIRD (BULKED) CUT, BUSH, 1981

LABELLED N APPLIED KG/HA	DRY YIELD KG/HA	TOTAL N KG/HA	LABELLED N %	LABELLED N KG/HA	UNLABELLED N KG/HA
0	690	20.4	0.00	0.0	20.4
60	971	40.8	32.92	13.4	27.4
120	2277	92.3	48.17	44.5	47.9
180	2541	109.0	54.50	59.4	49.6

TABLE 64. YIELD AND N UPTAKE OF SPRING BARLEY, PLOUGHED PLOTS, WINTON SOIL THIRD (BULKED) CUT, BUSH, 1981

LABELLED N APPLIED KG/HA	DRY YIELD KG/HA	TOTAL N KG/HA	LABELLED N %	LABELLED N KG/HA	UNLABELLED N KG/HA
0	472	17.0	0.00	0.0	17.0
60	1105	48.2	55.83	26.9	21.3
120	1917	85.7	65.35	56.0	29.7
180	2575	119.5	70.05	83.7	35.8

TABLE 65. YIELD AND N UPTAKE OF SPRING BARLEY, DIRECT-DRILLED PLOTS, MACMERRY SOIL THIRD (BULKED) CUT, BUSH, 1981

LABELLED N APPLIED KG/HA	DRY YIELD KG/HA	TOTAL N KG/HA	LABELLED N %	LABELLED N KG/HA	UNLABELLED N KG/HA
0	398	13.4	0.00	0.0	13.4
60	1352	45.1	46.75	21.1	24.0
120	2453	97.9	60.76	59.5	38.4
180	2195	100.3	74.30	74.5	25.8

TABLE 66. YIELD AND N UPTAKE OF SPRING BARLEY, DIRECT-DRILLED PLOTS, WINTON SOIL THIRD (BULKED) CUT, BUSH, 1981

LABELLED N APPLIED KG/HA	DRY YIELD KG/HA	TOTAL N KG/HA	LABELLED N %	LABELLED N KG/HA	UNLABELLED N KG/HA
0	438	10.2	0.00	0.0	10.2
60	542	24.0	35.26	8.5	15.6
120	1650	80.7	-	-	-
180	2151	93.6	66.14	61.9	31.7

TABLE 67. YIELD AND N UPTAKE OF SPRING BARLEY, PLOUGHED PLOTS, MACMERRY SOIL FOURTH (BULKED) CUT, BUSH, 1981

LABELLED N APPLIED KG/HA	DRY YIELD KG/HA	TOTAL N KG/HA	LABELLED N %	LABELLED N KG/HA	UNLABELLED N KG/HA
0	1760	32.2	0.00	0.0	32.2
60	5014	95.8	9.92	9.5	86.3
120	5232	127.1	35.42	45.0	82.1
180	4980	125.0	39.06	48.8	76.2

TABLE 68. YIELD AND N UPTAKE OF SPRING BARLEY, PLOUGHED PLOTS, WINTON SOIL FOURTH (BULKED) CUT, BUSH, 1981

LABELLED N APPLIED KG/HA	DRY YIELD KG/HA	TOTAL N KG/HA	LABELLED N %	LABELLED N KG/HA	UNLABELLED N KG/HA
0	1452	23.2	0.00	0.0	23.2
60	3059	73.0	47.72	34.8	38.1
120	4949	157.6	66.78	105.3	52.4
180	4890	156.5	66.11	103.5	53.0

TABLE 69. YIELD AND N UPTAKE OF SPRING BARLEY, DIRECT-DRILLED PLOTS, MACMERRY SOIL FOURTH (BULKED) CUT, BUSH, 1981

LABELLED N APPLIED KG/HA	DRY YIELD KG/HA	TOTAL N KG/HA	LABELLED N %	LABELLED N KG/HA	UNLABELLED N KG/HA
0	1378	25.2	0.00	0.0	25.2
60	2808	50.8	44.25	22.5	28.3
120	4191	97.0	42.10	40.8	56.2
180	4173	131.4	63.73	83.8	47.7

TABLE 70. YIELD AND N UPTAKE OF SPRING BARLEY, DIRECT-DRILLED PLOTS, WINTON SOIL FOURTH (BULKED) CUT, BUSH, 1981

LABELLED N APPLIED KG/HA	DRY YIELD KG/HA	TOTAL N KG/HA	LABELLED N %	LABELLED N KG/HA	UNLABELLED N KG/HA
0	1038	19.3	0.00	0.0	19.3
60	2943	87.0	33.38	29.0	57.9
120	5350	155.4	47.89	74.4	81.0
180	5858	154.6	57.05	88.2	66.4

TABLE 71. YIELD AND N UPTAKE OF SPRING BARLEY, DIRECT-DRILLED PLOTS, MACMERRY SOIL, FINAL HARVEST (GRAIN) BUSH, 1981

LABELLED N APPLIED KG/HA	DRY YIELD KG/HA	TOTAL N KG/HA	LABELLED N %	LABELLED N KG/HA	UNLABELLED N KG/HA
0	2348	32.8	0.00	0.0	32.8
60	3963	60.2	23.66	14.5	45.8
120	5250	86.2	38.10	33.1	53.1
180	5868	117.7	54.14	68.9	48.8

TABLE 72. YIELD AND N UPTAKE OF SPRING BARLEY, DIRECT-DRILLED PLOTS, WINTON SOIL, FINAL HARVEST (GRAIN) BUSH, 1981

LABELLED N APPLIED KG/HA	DRY YIELD KG/HA	TOTAL N KG/HA	LABELLED N %	LABELLED N KG/HA	UNLABELLED N KG/HA
0	1613	25.1	0.00	0.0	25.1
60	3327	51.1	18.63	9.9	41.2
120	4932	83.3	42.76	34.6	48.7
180	6033	125.3	57.38	72.1	53.1

TABLE 73. YIELD AND N UPTAKE OF SPRING BARLEY, PLOUGHED PLOTS, MACMERRY SOIL, FINAL HARVEST (GRAIN) BUSH, 1981

LABELLED N APPLIED KG/HA	DRY YIELD KG/HA	TOTAL N KG/HA	LABELLED N %	LABELLED N KG/HA	UNLABELLED N KG/HA
0	2384	29.7	0.00	0.0	29.7
60	4334	59.6	15.74	9.3	50.3
120	5087	88.0	32.29	27.7	60.2
180	7881	162.5	52.83	86.2	76.3

TABLE 74. YIELD AND N UPTAKE OF SPRING BARLEY, PLOUGHED PLOTS, WINTON SOIL, FINAL HARVEST (GRAIN) BUSH, 1981

LABELLED N APPLIED KG/HA	DRY YIELD KG/HA	TOTAL N KG/HA	LABELLED N %	LABELLED N KG/HA	UNLABELLED N KG/HA
0	1862	24.0	0.00	0.0	24.0
60	3194	45.9	42.45	19.2	26.7
120	5798	93.9	45.40	42.9	51.1
180	6215	130.4	53.97	71.3	59.1

TABLE 75. YIELD AND N UPTAKE OF SPRING BARLEY, DIRECT DRILLED PLOTS, MACMERRY SOIL, FINAL HARVEST (STRAW) BUSH, 1981

LABELLED N APPLIED KG/HA	DRY YIELD KG/HA	TOTAL N KG/HA	LABELLED N %	LABELLED N KG/HA	UNLABELLED N KG/HA
0	1875	9.5	0.00	0.0	9.5
60	4068	24.3	26.92	6.5	17.8
120	5765	37.1	39.07	14.3	22.8
180	6044	49.7	59.46	29.9	19.8

TABLE 76. YIELD AND N UPTAKE OF SPRING BARLEY, DIRECT DRILLED PLOTS, WINTON SOIL, FINAL HARVEST (STRAW) BUSH, 1981

LABELLED N APPLIED KG/HA	DRY YIELD KG/HA	TOTAL N KG/HA	LABELLED N %	LABELLED N KG/HA	UNLABELLED N KG/HA
0	1367	7.8	0.00	0.0	7.8
60	3335	22.2	19.03	4.7	17.6
120	5174	39.1	45.91	18.0	21.2
180	8159	77.8	59.69	46.4	31.5

TABLE 77. YIELD AND N UPTAKE OF SPRING BARLEY, PLOUGHED PLOTS, MACMERRY SOIL, FINAL HARVEST (STRAW) BUSH, 1981

LABELLED N APPLIED KG/HA	DRY YIELD KG/HA	TOTAL N KG/HA	LABELLED N %	LABELLED N KG/HA	UNLABELLED N KG/HA
0	2100	8.7	0.00	0.0	8.7
60	4170	15.9	15.62	2.7	13.2
120	5108	28.7	32.84	9.7	18.9
180	8553	66.5	52.62	35.2	31.3

TABLE 78. YIELD AND N UPTAKE OF SPRING BARLEY, PLOUGHED PLOTS, WINTON SOIL, FINAL HARVEST (STRAW) BUSH, 1981

LABELLED N APPLIED KG/HA	DRY YIELD KG/HA	TOTAL N KG/HA	LABELLED N %	LABELLED N KG/HA	UNLABELLED N KG/HA
0	1806	9.3	0.00	0.0	9.3
60	3041	16.6	43.56	7.2	9.4
120	5450	31.1	45.10	14.0	17.1
180	6495	59.9	53.86	33.3	26.5

TABLE 79. YIELD AND N UPTAKE OF SPRING BARLEY, PLOUGHED PLOTS, FIRST CUT BUSH, 1982

LABELLED N APPLIED KG/HA	DRY YIELD KG/HA	TOTAL N KG/HA	LABELLED N %	LABELLED N KG/HA	UNLABELLED N KG/HA
0	119	5.1	0.00	0.0	5.1
120	164	8.7	47.24	4.1	4.6

TABLE 80. YIELD AND N UPTAKE OF SPRING BARLEY, DIRECT-DRILLED PLOTS, FIRST CUT BUSH, 1982

LABELLED N APPLIED KG/HA	DRY YIELD KG/HA	TOTAL N KG/HA	LABELLED N %	LABELLED N KG/HA	UNLABELLED N KG/HA
0	68	2.3	0.00	0.0	2.3
120	132	6.9	63.97	4.5	2.5

