Better estimation of soil nitrogen use efficiency by cereals and oilseed rape

by

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Abstract

Making appropriate allowance for the contribution of soil N supply to crop requirement is of environmental and economic importance, and the assumed efficiency with which soil mineral nitrogen (SMN) is used is fundamental to most fertiliser recommendation systems. Estimates of efficiency with which SMN is used are normally obtained from unfertilised (zero N) crops or crops treated with ^{15}N-labelled fertiliser. The uptake of soil N depends on the amount of SMN present initially and also the amounts that are subsequently lost (mainly by leaching) or added through mineralisation of crop residues or soil organic matter. Data analyses and computer simulations using the SUNDIAL model were used to re-examine the efficiency with which SMN is used, and identify factors and management practices that might influence this.

Analysis of 400 winter cereal trials with zero N treatments revealed that crop N uptake varied widely in relation to the amount of SMN present. Apparent efficiencies of use for autumn- or spring-harvest ranged above and below 100% of the SMN, but average efficiency decreased with increasing SMN. Efficiencies were often below 100% for SMNs above 100 kg N/ha. Previous crops or soil types that gave the lowest SMN levels gave the highest apparent efficiencies. There were fewer datasets for winter oilseed rape and spring barley, but efficiencies of use again declined as the amount increased. These trends can be explained by higher N losses where the SMN amount was high, and also uptake being limited by crop demand. However, the data analyses and model simulations provided evidence that the actual efficiency of SMN use is likely to be less than 100%, with net increases in amount of available N between measurement and harvest accounting for higher apparent efficiencies. Better estimation of N losses and N mineralisation are therefore vital to improving estimates of soil N use efficiency.

Model simulations for winter wheat indicated that, with the same amount of SMN present, actual efficiencies of SMN use are lower on sandy soils and in high rainfall situations. SMN present at below topsoil depth in the autumn was found to be used less efficiently. This might also be the case where a high amount is present at depth on sandy soils in wet springs. Early sowing of winter cereals or oilseed rape improved N uptake and SMN use efficiency between autumn and spring, and early sowing of spring barley was also beneficial due to a longer growing season. Experiments on winter wheat, oilseed rape and spring barley revealed apparent increases in SMN use efficiency when fertiliser N was applied, but reductions where the N supply exceeded crop demand. Further research is needed to determine whether amount and timing of fertiliser N affects the efficiency with which crops recover SMN from different depths.

Summary

Introduction

Assessing the soil N supply and its likely contribution to crop requirement is a key component of NVZ action programme measures, aimed at meeting the UK's obligations for protecting water quality under the EU Water Framework Directive. Surplus nitrogen fertiliser remaining in the soil is also liable to increase losses of the greenhouse gas nitrous oxide. With nitrogen fertilisers representing an increasingly large proportion of variable costs, and accounting for close to half of the energy used to produce a tonne of conventionally-grown wheat or oilseed rape, the importance of making maximum use of this valuable resource cannot be over-stated.

The assumed efficiencies of use for N from different sources are crucial, as they underlie all of our fertiliser recommendations systems. However there has been a lack of Industry confidence in the guidance given in the Defra fertiliser recommendations handbook RB209, which states that Soil Mineral Nitrogen (SMN) is used with near 100% efficiency, compared to average recovery of fertiliser N of about 60% on most soils. Published literature, which has tended to focus more on recovery of fertiliser N than soil N, also reveals a high level of uncertainty and contradictory conclusions.

Quantifying the Soil N Supply

Determining how much soil-derived N a crop has recovered is not easy, as (apart from late season foliar N and a small amount of N in the atmosphere) all of the nitrogen that a crop takes up will have come via the soil and, once in the soil, fertiliser-derived N and soil-derived N are normally indistinguishable. There are two main approaches:

1. Field experiments that include both with and without fertiliser N treatments enable recovery of soil N (in zero fertiliser N plots) and fertiliser N (by deduction of uptake in zero N plots) to be calculated from N offtake in the harvested crop (grain plus straw).

2. Alternatively, field experiments can be done using fertilisers labelled with ^{15}N, a stable isotope of N which allows the crop N uptake to be partitioned between that derived from fertiliser (^{15}N labelled) and that from soil (unlabelled). This is a costly and labour-intensive technique, and is not therefore used routinely in agronomic field

trials. However, some computer simulation models, such as SUNDIAL developed by Rothamsted using ^{15}N experiments, can be used to model such situations.

At the simplest level, if the amount of N in an unfertilised crop (or unlabelled N in a crop treated with ^{15}N-labelled fertiliser) when harvested is exactly equal to the amount of SMN measured plus the N already in the crop at the time that the SMN was measured, then the apparent recovery (or efficiency of use) of the SMN is 100%. However, the actual soil N supply consists of more than just the SMN, and can be shown by the following equation:

Crop N (at harvest)   =   Crop N (at time SMN measured) + (SMN x efficiency of use)

+ (subsequent mineralised N x efficiency of use)

+ (N from the atmosphere x efficiency of use)

N deposited from the atmosphere is usually ignored, as it is a relatively small and stable amount (20-30 kg N/ha across the whole UK) some of which will be accounted for by SMN measurements done in the spring. Mineralised N is derived from the breakdown of crop residues, organic manures or soil organic matter, via the soil microbial biomass. Decomposition of these materials can either release (mineralise) or lock up (immobilise) N depending on conditions (notably the carbon:nitrogen ratio of the organic material or residues). The N mineralised in most arable soils is derived largely from recent crop residue inputs and the older humified soil organic matter. It is controlled by several factors, including:

i.   Soil temperature (mineralisation rate increases most rapidly between temperatures of 5°C and 25°C)

ii. Moisture (optimal at close to field capacity)

iii. Texture (clay soils contain more protected organic matter)

iv. Cultivations (ploughing increases mineralisation, but effects often only last for one or two weeks).

There are several reasons therefore why the eventual uptake of N by an unfertilised crop may differ from that predicted:

1. The initial crop N was greater or less than that estimated or measured. This is unlikely to be a major source of error in cereals, but for winter oilseed rape the N in the crop in spring often accounts for a significant proportion of final crop N uptake.

2. The amount of SMN present was greater or less than the measured value. This will always be a possible source of error, because measurements of SMN are subject to considerable variation. A limited amount of SMN may also be taken up from below sampling depth.

3. The amount of N mineralised after SMN was measured was greater or less than that estimated. What is important here is net mineralisation, or the balance between mineralisation and immobilisation. RB209 makes little adjustment for mineralised N unless the soil has 10% or more organic matter. However, it is acknowledged that the 100% efficiency of use of SMN stated in RB209 assumed that mineralised N would make up any shortfall in the actual efficiency.