TABLE 81. YIELD AND N UPTAKE OF SPRING BARLEY, SECOND AND THIRD (BULKED) CUTS, BUSH, 1982

CUT	TILLAGE	LABELLED N APPLIED KG/HA	DRY YIELD KG/HA	TOTAL N KG/HA	LABELLED N %	LABELLED N KG/HA	UNLABELLED N KG/HA
2	SP	0	275	10.3	0.00	0.0	10.3
2	DD	0	464	17.6	0.00	0.0	17.6
2	SP	120	536	28.9	50.23	14.5	14.4
2	DD	120	530	28.7	68.37	19.6	9.1
3	SP	0	795	14.9	0.00	0.0	14.9
3	DD	0	611	15.1	0.00	0.0	15.1
3	SP	120	2436	66.3	69.09	45.8	20.5
3	DD	120	2501	80.9	51.01	41.3	39.6

SP=PLOUGHED DD=DIRECT DRILLED

TABLE 82. YIELD AND N UPTAKE OF SPRING BARLEY, PLOUGHED PLOTS, FINAL HARVEST (GRAIN) BUSH, 1982

LABELLED N APPLIED KG/HA	DRY YIELD KG/HA	TOTAL N KG/HA	LABELLED N %	LABELLED N KG/HA	UNLABELLED N KG/HA
0	1421	16.9	0.00	0.0	16.9
120	3947	66.6	57.61	38.7	27.9

TABLE 83. YIELD AND N UPTAKE OF SPRING BARLEY, DIRECT-DRILLED PLOTS, FINAL HARVEST (GRAIN) BUSH, 1982

LABELLED N APPLIED KG/HA	DRY YIELD KG/HA	TOTAL N KG/HA	LABELLED N %	LABELLED N KG/HA	UNLABELLED N KG/HA
0	1140	16.6	0.00	0.0	16.6
120	3257	54.6	52.15	28.0	26.6

TABLE 84. YIELD AND N UPTAKE OF SPRING BARLEY, PLOUGHED PLOTS, FINAL HARVEST (STRAW), 1982

LABELLED N APPLIED KG/HA	DRY YIELD KG/HA	TOTAL N KG/HA	LABELLED N %	LABELLED N KG/HA	UNLABELLED N KG/HA
0	1232	6.0	0.00	0.0	6.0
120	4530	35.7	59.53	21.5	14.3

TABLE 85. YIELD AND N UPTAKE OF SPRING BARLEY, DIRECT-DRILLED PLOTS, FINAL HARVEST (STRAW), 1982

LABELLED N APPLIED KG/HA	DRY YIELD KG/HA	TOTAL N KG/HA	LABELLED N %	LABELLED N KG/HA	UNLABELLED N KG/HA
0	1057	7.5	0.00	0.0	7.5
120	3741	32.8	42.36	14.5	18.3

TABLE 86. YIELD AND N UPTAKE OF WINTER BARLEY, 2 TILLAGE TREATMENTS, FIRST CUT, GLENCOURSE, 1982

TILLAGE	LABELLED N APPLIED KG/HA	DRY YIELD KG/HA	TOTAL N KG/HA	LABELLED N %	LABELLED N KG/HA	UNLABELLED N KG/HA
SP	120	541	28.6	51.19	14.4	14.1
DD	120	516	25.8	48.15	12.4	13.5

TABLE 87. YIELD AND N UPTAKE OF WINTER BARLEY, 2 TILLAGE TREATMENTS, SECOND CUT, GLENCOURSE, 1982

TILLAGE	LABELLED N APPLIED KG/HA	DRY YIELD KG/HA	TOTAL N KG/HA	LABELLED N %	LABELLED N KG/HA	UNLABELLED N KG/HA
SP	120	3183	93.8	69.00	65.6	28.2
DD	120	2317	70.4	70.13	49.4	20.9

TABLE 88. YIELD AND N UPTAKE OF WINTER BARLEY, 2 TILLAGE TREATMENTS, THIRD CUT, GLENCOURSE, 1982

TILLAGE	LABELLED N APPLIED KG/HA	DRY YIELD KG/HA	TOTAL N KG/HA	LABELLED N %	LABELLED N KG/HA	UNLABELLED N KG/HA
SP	120	5620	116.6	64.77	76.9	39.7
DD	120	4988	104.6	65.98	67.0	37.6

TABLE 89. YIELD AND N UPTAKE OF WINTER BARLEY, 2 TILLAGE TREATMENTS, FINAL HARVEST (GRAIN), GLENCOURSE, 1982

TILLAGE	LABELLED N APPLIED KG/HA	DRY YIELD KG/HA	TOTAL N KG/HA	LABELLED N %	LABELLED N KG/HA	UNLABELLED N KG/HA
SP	120	6210	104.7	52.75	54.6	50.1
DD	120	5615	91.6	50.80	47.8	43.8

TABLE 90. YIELD AND N UPTAKE OF WINTER BARLEY, 2 TILLAGE TREATMENTS FINAL HARVEST (STRAW), GLENCOURSE, 1982

TILLAGE	LABELLED N APPLIED KG/HA	DRY YIELD KG/HA	TOTAL N KG/HA	LABELLED N %	LABELLED N KG/HA	UNLABELLED N KG/HA
SP	120	6174	32.8	56.26	18.4	14.4
DD	120	6653	35.1	52.29	18.3	16.8

DISCUSSION AND CONCLUSIONS

At Bush there was a general positive response of unlabelled N uptake to increasing levels of applied labelled N throughout the season (Tables 8, 10, 12 and 59-77). The response was observed in both grain and straw at final harvest, e.g. Figures 10, 11, 13, 14 and i-iv (appendix) for 1978 and 1979. Also in 1981 (Tables 71 - 78) and 1982 (Tables 84 and 85). Tillage effects on this response varied with the season, in 1978 and 1980 the response was greater on the ploughed plots, which also yielded better than the direct-drilled. In 1979 yields and response of unlabelled N uptake were both greater on the direct-drilled plots. In 1981 and 1982 uptake of unlabelled N was greater on the direct-drilled plots but dry-matter yields were greater on ploughed. There was an apparent interaction between the effects of tillage on yield and the seasonal distribution of rainfall. Total rainfall over the period March-May 1979 was much higher than for 1978, 1980, 1981 and 1982. This was followed by lower rainfall for June and July in 1979 than for the other years (Figures 7a and 7b).

Tillage effects described in the literature include an increase in the N concentration in young crops (Baeumer and Bakermans, 1973). At Bush, for the earliest sampling dates, the direct-drilled crops always had a higher proportion of labelled N than those on the ploughed plots. The effect was generally reversed later in the season. Another published effect of reduced cultivation is higher N mineralization (Dowdell and Cannell, 1975; Powlson, 1980). This is confirmed by the results of an incubation experiment presented in Table 56. As mentioned above, levels of unlabelled N uptake do not always show this effect, as other factors influencing plant uptake are involved.

The general response of unlabelled N uptake to labelled N application seen at Bush was seen at none of the other sites, although it was observed occasionally (see Tables 13-47). When a response to applied, labelled N was seen in unlabelled N uptake for these other sites, it was often only for the straw and not the grain e.g. at Aberlady (Figures 20, 21, 33 and 34) and Balerno (Figures 29, 30, 37 and 38). When this happened in spring barley, samples taken earlier in the season also showed a response e.g. at Balerno (Figure 27 and Table 44).

At Bush determination of available labelled and unlabelled N in soil (Tables 51 and 52) showed most of the labelled N to be in the top 20 cm of the profile. Estimated crop recovery of this labelled N was considerably higher than recovery of unlabelled available N which was more evenly distributed down the profile. In addition, recovery of unlabelled N increased with increasing rate of labelled N application (Table 53). This indicates that the response of unlabelled N uptake to labelled N application might be due to greater exploration of the profile by the fertilized crop than by the unfertilized crop. There was no marked increase in recovery of labelled N with increasing application rate (Tables 53 and 54) presumably because the available labelled N was concentrated in the upper layers of the soil profile.

An alternative explanation for the response of unlabelled N uptake to labelled N applications is that long term differential rates of N application at Bush had given rise to higher levels of readily mineralizable N in the fertilized plots than in the unfertilized ones. This explanation was not supported by the results of the potential mineralization determination presented in Table

56. Also, this explanation would not apply to the other sites. The possible effects of mineralization-immobilization turnover (see review chapter section 2.4) cannot be determined without measuring the entry of applied labelled N into the soil biomass. However, since nitrate fertilizers were used, the main effect of turnover was probably the dilution of labelled N by mineralization outflow, which would contribute to the general decline in the proportion of labelled N in the crop as the season progressed.

Comparison of the Bush site with those at Aberlady and Balerno show that the inherent N fertility (as measured by nitrogen uptake of unfertilized crops) was higher at Aberlady and Balerno. Although organic matter levels at Aberlady were lower than at Bush (Table 2). Also that fertilizer recoveries were greater than at Bush, where root growth is often restricted (Holmes, 1976 ; Pidgeon, 1980). Thus any restrictions to crop N uptake at these sites must be less severe than at Bush. It follows that there will be less response to any treatment overcoming such restrictions e.g. the response of unlabelled N uptake to applications of labelled N. In both years the response of unlabelled N uptake to labelled N application was more apparent at Balerno than at Aberlady. The soil is deeper at Aberlady than at Balerno and deep rooting would be encouraged by the drier conditions (Table 1). Presumably, exploitation of any unlabelled N in the profile at Aberlady will be more complete, regardless of applied N, than at Balerno.

At Aberlady and Balerno in 1981 a net loss of crop N occured between final harvest and the previous sampling occasion. This was the net result of a loss of labelled N, while there was a small increase in unlabelled N. In 1982 there were gains of N between harvest and the previous cut. Uptake of labelled N decreased but this loss was more than compensated for by the increase in unlabelled N uptake, which was particularly great at Balerno. For each year, the maximum response of labelled N uptake to labelled N application was similar for the sites at Aberlady and Balerno. About 20 kgN/ha for every 30 kg/ha labelled N applied in 1981 and 16 in 1982. Values for the proportion of labelled N in the crop at harvest at Balerno and for the winter barley at Aberlady were higher in 1982 than in 1981. This, together with the late gains of N in 1982 mentioned above, suggest delayed labelled N uptake in 1982. The spring barley at Aberlady had a higher proportion of labelled N in 1981 than 1982, but N uptake was probably delayed by the effects of mildew in 1981. Comparison of Figures 22 and 31 shows that unlabelled N uptake by spring barley at Aberlady was less in 1981 than in 1982.