4. The efficiency with which the SMN was used was less than 100%. This could be because some of it was lost (through leaching and/or denitrification) before it could be taken up, or some of it might simply remain in the soil until after harvest of the crop. Research has indicated that losses of soil N in the spring rarely exceed 10 kg N/ha, but much higher losses would be expected over winter.

In order to improve estimates for the efficiency of use of SMN for cereals and oilseed rape, and to identify management practices that might help to maximise efficiency and guide additional research to further improve understanding of factors that affect efficiency, a 12-month review was undertaken, which included the analysis of a large amount of published and unpublished data, and use of the computer simulation model SUNDIAL.

A review of published literature revealed several key areas where there were gaps or complexities in understanding the key factors that affect recovery of soil nitrogen:
- The extent to which differences in apparent efficiency of SMN use are the result of changes in the SMN supply (due to net mineralisation or losses)
- The validity of a single estimate of SMN use efficiency for all current and previous crop types, and for all soil types
- The importance of depth at which SMN is present in determining efficiency of use
- The effects of sowing date and length of growing season
- A concern that recovery of soil N by modern shorter wheat cultivars may be less efficient than that by older taller cultivars

- The appropriateness of estimates based on unfertilised (zero N) treatments when predicting SMN use efficiency in optimally-fertilised situations.

Estimates of Efficiency Obtained for Unfertilised Winter Cereal Crops

Data were analysed from more than 350 trials on winter wheat and 50 trials on winter barley, all of which included zero fertiliser N treatments. Measurements of SMN in autumn and/or spring (and sometimes at harvest) and measurements or partial estimates of crop N uptake in spring and at harvest, were used to calculate apparent efficiencies of SMN use for the autumn to harvest and spring to harvest periods.

The data analyses revealed that crop N uptake varied widely in relation to the amount of SMN measured (at 0-90cm depth) in the spring or previous autumn. A simple comparison of past and recent experiments indicated similar crop N uptakes (in proportion to the amount of SMN present) for old compared to newer cereal cultivars.

Crop uptake ranged from well below to well above 100% of the amount of SMN that was measured, but the average efficiency of use declined with increasing amounts of SMN. This was true both for the autumn to harvest and spring to harvest periods. In many cases where SMNs were greater than about 100 kg N/ha efficiencies were less than 100% (i.e. unfertilised crops recovered less N than the measured SMN). At very high SMN levels (above 200 kg N/ha) efficiencies were typically 70% or less, probably because uptake would have been limited by crop demand. For SMNs of 50 kg N/ha in autumn or spring, regression analysis indicated average apparent efficiencies of use of 130% and 100% for autumn-harvest and spring-harvest respectively. For SMNs of 100 kg N/ha in autumn or spring, efficiencies of use of 90% and 80% respectively were indicated. For SMNs of 150 kg N/ha in autumn or spring, the efficiencies indicated were both close to 75%.

Analysis of a subset of the winter cereal data (winter cereals following winter cereals on a clay soil) showed the same general trend towards decreasing efficiency of use with increasing amount of SMN. A fuller examination the effects of previous crop and soil type for winter wheat also provided further evidence. Mean quantities of SMN ranged from about 40 to 150 kg N /ha depending on previous crop and soil type, and time of measurement (autumn or spring). Apparent efficiencies of use varied from 81-124% in autumn and 62-160% in spring, with soil type. Apparent efficiencies varied from 93-258% in autumn and 84-155% in spring, with previous crop. Previous crops

(such as sugar beet) after which smaller amounts of SMN were measured, and sandy soils that had low SMN levels, tended to give higher apparent efficiencies of SMN use. The trend towards lower efficiency of use with increasing amount of SMN is likely to reflect both an increasing risk of SMN loss (especially that due to winter leaching) and decreasing uptake as the N supply meets and exceeds crop demand. However, the explanation probably also lies partly within the soil N supply equation shown earlier. The soil N supply depends not only on the amount of SMN and the <u>actual</u> efficiency with which this is used, but also the amount of N that becomes available subsequently (mainly by mineralisation), which affects the <u>apparent</u> efficiency of SMN use in the observed relationships. At low levels of SMN, subsequent mineralisation may contribute as much as, or more than, the SMN to the soil N supply, resulting in apparent efficiencies of more than 100%. At higher levels of SMN, subsequent mineralisation is likely to contribute proportionally less to the soil N supply than SMN, resulting in lower apparent efficiencies, although on organic or peaty soils very large amounts of SMN are often measured because they have a very high potential for mineralisation. The computer simulations suggested that, for the same amount of SMN, its apparent efficiency of use is likely to be less where the soil organic matter (SOM) content is lower. This is because less N will be mineralised. SOM was found to have no affect on the actual efficiency with which the SMN was used.

Therefore, data analyses indicate that the actual efficiency of use of SMN may be less than 100%, but uptake of N that subsequently becomes available results in apparent efficiencies averaging close to 100% for SMNs within the range often found in arable rotations on mineral soils (50-100 kg/ha at 0-90cm in spring). Computer simulations for fertilised winter wheat and spring barley on a range of soil types indicated that, if mineralised N is excluded, estimates of SMN use efficiency might be about 60% of those obtained when mineralised N is not excluded. In other words, where apparent efficiencies of around 100% are observed, actual efficiencies might be closer to 60%.

Estimates of Efficiency for Other Crops
Zero fertiliser N treatments from winter oilseed rape and spring barley experiments were also analysed, although the datasets were much smaller than for winter cereals. A wide range of N uptakes (and therefore SMN use efficiencies) relative to amount of SMN was observed for both crops, with efficiency again declining as SMN amount increased. For winter oilseed rape, crop N uptake accounted for nearly all of the decrease in SMN between autumn and spring, but efficiencies of SMN use tended to

be lower from spring to harvest. For spring barley, efficiencies below 100% were often obtained where SMNs were above only about 50 kg N/ha. This apparent difference to winter cereals might be due to differences in rooting depth (and therefore ability to recover SMN from depth) or crop demand for N, but in addition the dataset for spring barley included a number of Scottish sites, and would have included a greater proportion of lighter, shallower soils and high rainfall situations.

Factors Affecting Actual Efficiency of SMN Use

Although higher estimates of efficiency of SMN use were obtained for sandy soils in the data analyses, this is because they contained lower amounts of SMN. Model simulations for winter wheat showed that, with the same amount of SMN present, sandy soils (and high rainfall situations) are likely to give lower efficiencies of SMN use than clay soils (or low rainfall situations), especially if the entire period from autumn to harvest (rather than just spring to harvest) is considered. This is due to greater loss of SMN though leaching in sandy soils and/or with high rainfall. The winter cereal data analysis also showed a reduction in SMN use efficiency with increasing spring rainfall, suggesting increased losses by leaching or denitrification.