In 1982 soil water measurements were made at Balerno and Aberlady (D. B. Naysmith, personal communication) these indicated moisture stress for the spring barley at Aberlady, particularly at the highest rate of applied N. Unfortunately the measurements started on 23/5/82 at Aberlady, too late to confirm that lack of moisture caused the early delay in fertilizer uptake indicated by the samples taken on 7/5/82 (Table 36). However the moisture stress at the higher rates of applied N that had developed by early June would explain the poor response of labelled N uptake to the highest rate of applied N observed for the second cut (Table 37). Later stress appears not to have had much effect on N uptake, a rainfall event in mid-July probably allowed the late increase in unlabelled N uptake described above. Water uptake measurements allow indentification of the parts of the profile exploited by crop roots. At Aberlady the roots were already using the soil down to 100cm on

23/5/82. Water was extracted from the 30-100cm zone throughout the season, the rate of extraction being higher at the higher rates of applied N. The depth of extraction became slightly greater (110cm) at the higher rates of N. At Balerno measurements started on 14/5/82, rainfall was too high to allow reliable measurements of water extraction and the crop was only under moisture stress, at the highest rate of N, late in the season. However measurements indicated that the zone from which water was extracted was from 30-60 cm and that depletion of moisture increased with N rate. However much of the extra water removed by the crop receiving the highest rate of N came from the upper layer so there was no increase in extraction depth. Possible loss of applied N under the wet conditions at Balerno does not appear to have been severe as recovery of labelled N at harvest was greater than at Aberlady at the lowest rate of applied N and similar at other rates (although there was more labelled N in the straw at Balerno, Tables 40 and 41, 16 and 47). Comparison of the N accumulation throughout the season at Balerno in 1981 and 1982 (Figures 26 and 35) shows differences in the pattern of labelled N uptake at the higher rate of applied N. In 1982 labelled N uptake was higher in June than in 1981 and the difference between the 2 rates of N was greater in 1982. Figure 7b shows that June was much wetter in 1982 than 1981. The greater uptake of labelled N at the high rate of N in 1982 could be explained by the denser, more efficient root system indicated by the greater rate of water extraction, at the higher rate of N than at the lower, in 1982. This relatively late establishment of rooting differences would explain the late response to applied N observed in unlabelled N uptake. Presumably in 1981 the greater need for water promoted earlier and more complete exploitation of the labelled N and earlier establishment of rooting differences due to N applications. Also an earlier response of unlabelled N uptake to labelled N applications.

At Aberlady in 1981, the presence of twice as much available N before fertilizer application in the soil in which spring barley had recently been sown as under the autumn-sown crop (Table 55) highlights the likelihood of leaching of any available N not taken up by a crop. In the light of the estimate of rooting depth obtained using water extraction data, the samples taken from Aberlady for long term incubation were not taken to sufficient depth. However the estimate obtained for profile mineralization (135 kgN/ha) agreed well with A-values calculated from crop uptake data in 1981 (Table 58). The differences in 1982 could be due to differences in rooting depth or in fertilizer availability caused by the dry conditions.

CONCLUSIONS

At the Bush Estate site, the uptake of unlabelled N by the crop increased significantly with increasing rate of application of applied, labelled, fertilizer. This effect was seen in all seasons (see pp. 68-70, 118, 122 and 123) and was greatest in 1979 when, at harvest, unlabelled N uptake increased by about 10 kg/ha for every 60 kg/ha labelled N applied.

In contrast to the Bush site, there was no such consistent relationship between applied labelled N and the uptake of unlabelled N. Any response was weak or negative (see pp. 72, 74, 78 for the Aberlady site pp. 77 and 81 for the Balerno site).

Some workers (e.g. Jansson, 1958; Stewart et al., 1963 and Jenkinson et al., 1981) have postulated that increased uptake of unlabelled N, under these circumstances, is an artefact resulting from Mineralization-Immobilization Turnover (M.I.T.) i.e. that exchange between labelled inorganic N applied and unlabelled organic (unavailable) N results in a dilution of the ^{15}N in the available N pool (see p. 12). Another possibility is a "priming effect" i.e. a net increase in mineralization stimulated by addition of fertilizer N (see p. 13). It is concluded that these are unlikely explanations for the results presented here, for three reasons:

First, the phenomenon only occurs to any significant extent at one site (Bush). All known microbial processes which are likely to contribute to an isotopic dilution effect could be expected to occur at all the sites, and not just at one of the three.

Second, all labelled fertilizer used in this study was in the form of calcium nitrate. It is known that nitrate is far less likely to become immobilized into the biomass than is ammonium (see 2.4.3 p. 16).

Third, the unlabelled available N in the soil at Bush remained relatively constant across the different rates of applied N (Tables 51 and 52).

It is concluded that the results may be at least partly explained by the existence of impediments to root growth at the Bush site (Holmes, 1976; Pidgeon, 1980), particularly early in the growing season. This results in a very inefficient uptake of N derived from the soil (unlabelled N). In the later stages of growth, however uptake of the unlabelled N is much improved, thus the %NDFF in the plant falls with time (see Tables 4, 5 and 6 pp. 86 and 87). At the sites with better physical conditions, particularly the well-drained, stone-free soil at Aberlady, there is no impediment to satisfactory root exploration. Thus it is likely that unlabelled and labelled N are equally available. Increased relative uptake of unlabelled N late in the season was observed at all sites (see pp. 66, 75, 78 and 80), suggesting that in the cool climatic conditions typical of S.E. Scotland, late mineralization of N was a contributing factor. However, there was a much greater disparity between the time-course of labelled N uptake and that of unlabelled N at Bush (Fig. 8) than at the other two sites, (Figs 18, 22, 26, 31 and 35) reinforcing the conclusion that at Bush another factor, i.e. impeded rooting, was predominant.

APPENDIX

FIGURE 4 DETERMINATION OF AMMONIUM

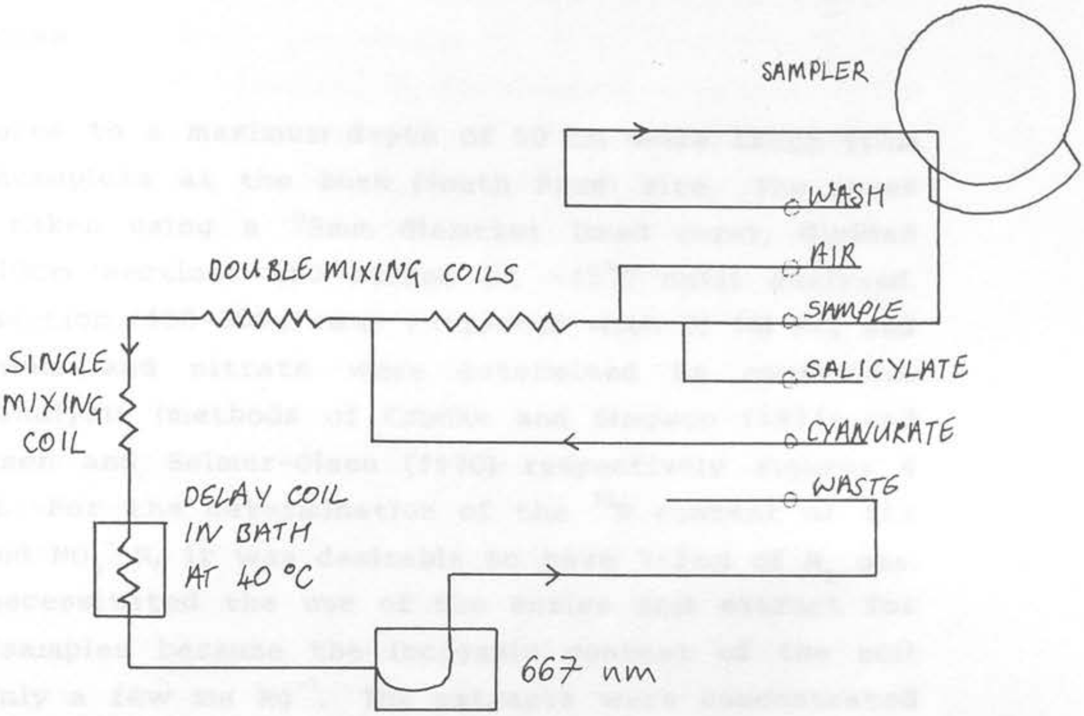
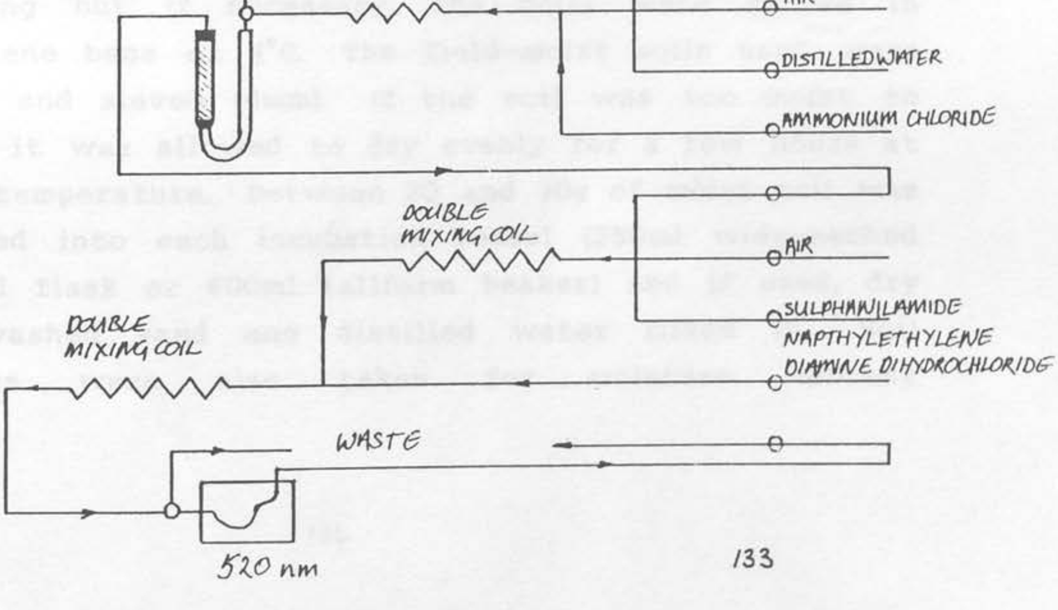


FIGURE 5 DETERMINATION OF NITRATE AND NITRITE



LABORATORY PROCEDURES

Soil Cores

Soil cores to a maximum depth of 50 cm were taken from the microplots at the Bush (South Road) site. The cores were taken using a 75mm diameter lined corer, divided into 10cm sections and stored at -15°C until analysed. Each section (400-500g) was extracted with 2l 1M KCl and ammomium and nitrate were determined by continuous flow analysis (methods of Crooke and Simpson (1971) and Henriksen and Selmer-Olsen (1970) respectively Figures 4 and 5). For the determination of the ^{15}N content of the NH_4^+ and NO_3^--N, it was desirable to have 1-2mg of N_2 gas. This necessitated the use of the entire soil extract for many samples because the inorganic content of the soil was only a few mg kg^{-1}. The extracts were concentrated to approx. 400ml and steam-distilled: the standard apparatus described by Bremner (1965 c) was modified by replacing the 100ml sample flask with a 1l round-bottomed flask heated by an electric heating mantle. Measurement of N isotope ratios was as described for crop samples.