A key argument, which has been used separately to support both higher and lower efficiency of use of SMN compared to fertiliser N, is that SMN tends to be distributed over a greater range of soil depths than fertiliser N (which is usually all located within the top few centimetres of soil). Analysis of a subset of the winter wheat data indicated that the depth at which SMN was present in the autumn was an important factor, with SMN used more efficiently when located mainly in the plough layer (0-23cm) than when located deeper. During the autumn and winter period cereal roots will be less able to access SMN at depth, and that which is already present at depth in the autumn is more likely to have been moved beyond effective rooting depth as a result of further leaching by the spring. Little relationship was found between depth of SMN in the spring (within the range 0-90cm) and efficiency of use from spring to harvest. By this stage, roots will in most cases have reached this depth, and the risk of N being leached even deeper will be less. However, computer simulations indicated that where a high amount of SMN was present at depths between 50 and 150cm in the spring, this might be used less efficiently in high rainfall situations (probably due to it being leached below the rooting zone).

Analysis of the data for unfertilised crops revealed that, for spring barley and winter oilseed rape in particular, early sowing increased uptake of N between sowing and harvest, and therefore improved efficiency of SMN use. For spring barley, the benefit from earlier sowing in the spring was associated with a longer growing season. For winter oilseed rape, the benefit from earlier sowing was primarily increased crop N uptake between autumn and spring. For winter wheat, early sowing improved uptake of N between autumn and spring, but the relationship between N uptake and sowing date for the autumn to harvest period was weaker. This is likely to be because other factors were having a more significant influence on crop growth and therefore N uptake from spring onwards. There was evidence from at least one experiment that high levels of take-all (often made worse by early sowing) substantially reduced the efficiency with which SMN was taken up.

Effects of N Fertiliser Application on SMN Use Efficiency

Data from ^{15}N labelled fertiliser experiments and model simulations were used to examine the impact of fertiliser N on efficiency of SMN use. A key consideration when estimating SMN recovery in unfertilised crops is whether or not this has a tendency to overestimate the likely efficiency of use that might occur in optimally-fertilised situations. In two experiments, one on winter wheat and one on winter oilseed rape, the apparent efficiency of SMN use was increased (not decreased) by the application of N fertilisers on silty clay loam, chalky clay loam and sandy loam soils, but not on clay soils. In experiments over two successive seasons on spring barley, apparent efficiency of SMN use was also increased by fertiliser N, at doses within crop demand. However, at doses in excess of crop requirement efficiency of SMN use did decrease.

There are two possible explanations for this. The application of N fertiliser, especially early in the growing season, might improve crop rooting, allowing crops to more readily access SMN that is present at depth. However, evidence to support this is limited. A second possible explanation is that when fertiliser N is applied, this substitutes for SMN that might otherwise have been immobilised or lost for example by denitrification. If this were the case, then application of increasing amounts of fertiliser N might still reduce the efficiency with which the overall supply of N is used, and it should not be seen therefore as a means of reducing N losses.

Conclusions and Implications

Although empirically an assumption of 100% efficiency of SMN use is likely to provide a reasonable estimate of the <u>average</u> amount of soil-derived N supplied in typical arable rotations on mineral soils, this is not because SMN (within the depth measured) is used with 100% efficiency. Instead, the supply of soil N depends on both SMN and N that subsequently becomes available in the soil, mostly due to mineralisation. For individual situations both actual efficiency of SMN use and the supply of mineralised N are likely to vary, and to a greater or lesser extent independently. This may partly explain why the relationship between SMN and optimum fertiliser N dose has often been relatively weak in, for example, winter wheat N dose response trials. On mineral soils, in arable rotations, adjusting fertiliser N doses (upwards or downwards) by the full amount indicated by differences in measured SMN may therefore not always be justified. Techniques that allow better estimation of the likely amount of mineralisation between application and harvest, such as SUNDIAL, are vital to improving prediction of the soil N supply, and therefore fertiliser N requirement.

The actual efficiency with which SMN located within the effective rooting zone is used is on average likely to be more similar to that assumed for fertiliser N (60%), although this may vary depending on the risk of losses. Higher leaching losses (lower efficiencies) would be expected on sandy soils, in high rainfall situations and/or where high levels of SMN are present at depth in the autumn. On heavier soils, losses through denitrification may be more significant. Better estimation of the principle loss processes (leaching and denitrification) would help to improve estimates of SMN use efficiency.

Husbandry factors that might help to maximise the actual efficiency with which SMN is used include:
1. Early sowing:
- of winter cereals and oilseed rape, to increase N uptake and reduce overwinter losses.
- of spring barley, to maximise the length of the growing season and therefore N uptake.
2. Avoidance of take-all in winter wheat through management of the crop or rotation.
3. Avoiding the application of N fertiliser in excess of crop requirement, although within this limit the application of N fertiliser can sometimes improve the efficiency with which SMN is used.

Further research is needed to determine whether or not amount and timing of fertiliser N affects the efficiency with which crops recover SMN from different depths in the spring. In

addition, more work to examine the relationship between take-all infection of cereals and the uptake of N from the soil would be beneficial. Additional N response trials on recent cultivars of winter wheat, winter and spring barley and winter oilseed rape are needed, and these should include a full spectrum of soil and crop N measurements in order that relationships between the soil N supply and crop N uptake can be fully examined.

1.0 Introduction

1.1 Background

Compliance with legislation aimed at controlling diffuse pollution and protecting water quality as required by the EU Water Framework Directive (Anon 2000b) and other associated EU directives (Anon 1980 and 1991) is one of the most important issues facing UK growers, with accurate nutrient management planning a key component. Limiting inorganic N fertiliser application to crop requirement, after allowing fully for residues in the soil and other sources, is a specific component of the Action Programme Measures that growers in Nitrate Vulnerable Zones (NVZs) must adopt (Anon 2002). The Government's target of reducing greenhouse gas emissions is also likely to drive increasing N use efficiency on farms, since agriculture is the main source of nitrous oxide in the UK (DEFRA 2007). In addition, the economic impact of high fertiliser costs has placed even greater emphasis on the need to optimise the use of applied N, whilst maximising the contribution of soil N.

Assessment of the Soil Nitrogen Supply (SNS) to enable field-specific N fertiliser recommendations to be generated is an integral part of the current UK fertiliser recommendation system (Anon, 2000a; Sinclair *et al.*, 2002). This can be achieved using the field assessment method, based on previous cropping, soil type and rainfall together with allowance for previous use of manures (Williams *et al.*, 1996). In Scotland this is the preferred system (Sinclair, 2002), partly because the high excess winter rainfall usually means that residual mineral nitrogen present in the soil in autumn has leached out of the rooting zone by spring, and partly because soil nitrogen uptake extends long into the growing season being supported by mineralisation from soil organic matter. However, SNS can be assessed directly by sampling and analysis of the soil. The main components in this approach are the soil mineral N content (ammonium plus nitrate), crop N uptake and an estimate of the N likely to be mineralised during the period of crop growth (Equation 1).