Soil Incubation Experiments

Soil incubations were set up as soon as possible after sampling but if necessary, the soils were stored in polythene bags at 4°C. The field-moist soils used were mixed and sieved (4mm). If the soil was too moist to sieve, it was allowed to dry evenly for a few hours at room temperature. Between 20 and 30g of moist soil was weighed into each incubation vessel (250ml wide-necked conical flask or 600ml tallform beaker) and if used, dry acid-washed sand and distilled water mixed in. Soil samples were also taken for moisture content determination. Replicate samples from each treatment were extracted immediately while the remaining samples were covered with semipermeable film ("Clingfilm") and placed in cooled incubators (Gallenkamp) controls, with sand and water only, were included. Each filled vessel was weighed to permit measurement of any loss of moisture during incubation. The incubators had been calibrated using a mercury in glass thermometer.

Extraction was for a minimum of 30 minutes on an orbital shaker, after which the samples were allowed to settle before filtration of the supernatant (Whatman No 42). Determination of mineral N in the filtrate was by continuous flow analysis (see Figures 4 and 5) using the methods of Henriksen and Selmer-Olsen (1970) and Crooke and Simpson (1971) for nitrate and ammonium respectively. Results were expressed on a dry weight basis and converted to kg/ha using dry bulk density measurements for the sampling areas used and the depth to which samples were taken.

The extractant used was 1N KCL and the extractant volume to soil weight ratio varied, however this did not affect the recovery of nitrate. A preliminary experiment using 2N KCl and a ratio of 100ml to 20g, shaken for 1 hour, showed levels of ammonium in the soils used to be insignificant. Thus since nitrate was the dominant form soil mineral N only the nitrate data is presented.

Crop samples, Total N Determinatons and Measurement of N Isotope Ratios

A semi-micro Kjeldahl method with modification to include nitrate similar to that described by Bremner (1965 b) was used. Precautions were taken to avoid loss of N or cross-contamination between labelled materials. For example, rinsing of glassware with 2% hydrogen flouride solution, and analysis of samples in order of increasing ^{15}N enrichment. The amount of sample in a digest was sufficient for duplicate measurement of isotope ratios using the A.E.I. MS10 S mass spectrometer (5-10 mgN).

Duplicate samples were weighed into 50ml Kjeldahl flasks and 10ml salicylic acid-sulphuric acid mixture (50g in 2l) added to each. This was left overnight, then 0.5g sodium thiosulphate was introduced using a thistle funnel. After 4 hours, 2.5g potassium sulphate and 0.05g copper sulphate were added in tablet form and heating commenced. The digest was refluxed for 4 hours after clearing, then allowed to cool. The digest was then carefully transferred to a volumetric flask and made up to 50ml with distilled water when cool. An aliquot was taken for separation of ammonia by steam distillation, after addition of 40% sodium hydroxide. The distillate was collected in 10ml 2% boric acid-indicator solution (The indicator contained 0.099g bromo cresol green and 0.066g methyl red per 100ml ethanol and 40ml of this was used for every 2 litres of boric acid-indicator solution). Distillation was for 3 minutes from the first colour change in the indicator solution and continued for an additional 3 minutes after addition of absolute alcohol to the residue. The condenser was rinsed with distilled water before the sample was removed for N determination by titration against 0.02N hydrochloric or 0.01M sulphuric acid. The results of duplicate

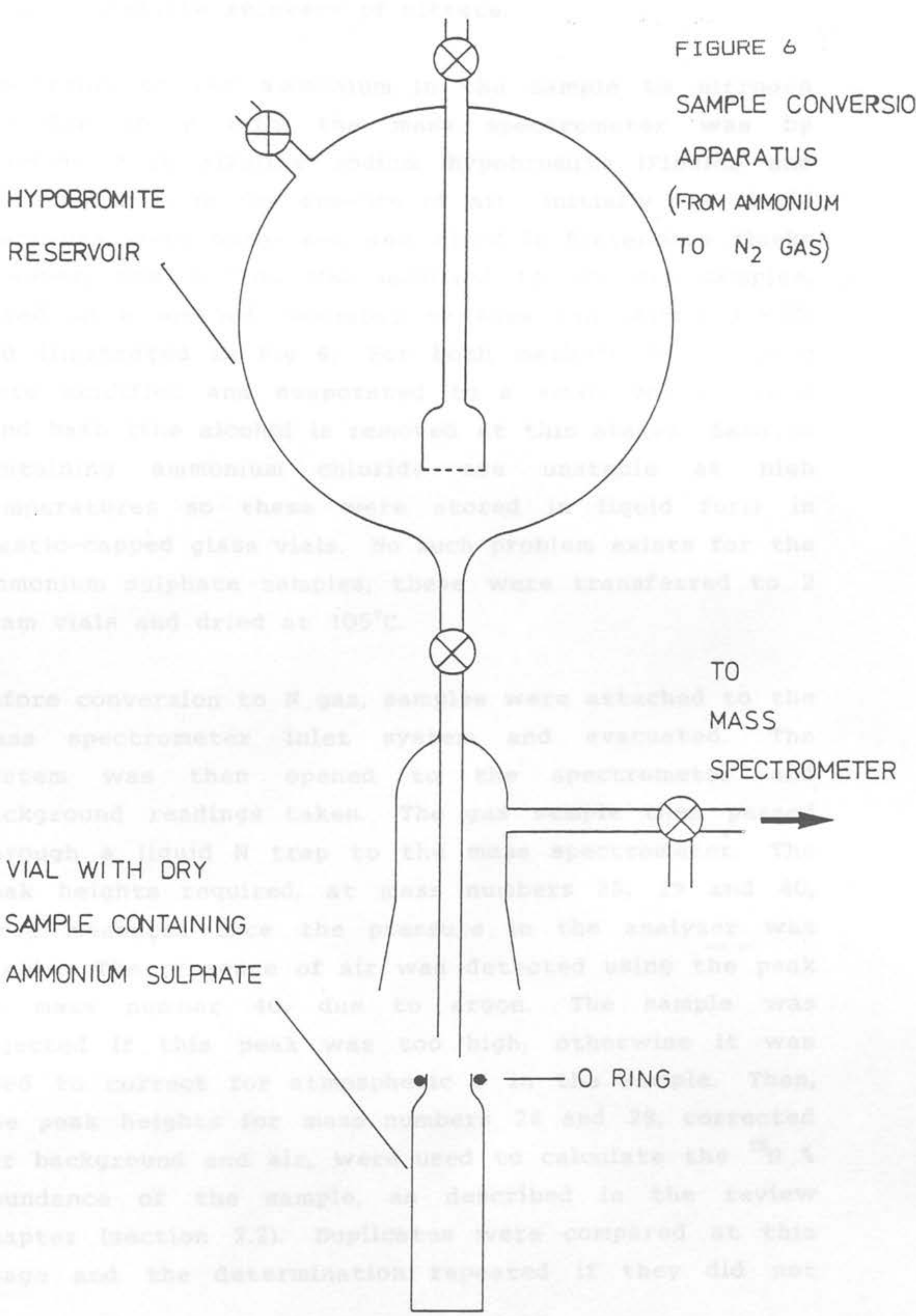


FIGURE 6

SAMPLE CONVERSION APPARATUS (FROM AMMONIUM TO N_2 GAS) determinations were compared and the determination repeated if they did not agree. This method was found to give complete recovery of nitrate.

Conversion of the ammonium in the sample to nitrogen gas for entry into the mass spectrometer was by reaction with alkaline sodium hypobromite (Fiedler and Proksch, 1975) in the absence of air. Initially the liquid reactants were outgassed and mixed in Rittenberg flasks however, the method was modified to use dry samples, based on a method described by Ross and Martin (1970) and illustrated in Fig 6. For both methods the samples were acidified and evaporated to a small volume on a sand bath (the alcohol is removed at this stage). Samples containing ammonium chloride are unstable at high temperatures so these were stored in liquid form in plastic-capped glass vials. No such problem exists for the ammonium sulphate samples, these were transferred to 2 dram vials and dried at 105°C.

Before conversion to N gas, samples were attached to the mass spectrometer inlet system and evacuated. The system was then opened to the spectrometer and background readings taken. The gas sample then passed through a liquid N trap to the mass spectrometer. The peak heights required, at mass numbers 28, 29 and 40, were measured once the pressure in the analyzer was stable. The presence of air was detected using the peak at mass number 40, due to argon. The sample was rejected if this peak was too high, otherwise it was used to correct for atmospheric N in the sample. Then, the peak heights for mass numbers 28 and 29, corrected for background and air, were used to calculate the ^{15}N % abundance of the sample, as described in the review chapter (section 2.2). Duplicates were compared at this stage and the determination repeated if they did not agree. The abundance of samples was corrected using the value obtained for a standard of similar abundance analysed on the same day.