SNS = Soil mineral N (SMN, 0-90cm) + Crop N + mineralisable N   Eqn 1.

Soil mineral nitrogen in the rooting zone can vary widely depending on soil management, soil type and climatic conditions, and is also expensive to measure.

The estimate of SNS forms the basis of an index system used to determine the appropriate N fertiliser application rate. In their early research in Germany, Jungk and Wehrmann (1978) concluded that the quantity of mineral nitrogen in the rooted soil layer has the same effect as fertiliser applied in early spring, and should be fully taken into account when recommending fertiliser application. The current UK recommendation system assumes that SMN is effectively used with more or less 100% efficiency. However, evidence from N response curve studies has sometimes challenged this assumption. For example, based on an overall regression between optimum N dose and total SMN, Harrison (1995) observed that on average SMN might only be 62% as efficient as fertiliser N in supplying plant requirements.

In practice, the actual SNS depends both on the efficiency of SMN use and the supply of SMN derived from the mineralisation of soil organic matter (the mineralisable N). Factors which decrease efficiency of SMN use may lead to inadequate fertiliser application and poor crop performance. Conversely, greater than anticipated supply of SMN through net mineralisation may lead to the overuse of fertiliser N. In addition to being an economic waste this may lead to pollution of ground and surface waters, and enhanced emissions of greenhouse gases. Therefore, the efficient use of fertiliser N depends critically on an accurate estimate of SNS.

It is widely acknowledged that crops do not recover all of the fertiliser nitrogen that they receive. Bloom *et al.* (1998) found apparent recoveries ranging from 43-88% in 70 experiments on winter wheat, but were unable to account for the variability. Working on seven winter cereal sites over three years in Eastern England, King *et al.* (2001) also found apparent recoveries of fertiliser N within the range of 45-85%. Soil type and fertiliser application timing had no effect on N recovery, but apparent recovery was almost exactly explained by the amount of fertiliser N immobilised during May when crop uptake was most rapid. This immobilisation appeared to be a consequence of the presence of the crop (probably turnover of fine roots in the soil surface layers). Powlson (1997) reported that under UK conditions around 15-25% of the nitrogen applied to cereals in the spring may be lost during the growing season. Scott *et al.* (1994) showed that crop recovery of fertiliser N by wheat remains stable over a wide range of N amounts (0-250 kg/ha). The Defra fertiliser recommendations handbook RB209 (Anon, 2000a) suggests that average recovery in the grain and straw is about 60% on most soils (70% on light sands, but only 55% on shallow soils). This is substantially less than the near 100% assumed for SMN.

1.2 Aims and Objectives

The aim of this research review was to improve estimation of the availability of soil nitrogen to key combinable crops. The specific objectives of the review were to:

- Investigate, using published and unpublished data, the efficiency of use of SMN by winter wheat, barley and oilseed rape (including situations where inorganic N fertilisers are also being applied).
- Use model simulations to identify and prioritise the factors that influence SMN use efficiency.
- Identify management practices that may help to optimise the efficiency of use of SMN.
- Identify future research that will improve our understanding of the factors affecting the availability and uptake of SMN, and our ability to predict and maximise its contribution to crop requirement.

1.3 Approaches

The review took the form of a one year desk study, consisting of three main elements that are reported separately here, and then drawn together in the conclusions:

- A review of published literature, including estimates and calculation of SNS, and factors affecting the recovery or efficiency of use of soil-derived nitrogen.
- A data compilation and analysis exercise, including published and unpublished data from a variety of sources, leading to calculated efficiencies of use for soil N by winter wheat, barley and oilseed rape, using established and (where possible) alternative methods.
- Model simulations, using SUNDIAL (Bradbury *et al., 1993;* Smith *et al.*, 1996), of soil N uptake to compare with calculated values from actual data, and to examine in more detail the impact of factors that might affect efficiency of use.

2.0 Literature Review

2.1 Quantifying the Soil N Supply by Crop N Uptake

The supply of N to a crop can broadly be quantified from its N uptake, or for a cereal crop by the offtake of N at harvest as follows:

Grain yield x grain N concentration +   =   soil N x recovery +
straw yield x straw N concentration   fertiliser N x recovery

Straw yield and N concentration are often not measured, so this has to be substituted with an assumed N harvest index (for example Bloom *et al.*, 1998). Field experiments that include both with and without fertiliser N treatments enable recovery of soil N (in zero N plots) and fertiliser N (by deduction of uptake in zero N plots) to be calculated from the harvested crop. Alternatively, in experiments that have used ^{15}N-labelled fertiliser, uptake of soil N can be calculated separately in fertilised treatments.

Retention of N in stubbles and roots is generally ignored. For fertiliser N this is usually considered acceptable as its contribution to root growth is relatively small (Kumar and Goh, 1999). However the amount of N in the roots can amount to 20% of the amount in the grain + straw, which implies that much of this must be derived from soil N (in particular from establishment in the autumn until N fertiliser is applied in the spring).

If the uptake of N by a crop that receives no N fertiliser (or the uptake of unlabelled N by a crop that receives ^{15}N-labelled fertiliser) exceeds the amount that would have been predicted from Equation 1 (page 10, assuming 100% recovery), then there are three possible explanations:

1. The amount of N already in the crop was underestimated or higher than measured.
2. The amount of SMN present was higher than the measured value suggested.
3. The amount of mineralisable N was underestimated.

Measurement of SMN will always be a possible source of error because it is subject to considerable variation, and it will undoubtedly account for apparent efficiencies of use in excess of 100% in some cases. However, where the supply of soil N is substantially higher than predicted, in many cases this is likely to be due to higher than expected

net mineralisation. Other possibilities though include uptake of SMN from below the measured depth (usually 90cm), or atmospheric deposition between the time of SMN measurement and harvest. Annual deposition from the atmosphere is relatively small and stable at around 20-30 kg N/ha (Goulding, 1990) across the whole of the UK.

If the uptake of soil N is less than would have been predicted, there are four possible explanations:

1. The amount of N already in the crop was overestimated or lower than measured.
2. The amount of SMN present was lower than the measured value suggested.
3. The amount of mineralisable N was overestimated.
4. The efficiency with which the soil N present was used was less than 100%, either because a proportion was lost from the soil, or because it remained in the soil but was not all taken up.

If taken literally, the assumption of 100% efficiency of use of soil N could be interpreted as meaning that all of the SMN measured must be taken up by the plant, and none lost. In practice though, what is in most cases actually meant is that an amount of N will be taken up by the crop between the time of SMN measurement and the time of maximum N uptake that is equivalent to the amount of SMN initially measured. Any loss of SMN from that initially measured is then replaced (mainly) by net mineralisation during the season. This means that mineralisation then becomes a determinant of (apparent) efficiency of use, as well as a determinant of the soil N supply.

2.2 Processes Affecting the Soil N Supply

The amount of SMN present in the autumn or spring is dependent upon a number of factors, including soil type and organic matter content, rainfall, previous crop, dose of N fertiliser applied and manure use. Using a computer model, Addiscott and Whitmore (1987) found that simulated amounts of SMN present in spring were influenced by changes in rainfall, soil water content, mineralisation and soil temperature. However, mineralisation and losses (by leaching and/or denitrification) are two key processes that are likely to have an impact on apparent or actual efficiency of SMN use.

2.2.1 Mineralisation of Soil Organic N

The primary sources of N for crop growth (other than fertiliser N and residual SMN) include that derived from the mineralisation of crop residues, organic manures and the indigenous soil organic matter (SOM). The mineral N derived from these sources represents the balance between mineralisation and immobilisation. It is influenced by many factors, including the rate and timing of N inputs, the type and management of crop residues and cultivation practices. Mineralisation of organic material is performed by non-specific heterotrophic micro-organisms under aerobic and anaerobic conditions when they use organic N as energy sources (Jarvis *et al.*, 1996). Mineralisation and immobilisation are linked because micro-organisms utilise some of the available N to meet their nutritional requirements (immobilisation). However, when these organisms die some of this N is mineralised and becomes available to plants.

Temperature and moisture are probably the most important environmental factors controlling N mineralisation, because of their effects on microbial growth and activity. The mineralisation of soil organic matter by Mesophyllic soil organisms is optimal at 25-37°C, with a basal rate at about 5°C. Estimates in the literature indicate that mineralisation increases by 1.5-3 times for a soil temperature increase of 10°C. In contrast, Psychrophiles are active at low temperatures and may contribute to mineralisation in winter and early spring. Gill *et al.* (1995) estimated that only 21-38% of the annual net N mineralisation in long-term grassland occurred in Nov-Feb. The soil water content is also important because of its effects on the microbial population and soil/plant interactions. In general, mineralisation is optimal between -0.33 and -0.1 bar (80-90% water filled pore space, or close to field capacity). However significant mineralisation can still occur in dry soil (at wilting point).

Net N mineralisation can be enhanced or depressed following the addition of crop residues or organic manures. Shen *et al.* (1989) reported that crop residues are much more decomposable than the indigenous soil organic matter. The N supply from crop residues is linked to the amount and type of residue returned and its management. Break crops (e.g. oilseed rape, potatoes, sugar beet, beans) tend to leave larger amounts of readily-mineralisable crop residues than cereals. The incorporation of residues with C/N ratios greater than 15, such as cereal straw may enhance net N immobilisation (Powlson *et al.*, 1985), but residues with smaller C/N ratios tend to enhance net N mineralisation. The long-term application of mineral fertilisers may also

enhance net N mineralisation (Glendining and Powlson, 1995) because of its capacity to increase the soil organic matter content and hence its mineralisation potential. The increase in soil organic N is considered to be through enhanced inputs from roots, stubble, leaf litter and microbial immobilisation of N.

Soil texture can also influence N mineralisation. Clay soils contain a larger proportion of physically protected organic matter than sandy soils, because more is located in small pores ($<1.2\mu m$) or adsorbed on clay surfaces (Jarvis *et al.*, 1996). In general, mineralisation of both C and N declines with decreasing pore size. Therefore, physical protection of organic matter increases with increasing clay content. Consequently, clay soils often contain more organic matter than coarser textured soils. Ultimately, this may lead to greater net N mineralisation. This leads to an apparent paradox that clay soils stabilise organic matter more than sandy soils and yet mineralise more. The explanation is that turnover of organic matter in clay soils is slower than in sandy soils but there is a much larger pool turning over, hence greater net mineralisation. Whilst mineralisation occurs predominantly in the topsoil where much of the organic matter and microbial activity occurs some also occurs at depth. Cassman and Munns (1980) reported that after thirteen weeks 42% of the N mineralised in soil incubated at $25^{o}C$ was derived from the 0-18 cm layer, the remainder was from the 18-108 cm depth.

Cultivation can dramatically change the physical, chemical and biological interactions within the soils. Intensive cultivation increases soil porosity and temperature and decreases the stability of soil aggregates resulting in decreases in soil organic matter content and water holding capacity. The physical disruption of soil organic matter by ploughing often enhances net N mineralisation as a result of increasing aerobicity and exposure of organic matter to microbial decay (Silgram and Shepherd, 1999). The enhanced mineralisation of C and N following cultivation indicates that easily mineralised organic matter is associated with macro-aggregates (perhaps microbial residues). When these aggregates are disrupted by cultivation the organic matter within them is exposed to microbial attack. However, the effects of cultivation may be relatively short-lived, lasting only 5-14 days; indicating that both C and N mineralisation are rapid. Thus, crop establishment after cultivation should be rapid if it is to utilise this N efficiently and minimise N leaching losses.

SMN may be increased by up to 65 kg N/ha following cultivation compared with no-till, and nitrate leaching may be increased by up to 25 kg N/ha. This effect may depend

on soil texture. Heavy clay and loam soils with larger organic matter contents may mineralise more than coarse textures sandy soils. However, losses of spring fertiliser N may be slightly greater under no-till due to leaching through deep pores and fissures, which are disrupted by cultivation. Also no-till crops may require some seedbed N, because of greater N immobilisation in the presence of crop residues in surface soil layers.

The role of soil fauna is poorly understood. However, it is known that earthworm activity enhances carbon and nitrogen mineralisation by increasing soil mixing which in turn enhances contact between organic residues and the soil microbial population. Work by Subler *et al.* (1997) indicated that the composition of earthworm communities may influence the availability and leaching of nitrogen in the surface soil of some grain cropping systems. Micro-bivorous fauna such as protozoa and nematodes may also enhance N mineralisation and recycling of N in root exudates.

The amount of soil nitrogen likely to become available for crop uptake is extremely variable and difficult to predict. Many biological and chemical methods for predicting fertiliser N requirements have been proposed (Keeney, 1982; Gianello and Bremner, 1986), although none have yet proved entirely successful. Rees *et al.* (1996) found a good relationship between the uptake of soil nitrogen in spring barley and the amount predicted using a chemical extraction method where soil was mixed with hot KCl solution. However, McTaggart and Smith (1993) found that the relationship did not hold on soils with higher amounts of soil organic matter. Fox and Piekielek (1984) found that predictions using chemical indexes were improved when soils that were previously cropped with legumes were excluded from the relationships. They concluded that it may not be possible for any one test to predict nitrogen availability under a wide range of conditions and therefore tests might have to be restricted for use under clearly defined conditions.