The proportion of labelled N in the crop and uptake of labelled and unlabelled N were calculated with reference to the ^{15}N abundance of the fertilizer applied and the mean natural abundance as measured at the site. Where:

AO = Mean natural abundance
AS = Mean abundance of sample
AF = Abundance of fertilizer
(all expressed as at% ^{15}N)

NPFF = [AS - AO]/[AF - AO]
Labelled N % = NPFF X 100
Labelled N uptake = Nitrogen uptake x NPFF
Unlabelled N uptake
 = Nitrogen uptake - Labelled N uptake
(uptake in kg/ha)

Fig. i Uptake of labelled and unlabelled N by spring barley vs. labelled N fertilizer applied, final harvest (straw) ploughed plots, Bush, 1978

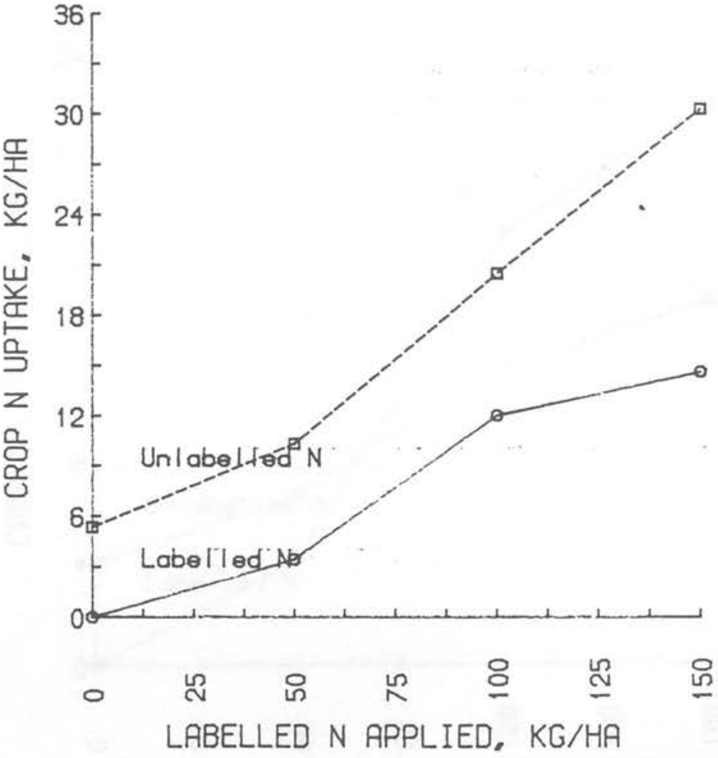


Fig. ii Uptake of labelled and unlabelled N by spring barley vs. labelled N fertilizer applied, final harvest (straw) direct-drilled plots, Bush, 1978

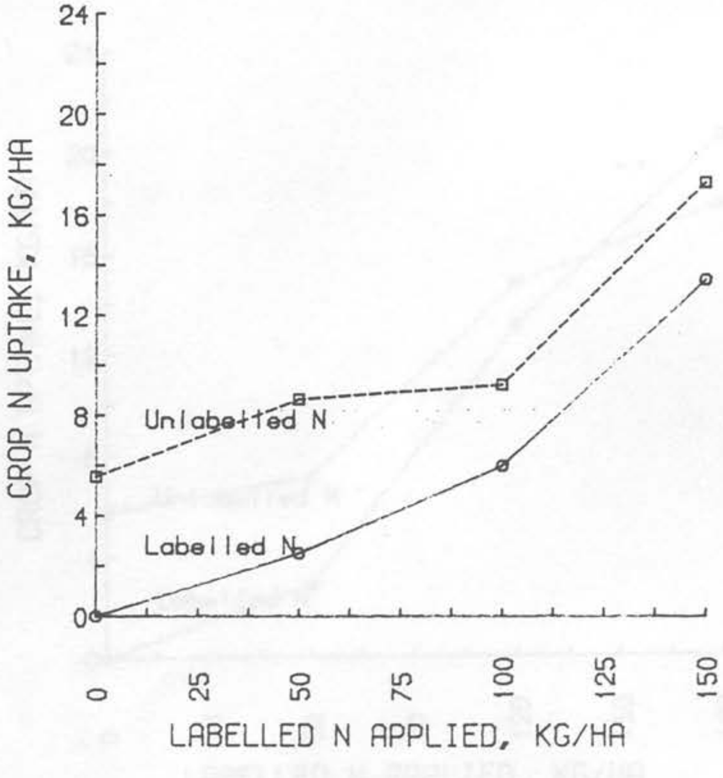


Fig. iii Uptake of labelled and unlabelled N by spring barley vs. labelled N fertilizer applied, final harvest (straw) ploughed plots, Bush, 1979

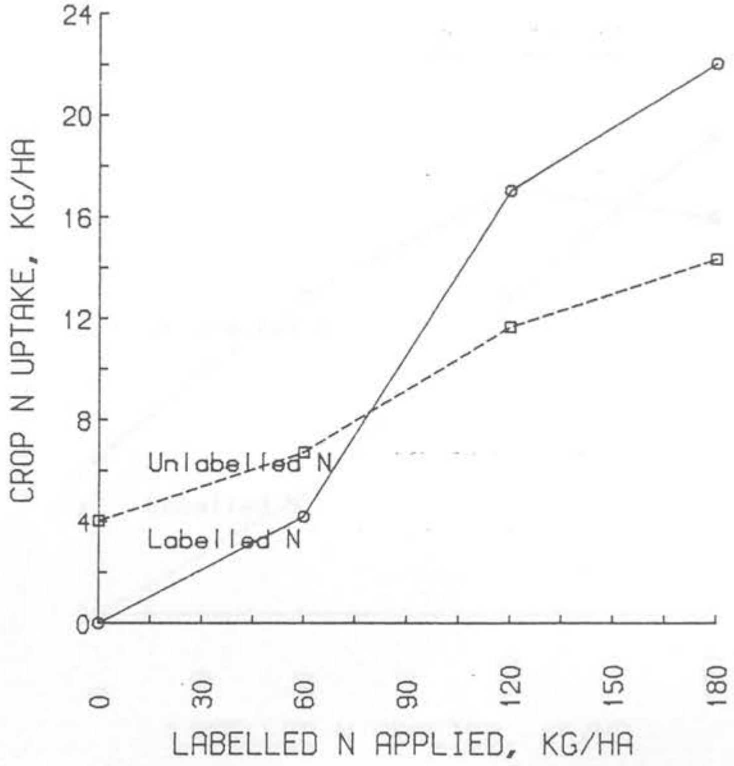


Fig. iv Uptake of labelled and unlabelled N by spring barley vs. labelled N fertilizer applied, final harvest (straw) direct-drilled plots, Bush, 1979

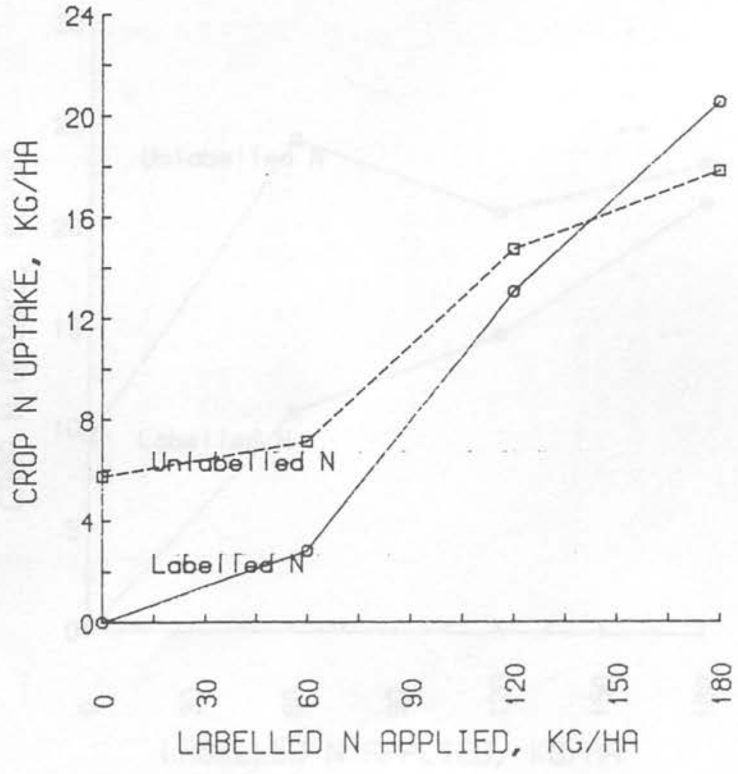


Fig. v Uptake of labelled and unlabelled N by spring barley vs. labelled N fertilizer applied, final harvest (straw) ploughed plots, Bush, 1980

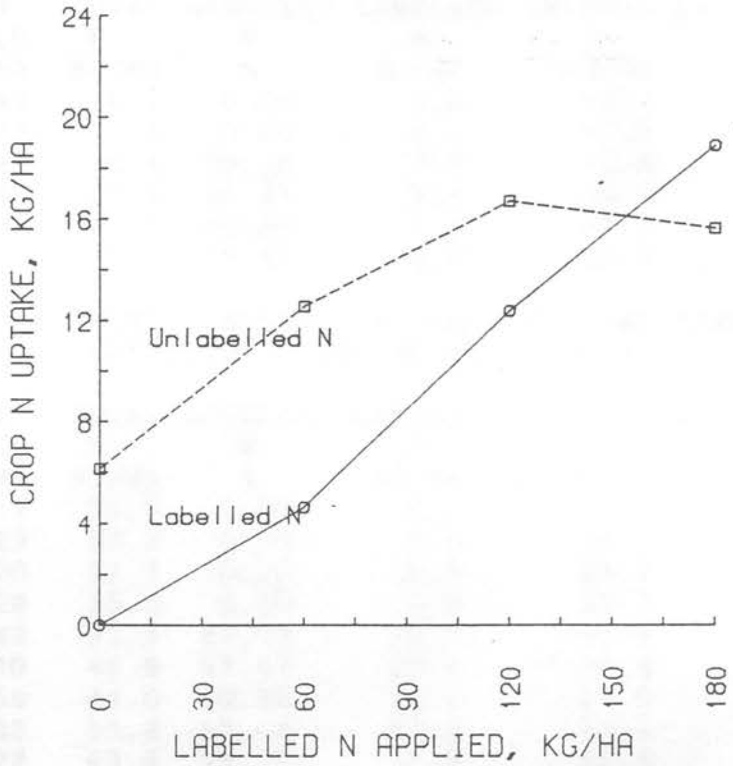


Fig. vi Uptake of labelled and unlabelled N by spring barley vs. labelled N fertilizer applied, final harvest (straw) direct-drilled plots, Bush, 1980