2.2.2 Losses of N from the Soil

Powlson *et al.* (1992) investigated losses of soil N. Quantities of unrecovered ^{15}N were used to estimate loss of unlabelled N between the time of application of ^{15}N-labelled fertiliser in spring and time of final harvest. It was assumed that labelled and unlabelled N taken up during this period come from the same pool, such that the uptake:loss ratios should be equal:

Loss of unlabelled N   =   loss of labelled N
Plant uptake of unlabelled N   plant uptake of labelled N

For labelled N, data was used from the fertiliser dose that resulted in labelled N uptake as closely matched as possible to the uptake of unlabelled N. For unlabelled N, data from unfertilised plots was used. Calculated amounts of soil N lost were small, only exceeding 10 kg N/ha in two cases. Both situations were where there was a high % loss of labelled fertiliser due to rain after application, and also a large uptake of unlabelled N. However, it was noted that much higher losses of soil N would be expected over the winter.

Under wet conditions in particular early in the season there is a potential for loss of both fertiliser and soil derived nitrogen by denitrification processes. Dobbie *et al.* (1999) found that emissions from cereal crops were between 0.2-0.7 kg N/ha per year, although these emissions were influenced by year-to-year variability in climate. The IPCC assumes that 1% of fertiliser is emitted as N_2O in temperate soils, however total losses of N (which includes N_2 and NO) can be several times greater than this. These fluxes represent an important contribution to greenhouse gas emissions, but are probably less important in terms of influencing the magnitude of plant available N (given that N fluxes by plant uptake and mineralisation-immobilisation turnover can be 100 times greater).

2.3 Efficiency of Use of SMN

2.3.1 Winter Wheat

Field experiments on the efficiency of N fertiliser use can provide useful information on factors controlling the efficiency of use of soil-derived N, especially where ^{15}N-labelled fertilisers and unfertilised control plots are included.

Wilson and Vaidyanathan (1994) reported yields and N uptakes for winter wheat grown on 21 sites on 5 different soils in Essex in 1985-86. The crops received fertiliser N at seven rates, from 0 to 280 kg N/ha. SMN (0-90 cm) was measured in November 1985 and March 1986. Dry matter production exerted the dominant influence on soil and fertiliser N use efficiency. Crop growth and N uptake without N fertiliser were well related to SMN (or SNS) in autumn. The 'extra' N uptake due to fertiliser application (i.e. N uptake in excess of the unfertilised crop) was negatively related to SMN present in autumn, with no increased dry matter production or N uptake when SMN exceeded 140 kg N/ha.

Wilson and Vaidyanathan (1994) expressed the efficiency of SMN use by the crop as the crop N uptake at harvest as a percentage of that present in soil in autumn (Equation 2). Efficiencies calculated in this way ranged from 79 to 103%, when no fertiliser N was applied. In contrast, when fertiliser N was added to the SMN content, the efficiency of available N use was 64-75% at the optimum fertiliser N application rate. In the following year (1986-87) efficiency of SMN by unfertilised winter wheat at four sites was 73-132% and for winter barley 67-142%.

$$SMN_{eff} = 100 \text{ x } (CN_{T2} - CN_{T1})/SMN_{T1} \quad \text{(Eqn 2)}$$

Where:
SMN_{eff} = %Efficiency of SMN (0-90 cm) use by the crop.
CN_{T2} = Crop N content at harvest
CN_{T1} = Crop N content at the start of the growth period (autumn or spring)
SMN_{T1} = Soil mineral N content at the start of the growth period (autumn or spring)

Efficiencies of available N use for fertilised crops (including SMN and fertiliser N) were 48-80% overall. There was clear evidence of the effects of soil type on SNS, with

greater efficiency of SMN uptake (>100%) by cereals on some silty loam sites compared with sandy loams. It was suggested that this may be a result of capillary rise of soil solution and nitrate from below 90 cm, or extension of roots below 90cm. Sowing date and crop type were also found to influence efficiency of SMN use. Wheat after break crops (sugar beet and peas) and permanent grass often contained more N than could be accounted for from a measure of SNS alone, indicating significant net release of mineral N. It may also be in part due to a decrease in the effects of soil borne diseases after break crops e.g. take all. There was a reasonable relationship between autumn SMN in 1986 and crop N uptake (wheat and barley) to March 1987. The proportions recovered depended on sowing date and to a lesser extent crop type, but soil type was the dominant effect with 12-24% of SMN recovered by crops on sandy & sandy/silt loams compared with 49-75% on silt loams. A similar trend was seen in crop N uptake in April 1987 when 29-46% of the SMN was recovered by the crop on sandy sites compared with 76-194% on silts. Presumably these differences were in part due to greater over winter nitrate leaching losses in the sandy loam compared with the silty loam soils.

Wilson *et al.* (1996) reported efficiencies of nitrogen fertiliser and SMN use by winter wheat grown on 20 sites in Essex in 1987/88 with and without fertiliser N. These sites comprised five soil types (sandy loam, sandy silt loam, silt loam, calcareous clay loam and clay loam) following winter wheat, field beans or winter oilseed rape, and with SMNs ranging from 40-198 kg N/ha in 0-90cm. Efficiency of autumn SMN in the absence of fertiliser N was 50 – 159 % (mean of 88%). At 5 sites 39-59% more N was recovered than was present as SMN (0-90 cm). Recoveries of total available N (SMN + Fertiliser N) were 43-80%. It was concluded that the soil mineral N content after break crops was often greater than after cereals. It was also greater in silt and clay loams than in sandy loams. There was an indication of more efficient use of available mineral N (fertiliser plus soil mineral N) in the calcareous clay loam (72%) compared with the other soils (50-62% - sandy loam, sandy silt loam, silt loam, clay). Efficiency of SMN use was greater for unfertilised than fertilised crops.

Previously, in 36 experiments on winter wheat in 1981-1983 on Hanslope clay in Eastern England, ADAS (1985) found that soil N uptake calculated from ^{15}N measurements was related to spring SNS (= 0-90cm SMN + crop N) but the relationships were weak if the influence of previous crop was eliminated. Spring SNS could be used as a predictor of soil N uptake, but with adjustment for greater

apparent recovery (about 80%) than for fertiliser N. They found no relation between crop N uptake without fertiliser and spring SNS assuming regressed recoveries of fertiliser N applied equally to soil N, but considered this was likely to be due to unreliability of this assumption rather than large fluctuation in SNS or in the relationship between soil N and fertiliser N recovery.

Webb *et al.* (1995) working on spring wheat sown between October and March found that crops appeared to recover about 60% of the SMN measured in spring, with a further 20 kg N/ha recovered from N mineralised after SMN samples were taken. Stokes *et al.* (1998) found that SMN at 0-90cm in February accounted for 75% of the variation in crop N uptake between February and harvest, and that this relationship was tighter at higher levels of SMN. They concluded that recovery of SMN (as measured in the spring) in unfertilised crops was at least 100% (with on average an extra 30 kg N/ha taken up), indicating a tight balance between mineralisation and immobilisation.

Macdonald *et al.* (1997) measured uptake of both soil and fertiliser N by winter wheat given ^{15}N-labelled fertilisers at recommended rates in 1987. In addition, uptake of soil N by unfertilised crops was measured in 1987. In both years crops were grown on four different soil types, a silty clay loam, a sandy loam, a heavy clay and a chalky loam. SMN was measured in autumn, spring and at harvest. Therefore it was possible to estimate the efficiency of SMN use for autumn-harvest and spring-harvest using equation 2. More detailed analyses of these data are given on pages 49-51 of this review.

Sylvester-Bradley *et al.* (2001) reported effects of the previous crop N fertiliser applications on uptake of N by early and late sown subsequent winter wheat (cv. Mercia) crops given no fertiliser N at 17 sites between 1993 and 1995. In all cases wheat followed oilseed rape given a small amount of N (0-50 kg N/ha) or a large amount (200-350 kg N/ha). Previous N application rates did not affect subsequent crop N in spring, presumably because sowing was too late for N capture in autumn, but it did affect SMN in subsoil (60-90 cm) in spring. N uptake rates from spring to harvest were increased by previous N rates and late sowing. Rates of N uptake related closely to SMN in spring, such that equivalent recovery was achieved by late May/June. There was a good correlation (r^2=0.95) between crop N uptake from February to harvest and SMN (0-90 cm) in spring, but in all cases crop N uptake

exceeded SMN, indicating that efficiency of SMN was on average about 130%. When efficiency of SMN use was calculated as a percentage of the apparent net N mineralisation (Equation 3, page 50), estimated efficiencies of SMN use decreased from 153 to 142% on a clay loam, and from 154 to 101% on a sandy loam; perhaps reflecting the greater contribution from N mineralisation in the subsoil in the clay loam. However, it was acknowledged that recovery of SMN by unfertilised wheat crops after oilseed rape would almost certainly be greater than for second or third wheat crops where take-all would almost certainly diminish crop N uptake and hence efficiency of SMN use. It was suggested that delaying fertiliser applications may help facilitate more complete utilisation of SMN in deeper soil layers.

Bhogal *et al.* (2000) also found that crop N offtake in the absence of fertiliser N was related to SMN (0-90 cm) in spring. In two out of five trials crop N uptake accounted for only 75% of the SMN present in spring, but in three cases recoveries were greater than 100%. It was postulated that the additional supply could include some of the N deposited from the atmosphere, N from below 90cm depth, or subsequent mineralisation (greater in plots that had previously had higher N doses).

2.3.2 Winter Oilseed Rape

Macdonald *et al.* (1997) reported that the uptake of soil N by unfertilised oilseed rape grown at four sites in SE England was 55-88 kg N/ha. The corresponding winter wheat crops recovered 29-87 kg N/ha; excluding one which was severely infected with take-all and recovered only 19 kg N/ha. Uptakes of unlabelled N by both winter wheat and oilseed rape crops given ^{15}N-labelled fertiliser were similar and were strongly related to crop N plus soil mineral N (0-100 cm) in spring and efficiencies of fertiliser N uptake were similar, averaging 45 and 52% respectively. More detailed analyses of these data are given on pages 51-53 of this review. In other work it has been noted that oilseed rape accumulates a substantial amount of N in autumn (Rathke *et al.*, 2006) and continues taking up N rapidly until flowering, but subsequent N uptake is low. Consequently, because flowering of oilseed rape in the UK usually occurs in April/May, about a month earlier than for cereals, recovery of soil N by oilseed rape in the winter and early spring may well be more efficient than for cereals, which continue to take up N later in the growing season. However, incomplete translocation of N from the vegetative organs into the seed may result in large N surpluses (N inputs – crop N offtake) on land following oilseed rape compared with winter wheat.

2.3.3. Spring Barley

Uptake of soil-derived nitrogen by cereal crops grown on Scottish soils shows considerable variability between sites and between seasons. McTaggart and Smith (1992) found that soil derived N uptake by spring barley varied by up to 100% between sites that were similar when classified according to previous cropping history. Soil nitrogen uptake at these Scottish sites was also found to extend long into the growing season, being supported by mineralisation from soil organic matter pools (McTaggart and Smith, 1995). This difference in the contribution of soils to crop N supply may be partly explained by the significantly higher concentrations of soil organic matter found in Scottish soils (Bradley *et al.,* 2005), and the cooler wetter summer conditions, which delay mineralisation in the spring, but allow a longer period of uptake over the summer. This also makes autumn and spring SMN measurements less valuable indicators of potential nitrogen uptake at Scottish sites.

2.4 Potential Factors Affecting Efficiency of SMN Use

2.4.1 Rooting and SMN Depth

Harrison (1995) observed that, if it is assumed that soil nitrogen substitutes 1:1 for fertiliser nitrogen, the optimum nitrogen dose for winter wheat was best predicted by soil nitrogen in only the top 0-30cm depth. However, more of the variation in optimum dose was explained by not assuming a 1:1 relationship, and by including the 30-60cm depth. He concluded that it was likely that this was because the soil nitrogen below 30cm depth was more prone to losses, and taken up less readily by plant roots. This might apply particularly to soil nitrogen observed at 90cm depth in either the autumn or early spring. By the time that root systems are well developed at depth, in most practical situations fertiliser nitrogen will already have been applied and crops will be less reliant on scavenging for soil nitrogen at depth.

Addiscott and Darby (1991) using computer simulation and regression analysis between optimum N and SMN to different depths showed that the depth at which best correlations are obtained increases through the winter and spring. By mid April, optimum N was best correlated with SMN to 1.66m, but the regression coefficient decreased with time so that SMN at shallower depths measured earlier decreased optimum N to a greater extent than SMN at greater depths measured later.

Foulkes *at al.* (1998) suggested that one explanation for greater efficiency of use of spring soil N would be that this tends to be evenly distributed within soil depth under cereals, whereas fertiliser N is mainly located in the topmost layers. Duration of soil N uptake would be greater than that for fertiliser N, partly because availability is not subject to vagaries of water deficits that may exist in surface layers.