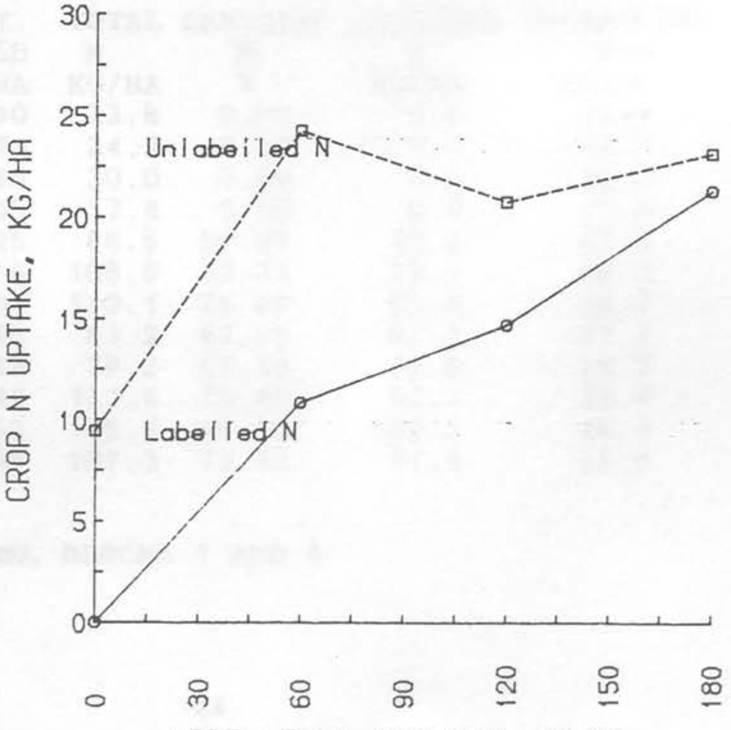


TABLE iv. ABERLADY WINTER BARLEY FIRST CUT 1982 YIELD AND N UPTAKE FOR INDIVIDUAL PLOTS BLOCKS 1 AND 4

LABELLED N APPLIED KG/HA	DRY YIELD KG/HA	TOTAL N KG/HA	LABELLED N %	LABELLED N KG/HA	UNLABELLED N KG/HA
0	443	16.7	0.00	0.0	16.7
0	333	12.5	0.00	0.0	12.5
*40	443	20.4	38.38	7.8	12.6
*40	562	25.5	36.77	9.4	16.1
*50	431	20.7	44.24	9.1	11.5
*50	602	27.5	38.45	10.6	16.9

TABLE v. ABERLADY WINTER BARLEY SECOND CUT, 1982 YIELD AND N UPTAKE FOR INDIVIDUAL PLOTS BLOCKS 1 TO 4

LABELLED N APPLIED KG/HA	DRY YIELD KG/HA	TOTAL N KG/HA	LABELLED N %	LABELLED N KG/HA	UNLABELLED N KG/HA
0	811	25.0	0.00	0.0	25.0
0	823	27.2	0.00	0.0	27.2
0	800	21.7	0.00	0.0	21.7
0	728	25.3	0.00	0.0	25.3
*120	982	53.9	67.79	36.5	17.4
120	910	46.9	47.87	22.4	24.4
120	966	44.0	50.45	22.2	21.8
*120	1188	59.4	63.64	37.8	21.6
*150	1172	63.4	59.78	37.9	25.5
150	1069	55.7	48.35	26.9	28.8
150	926	44.3	50.17	22.2	22.1
*150	665	41.7	65.01	27.1	14.6

TABLE vi. ABERLADY WINTER BARLEY THIRD CUT, 1982 YIELD AND N UPTAKE FOR INDIVIDUAL PLOTS BLOCKS 1 TO 4

LABELLED N APPLIED KG/HA	DRY YIELD KG/HA	TOTAL N KG/HA	LABELLED N %	LABELLED N KG/HA	UNLABELLED N KG/HA
0	1290	23.8	0.00	0.0	23.8
0	1370	24.7	0.00	0.0	24.7
0	1595	30.0	0.00	0.0	30.0
0	1045	17.8	0.00	0.0	17.8
*120	3325	86.5	50.42	43.6	42.9
120	3056	108.6	73.33	79.7	29.0
120	3008	110.1	76.08	83.8	26.3
*120	2965	83.2	62.59	52.1	31.1
*150	2518	78.2	63.33	49.5	28.7
150	3242	121.6	75.80	92.2	29.4
150	4263	148.6	68.78	102.2	46.4
*150	3535	107.3	72.13	77.4	29.9

*SPLIT APLICATIONS, BLOCKS 1 AND 4

TABLE vii. ABERLADY WINTER BARLEY FOURTH CUT 1982 YIELD AND N UPTAKE FOR INDIVIDUAL PLOTS BLOCKS 1 TO 4

LABELLED N APPLIED KG/HA	DRY YIELD KG/HA	TOTAL N KG/HA	LABELLED N %	LABELLED N KG/HA	UNLABELLED N KG/HA
0	3056	32.5	0.00	0.0	32.5
0	3325	33.6	0.00	0.0	33.6
0	3460	37.0	0.00	0.0	37.0
0	3673	39.5	0.00	0.0	39.5
*120	7672	103.9	44.17	45.9	58.0
120	7735	138.8	69.60	96.6	42.2
120	7727	124.4	65.47	81.4	43.0
*120	8875	135.8	64.35	87.4	48.4
*150	8345	146.9	66.54	97.7	49.1
150	7046	142.7	79.94	114.1	28.6
150	7679	145.1	61.89	89.8	55.3
*150	6326	108.5	71.84	77.9	30.5

TABLE viii. ABERLADY WINTER BARLEY GRAIN 1982 YIELD AND N UPTAKE FOR INDIVIDUAL PLOTS BLOCKS 1 TO 4

LABELLED N APPLIED KG/HA	DRY YIELD KG/HA	TOTAL N KG/HA	LABELLED N %	LABELLED N KG/HA	UNLABELLED N KG/HA
0	4034	37.5	0.00	0.0	37.5
0	4046	35.8	0.00	0.0	35.8
0	2890	27.2	0.00	0.0	27.2
0	2058	22.5	0.00	0.0	22.5
*120	8265	98.8	51.80	51.2	47.6
120	3436	44.0	56.44	24.8	19.2
120	2929	42.8	57.22	24.5	18.3
*120	4117	55.4	49.47	27.4	28.0
*150	7996	127.9	59.94	76.7	51.3
150	2763	40.6	61.55	25.0	15.6
150	5930	82.7	63.05	52.2	30.6
*150	3705	60.9	58.97	35.9	25.0

*SPLIT APPLICATIONS, BLOCKS 1 AND 4

TABLE ix. ABERLADY WINTER BARLEY STRAW 1982 YIELD AND N UPTAKE FOR INDIVIDUAL PLOTS BLOCKS 1 TO 4

LABELLED N APPLIED KG/HA	DRY YIELD KG/HA	TOTAL N KG/HA	LABELLED N %	LABELLED N KG/HA	UNLABELLED N KG/HA
0	3400	11.3	0.00	0.0	11.3
0	2981	8.6	0.00	0.0	8.6
0	3499	15.6	0.00	0.0	15.6
0	1251	5.2	0.00	0.0	5.2
*120	8986	78.0	51.18	39.9	38.1
120	3499	34.3	54.31	18.6	15.7
120	3016	40.1	56.83	22.8	17.3
*120	4671	53.0	47.43	25.1	27.9
*150	9287	108.2	62.72	67.9	40.3
150	3293	41.3	63.05	26.1	15.3
150	6413	77.6	62.64	48.6	29.0
*150	4275	58.4	59.35	34.6	23.7

*SPLIT APPLICATIONS, BLOCKS 1 AND 4

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The uptake of soil and fertilizer-nitrogen by barley growing under Scottish climatic conditions

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Key words Ammonium Barley Fertilizer Mineralization Nitrate Nitrogen Nitrogen-15

Summary Field experiments were carried out using ^{15}N-labelled calcium nitrate, to investigate the relative uptake by barley of fertilizer-N and soil-N. On imperfectly drained till soils uptake of soil-N increased with increasing rate of fertilizer, but remained constant on a brown sand, possibly due to more efficient root exploration in the latter soil. In four out of five seasons, late uptake of soil-derived N was a major feature, and uptake from ploughed soil as compared with uptake from direct-drilled soil was correlated with seasonal rainfall patterns. Significantly higher quantities of both fertilizer- and soil-derived N were taken up by winter barley than by spring barley, reflecting the longer growth period and higher dry matter yield from the former crop.

Introduction

Arable crops generally take up fertilizer N less efficiently than grass, resulting in substantial residues which may be either leached or lost by denitrification. Furthermore, fertilizer recommendations often diverge greatly from the optimum because of inability to predict the quantity released from soil organic matter. Optimisation of the use of N depends on better information on this soil contribution, but quantitative data applicable to Scottish environmental conditions are lacking. These conditions are characterised by lower ambient temperatures, lower moisture deficits and higher soil organic matter contents than occur in the more southerly parts of Britain. All these factors may be expected to have an effect on the extent or rate of mineralization.

The use of ^{15}N-labelled fertilizer, and the application of the principle of isotope dilution, make it possible to assess the relative contributions to the N uptake by plants derived from the soil N pool and from the fertilizer. Early studies on cereal crops in the field commonly used isotopic enrichments of 1 atom per cent excess ^{15}N or more (*e.g.* Bartholomew *et al.*[2]; IAEA[8]). However, Rennie and Fried[11] showed that lower enrichments of the order of 0.3 atom per cent excess ^{15}N could have been used without a significant increase in the error. Accordingly it was decided to use similarly labelled material in the present study, the intention being to investigate the effects of cultivations and soil texture on the relative contributions of soil-derived N and

Table 1. Soils on which experiments with ^{15}N-labelled fertilizers were located

Site	Soil series	Classification	Particle size analysis [(a)]				%C	%N	pH ($0.01\,M$ $CaCl_2$)
			Sand %	Silt[(b)] %	Clay %	Textural class			
Bush, Midlothian	Macmerry	Stagnogleyic brown earth[(c)]	49.5	35.2	15.2	L	3.1	0.22	6.6
	Winton	Cambic stagnogley[(c)]	47.5	35.3	17.4	L	2.2	0.16	6.5
Aberlady, East Lothian	Fraserburgh	Calcareous brown sand[(d)]	85	7	8	LS	1.4	0.14	7.8

[(a)] Topsoil

[(b)] 50–2 μm

[(c)] Till derived from carboniferous sediments

[(d)] Raised beach sediments

fertilizer-N to the total uptake by barley, which is the most important arable crop in Scotland both in terms of area planted and economic value.

Sites, materials and methods

The longest-running experiment (1978–82) was carried out at the Edinburgh School of Agriculture farm at Bush, Midlothian, on the ploughed and direct-drilled plots of a long-term continuous spring barley experiment[7]. This site included two soil series: Macmerry and Winton (Pidgeon[9]) classified (after Avery[1]) as a stagnogleyic brown earth and cambic stagnogley, respectively. In 1981–2 winter and spring barley were compared on a Fraserburgh series brown sand (raised beach) at Aberlady, East Lothian. Details of the soils are given in Table 1.

^{15}N-labelled calcium nitrate containing *ca* 0.35 atom per cent excess ^{15}N was prepared by mixing, in aqueous solution, calcium nitrate containing 5 atom per cent ^{15}N (BOC Prochem, London, UK) with a calculated quantity of the same salt but of normal isotopic composition, recrystallising, grinding to a powder and mixing again. Sub-samples were taken for isotopic analysis to confirm the actual enrichment achieved and its uniformity; results were satisfactory on all occasions.

A basal dressing of P and K fertilizer was applied to the seedbed in all experiments. Rates (kg ha^{-1} of P, K, respectively) were: 33, 62 annually at Bush; 11, 20 (winter barley) and 24, 46 (spring barley) at Aberlady. N fertilizer was applied separately in spring in all experiments. Labelled material was broadcast by hand over 2 m × 1.5 microplots located within larger main plots (at rates equivalent to 0–150 kg ha^{-1} at Bush in 1978 and at Aberlady, and 0–180 kg ha^{-1} at Bush in 1979 and 1980). The remainder of each main plot was similarly treated with unlabelled N fertilizer.

Plant samples (usually from 2 × 0.5 m lengths of row) were taken on 5 or 6 occasions during the growing season by cutting with shears within a few mm of ground level. Total N was determined in all samples by Kjeldahl digestion, and ^{15}N content was determined by mass spectrometry using the alkaline hypobromite method of Rittenberg[12]. Larger plant samples were taken from the main plots on each occasion to determine dry matter yield.

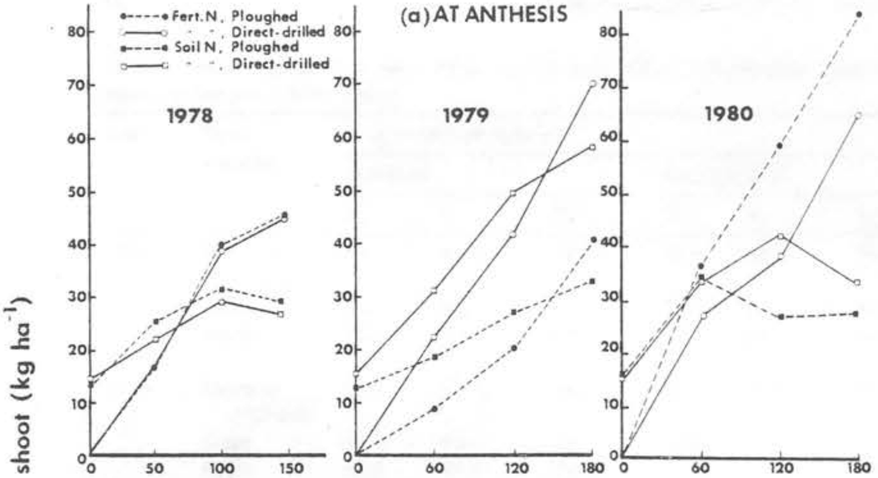

Fig. 1. Uptake of fertilizer and soil N in whole plant shoot as a function of fertilizer N applied: Bush Estate, 1978–1980.

Soil cores down to 40–50 cm depth were taken from a limited number of plots at Bush, using a 75 mm diameter lined corer. The cores were divided into 10 cm segments and stored at − 15°C until analysed. Each segment (400–500 g) was extracted with 2 l of 1 *M* KCl, and NH_4^+ and NO_3^- were determined by continuous flow analysis (methods of Crooke and Simpson[5] and Henriksen and Selmer-Olsen[6] respectively). For the determination of the ^{15}N content of the NH_4^+ and NO_3^--N, it was desirable to have 1–2 mg of N_2 gas. This necessitated the use of the entire soil extract for many samples because the inorganic N content of the soil was only a few μg g^{-1}. The extracts were concentrated to *ca* 400 ml and steam-distilled[4]: the standard apparatus described by Bremner[4] was modified by replacing the 100 ml sample flask with a 1 l round-bottomed flask heated with an electrical heating mantle.

Soil particle size distribution, total C, total N and pH were all determined by standard methods[3].

Table 2. Percentage of N in plant shoot derived from soil at 3 N-fertilizer rates, ploughed and direct-drilled plots, Bush Estate

Year	Plant material	% of N derived from soil						SED(a)
		ploughed			direct drilled			
		N_1	N_2	N_3	N_1	N_2	N_3	
1978	Shoot at Anthesis	59.5	44.3	38.7	56.5	42.8	36.3	1.7
	Grain	74.3	62.3	60.1	79.3	64.1	58.7	3.5
	Straw	76.1	63.4	67.8	77.6	60.7	56.0	5.0
1979	Shoot at Anthesis	67.5	57.7	44.5	60.0	54.2	45.5	
	Grain	65.0	43.3	40.2	78.3	53.6	45.9	2.2
	Straw	63.6	40.3	39.4	72.3	54.8	46.0	2.8
1980	Shoot at Anthesis	48.2	31.5	24.9	55.2	53.8	33.5	
	Grain	74.0	56.4	49.0	69.8	56.2	51.2	3.5
	Straw	72.0	58.1	46.4	69.2	57.7	55.6	5.0

(a) Standard error of the difference

Results and discussion

Fig. 1 shows the uptake of soil and fertilizer N on the ploughed and direct-drilled plots at the Bush Estate site. Increasing the application of fertilizer N increased the uptake of fertilizer N by the plant and always lowered the proportion of soil N in the plant (Table 2). The application of fertilizer N also had an effect on the absolute uptake of soil-derived N by the plant. A comparison between unfertilized plots and the mean of the fertilized plots always showed a greater uptake of soil N on the fertilized plots. Also, at harvest in 1978 and 1979 and at anthesis in 1979, there was evidence of a positive linear response of soil N uptake to increasing applications of fertilizer N.

The tillage also influenced the uptake of soil N and the relative contribution of soil-derived N to total N uptake by the plants. In 1978, at harvest, the ploughed plots showed more uptake of soil N than the direct-drilled. Uptake of fertilizer N was also greater on the ploughed plots and the proportion of soil N in the plant at harvest did not show any tillage effect. Throughout the 1979 growing season the uptake of soil N was greater on the direct drilled than on the ploughed plots (Fig. 2). The proportion of soil N in the plant at harvest was also greater on the direct drilled plots (Table 2). However, the proportion of soil N in the plant at anthesis showed the opposite effect. It was higher than at harvest on the ploughed plots but lower than at harvest, particularly at the lowest rate of applied N, on the

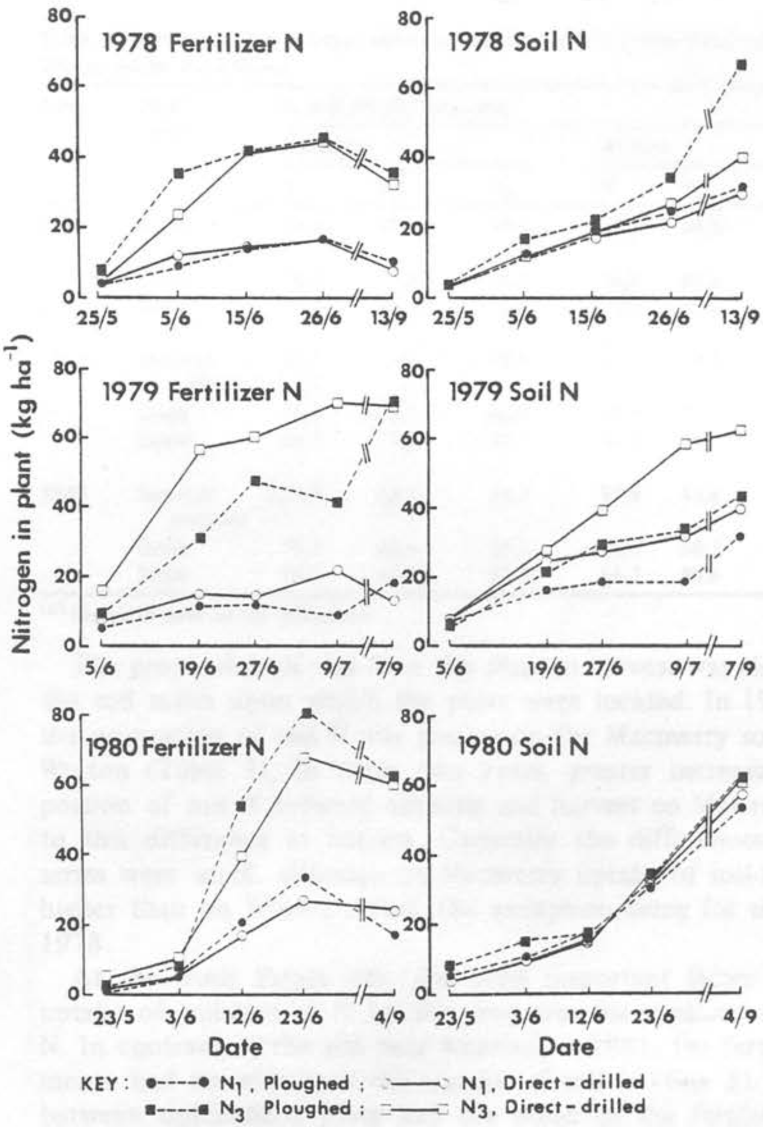

Fig. 2. Uptake of fertilizer and soil N during growth: Bush Estate, 1978–1980.

direct drilled plots. The proportion of soil N in the 1980 crop at anthesis was higher on the direct drilled than on the ploughed plots (Table 2), particularly at the higher rates of applied N. The proportion of soil N had risen by harvest but by much less on the direct drilled than on the ploughed plots.

In general, the proportion of soil N in the plant was higher at harvest than at anthesis, the exception being in 1979 on the ploughed plots (as discussed previously).

Table 3. Percentage of N in plant shoot derived from soil at 3 N-fertilizer rates, Macmerry and Winton Series, Bush Estate

Year	Plant material	% of N derived from soil						SED(a)
		Macmerry			Winton			
		N_1	N_2	N_3	N_1	N_2	N_3	
1978	Shoot at Anthesis	59.6	43.0	33.0	53.4	44.2	42.0	1.7
	Grain	78.9	69.8	64.5	74.6	61.6	54.3	3.7
	Straw	75.7	61.0	63.6	77.9	63.1	60.1	5.0
1979	Shoot at Anthesis	62.5	53.8	42.0	65.0	58.1	48.1	
	Grain	72.2	45.3	40.0	69.3	50.5	48.1	1.6
	Straw	58.5	37.5	43.5	67.7	56.2	54.7	2.9
1980	Shoot at Anthesis	55.6	39.7	28.5	47.8	45.6	30.0	
	Grain	75.1	62.0	56.3	68.7	50.5	43.9	3.8
	Straw	74.6	65.2	58.2	66.7	50.6	43.8	5.0

(a) Standard error of the difference

The proportion of soil N in the plant at harvest was also affected by the soil series upon which the plots were located. In 1978 and 1980 the proportion of soil N was greater on the Macmerry soil than on the Winton (Table 3). In these two years, greater increases in the proportion of soil N between anthesis and harvest on Macmerry gave rise to this difference at harvest. Generally the differences between soil series were small, although on Macmerry uptake of soil-N was usually higher than on Winton series, the exception being for the first cut in 1978.

At the Bush Estate site, the most important factor affecting the uptake of soil-derived N by the crop was the application of fertilizer N. In contrast, at the site near Aberlady in1981, the fertilizer N treatments had no effect on the uptake of soil N (Fig. 3). The contrast between unfertilized plots and the mean of the fertilized plots was not significant. Table 4 shows the percentages of plant N derived from soil. The proportion of soil N in the plant always decreased with increasing rate of applied N fertilizer. The application of fertilizer-N had a greater effect on the proportion of soil N in spring barley than in winter barley. Also, there was a higher proportion of soil N, at low rates of applied N, in spring than in winter barley. The reverse was seen at high N rates. Again there was a greater proportion of soil N in the grain at harvest than in the shoot at anthesis, for both crops. Data for 1982 will be reported elsewhere. At Bush Estate, the distribution of annual rainfall seemed to be an important factor

Table 4. Percentage of N in plant shoot derived from soil at 5 N-fertilizer rates between 30 and 150 kg ha^{-1}; winter and spring barley; Aberlady, 1981

Crop	Plant material	% of N derived from soil					SED[(a)]
		30	60	90	120	150	
Winter barley	Shoot at anthesis	75.3	58.8	43.2	39.2	37.3	5.1
	Grain	77.3	62.7	51.1	48.1	44.9	4.1
Spring barley	Shoot at anthesis	79.1	63.5	43.7	35.0	29.2	6.0
	Grain	82.7	63.9	59.9	46.0	38.9	5.0

(a) Standard error of the difference

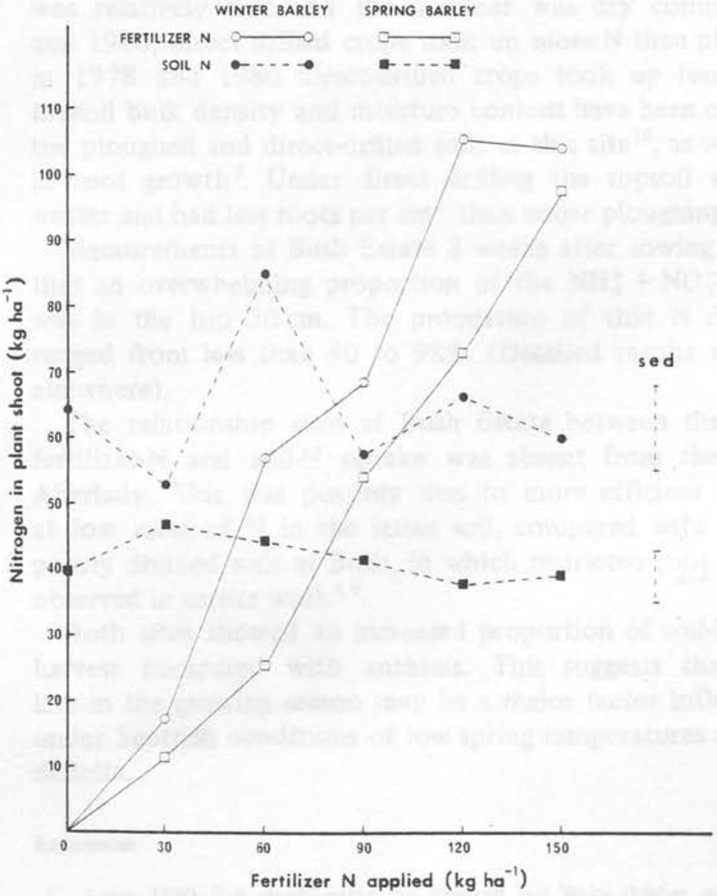

Fig. 3. Uptake of fertilizer and soil N in plant shoot at anthesis as a function of fertilizer N applied: Aberlady, 1981.

determining the difference between years. The total rainfall over the period March–May 1979 was much higher than for 1978 and for 1980 (275 mm compared with 164 and 115 mm respectively). This spring rainfall pattern in 1979 was followed by a lower total rainfall than in 1978 and 1980 for June and July (35.5 mm compared with 103 and 163 mm), accompanied by more sunshine from June onwards. In 1979 the soil water deficit remained relatively low until July as a result of the high rainfall in spring. In 1980, however, a large deficit had developed by May. This could explain the small amount of fertilizer-N in the crop in early June 1980 compared with that found in 1979. The higher rainfall during June in 1978 and 1980 could explain the June peaks in fertilizer-N uptake. There seems to be an interaction between the effects of tillage and the seasonal distribution of rainfall on the uptake of N by spring barley. In 1979 when the spring was relatively wet and the summer was dry compared with 1978 and 1980, direct drilled crops took up more N than ploughed, whereas in 1978 and 1980 direct-drilled crops took up less. Differences in topsoil bulk density and moisture content have been observed between the ploughed and direct-drilled soils at this site[10], as well as differences in root growth[7]. Under direct drilling the topsoil was more dense, wetter and had less roots per cm^3 than under ploughing.

Measurements at Bush Estate 8 weeks after sowing in 1979 showed that an overwhelming proportion of the $NH_4^+ + NO_3^-$-N in the profile was in the top 30 cm. The proportion of that N derived from soil ranged from less than 40 to 98%. (Detailed results will be published elsewhere).

The relationship seen at Bush Estate between the rate of applied fertilizer-N and soil-N uptake was absent from the brown sand at Aberlady. This was possibly due to more efficient root exploration at low rates of N in the latter soil, compared with the imperfectly/poorly drained soils at Bush, in which restricted root growth had been observed in earlier work[7, 9].

Both sites showed an increased proportion of soil-N in the plant at harvest compared with anthesis. This suggests that mineralization late in the growing season may be a major factor influencing N supply under Scottish conditions of low spring temperatures and low moisture deficits.

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The Nitrogen Requirement of Cereals

Uptake of nitrogen by barley in Scottish climatic conditions

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Field experiments have been carried out since 1978 using ^{15}N-labelled nitrogen fertiliser to investigate how the uptake of fertiliser nitrogen and soil nitrogen is affected by soil type and tillage practices. The study began on the long-term cultivation experiment at Bush Estate, near Penicuik, Midlothian, where spring barley has been grown continuously since 1968 on Macmerry series (stagnogleyic brown earth) and Winton series (cambic stagnogley) soils (Holmes, 1976; Pidgeon, 1980). The work has now been extended to include other sites with contrasting soil and climatic conditions, and winter and spring barley are also being compared at a site at Aberlady, East Lothian on a brown sand soil.

Calcium nitrate fertiliser containing ca. 0.7 atom per cent ^{15}N (i.e. about twice the natural abundance) was applied to 2 m × 1.5 m microplots within larger plots treated with unlabelled fertiliser at rates up to 180 kg ha^{-1}. Plant samples were taken on five or six occasions during the growing season for ^{15}N and total nitrogen analysis. The atom per cent ^{15}N in the plants was determined by mass spectrometry, thus enabling the fraction of nitrogen in the plant derived from fertiliser to be calculated.

At Bush Estate in 1978 and 1980, late uptake of soil-derived nitrogen significantly reduced the proportion of nitrogen in the plants derived from fertiliser; this did not occur in 1979. Differences between years were also seen in the effects of tillage. In 1978 and 1980, uptake of nitrogen in the earlier stages of growth was generally greater from ploughed than from direct-drilled soil, but this was reversed in 1979. The relative contributions from soil nitrogen and fertiliser nitrogen varied considerably between years, both at anthesis and at final harvest. These variations are correlated with differences in rainfall distribution. In 1979 there was a much higher rainfall in March–May, but less in June and July, than the other years. Uptake of nitrogen was generally greater from the lighter Macmerry soil, particularly in the earlier part of the season, but differences between soils were usually less than those between tillage treatments.

In 1981, the first year of the comparison between winter and spring barley, on the brown sand at Aberlady, yields of grain were much higher from the winter crop at all rates of fertiliser applied up to 90 kg ha^{-1}. In general, the uptake of soil nitrogen remained fairly constant, while that of fertiliser-derived nitrogen increased, with increasing rates of fertiliser, but absolute quantities of nitrogen from both sources were significantly higher in the winter than in the spring barley. The constant uptake of soil nitrogen contrasts with the results for Bush Estate, where uptake increased significantly with level of fertiliser nitrogen in all three years for which results are available.

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