Soils in Scotland are generally shallower than those further south in the UK, and soil sampling reflects this, with SMN analyses often limited to the top 40 cm (McTaggart and Smith 1992; Rees *et al.* 1996), or 60 cm (HGCA Project No. 3084, unpublished). In some circumstance this can also coincide with the total depth of soil available for root growth as a consequence of the presence of indurated soil horizons or waterlogging.

Sylvester-Bradley *et al.* (2001) concluded that SNS in early spring on nitrate retentive soils was a good indicator of N availability throughout the growth of unfertilised wheat because the SMN from previous fertiliser applications and mineralised N remained within the rooting depth of the crop. They noted that net decreases in SMN to June largely resulted from changes below 30cm rather than in the topsoil, and that this was surprising that the intensity of rooting was likely to have been greater in that layer, and a larger proportion of the soil's water was likely to have been extracted from that layer. The extra N uptake over and above that present in soil in spring was ascribed largely to uptake of N mineralised in subsoils (30-90 cm) and/or uptake from deeper soil layers. They also concluded that unfertilised wheat crops obtain more of their N from deeper soil layers than fertilised crops.

Further evidence of this is provided by unpublished work done at Rothamsted in which ^{15}N labelled nitrate was placed at two depths under winter wheat. This indicated that recovery of nitrate at 60 cm was only 79% of that recovered from surface applied N. The efficiency of recovery of nitrate at 120 cm was 68% of that applied to the surface and the proportion of nitrate recovered by the crop decreased with increasing depth. These findings are broadly consistent with other work on winter wheat (Kuhlmann *et al.*, 1989) and vegetables (Kristensen and Thorup-Kristensen, 2004).

Kuhlmann *et al.* (1989) examined the utilisation by wheat of SMN from the subsoil at depths down to 200cm. They found that subsoil mineral N content varied widely with farming practice, but that winter wheat roots could take up nitrogen from depths down to 150cm. Averaged over 22 sites, 33% of the total nitrogen uptake was from the subsoil (range 9-75%), with 25% from 30-90cm and 8% from 90-150cm. Decreasing the nitrogen supply to the topsoil increased uptake (by proportion) from the subsoil. A wheat crop given fertiliser N took up 155 kg N/ha between tillering and flowering, of which 65% (101 kg) came from the top 0-30cm of soil, 20% (31 kg N/ha) from 30-90cm and 23 kg N/ha from the 90-150cm layer. An unfertilised crop took up 41 kg/ha in the same period, 32% (13 kg/ha) from the top 0-30cm, and 34% (14 kg/ha) from each of the 30-90 and 90-150cm layers.

Uptake from the subsoil was not dependent on water uptake as nitrate was readily transported to absorbing roots by diffusion. Both fertilised and unfertilised crops had sufficient rooting densities in all layers down to 120cm to virtually deplete them of nitrate. Rooting densities below 120cm were insufficient to extract much nitrogen

(only 5 kg/ha between tillering and flowering) until after flowering (when 11 kg/ha was taken up), but this could be important during grain fill if topsoil nitrogen is made unavailable by summer drought. If not taken up, this same nitrogen could be at risk from loss by leaching.

Kristensen and Thorup-Kristensen (2004) indicated that N uptake per unit length of root were similar irrespective of species and depth. Consequently, it seems likely that crop N uptake may well be controlled to a greater extent by factors influencing root development than by the root uptake capacity per se.

Therefore, if much of the SMN present in the soil profile (0-90 cm) under cereals and oilseed rape is in the topsoil, where roots are most abundant, it may well be used more efficiently than if it is distributed more evenly throughout the profile. Presumably in the early stages of crop growth, when roots have not yet reached the subsoil, SMN present in deeper soil layers is at greater risk to loss by leaching than that in the surface soil so will be recovered less efficiently.

2.4.2 Crop Establishment and Growth

Improving the ability of root systems to recover soil nitrate N by earlier and faster uptake of nitrate N is a possible strategy to minimise nitrate losses and improve nitrogen uptake efficiency. This strategy dictates that roots grow faster and proliferate earlier to intercept and capture the nitrate N before it moves below the rooting depth of wheat crops. Correlation between root biomass, root length and uptake of nitrate N have been reported in wheat (Liao *et al.*, 2004) indicating that wheat crops with bigger and deeper root systems may be more effective in capturing nitrogen.

Work with cereals, comparing early September with mid October sowing of winter wheat (Widdowson et al., 1987) and cover crops (Macdonald et al., 2005) has highlighted the importance of early plant establishment, before the onset of drainage, to ensure effective N uptake and decrease losses by nitrate leaching. Early establishment of cereals and oilseed rape may also therefore help enhance the efficiency of SMN use.

However, Webb *et al.* (1995) found that the uptake of soil N by a spring wheat cultivar sown in October was no greater than when sown between November and

March, contrary to expectation that with later sowing the root system would develop more slowly and the crop would be less able to recover SMN before leaching occurred. It was suggested that the less well developed rooting systems of later sown crops may remove soil moisture less quickly in spring and summer, allowing more mineralisation to balance any increase in leaching from later sowing.

Rooting and establishment may be dependent on physiological factors under genetic control. If this is so, there may be scope for enhancing the efficiency of SMN use by breeding. Cosser *et al.* (1997) found that, when grown organically, older taller wheat cultivars appeared to be more efficient at taking up residual soil N than modern shorter cultivars. Foulkes *et al.* (1998) found a negative relationship between year of entry into National List trials and offtake of N in grain when unfertilised, suggesting that genotypes produced from the mid 1970s to the late 1980s were progressively less efficient at acquiring soil N (but only by 15 kg N/ha over 20 years). This was attributed to introduction of semi dwarf cultivars from 1969, with less straw, dry matter and overwinter growth, so poorly adapted to soil N uptake in winter and early spring. Also in recent years wheat cultivars have been bred and tested in presence of ample fertiliser N, potentially decreasing the importance of the plants ability to acquire soil N.

2.4.3 Time of SMN Uptake and the Impact of Fertiliser N Application

Vaidyanathan *et al.* (1987) found that, unlike with fertiliser N, moderate amounts of soil N were not associated with any larger grain nitrogen concentrations than resulted with small amounts of soil N, explained by soil N being taken up earlier than fertiliser N. Stokes *et al.* (1998) found that 25% of the SMN recovered by unfertilised crops was taken up after flowering, and that uptake was least effective at this time where most of the SMN was close to the soil surface. Powlson *et al.* (1992) working with ^{15}N-labelled fertiliser found that unlabelled N accounted for 20-50% of the total N of fertilised crops at harvest. 50% of this had already been taken up by the time fertiliser N applied, and the final quantity closely correlated (83%) with amount in the crop at that time.

McTaggart and Smith (1992) found that recovery of SMN occurred predominately between June and August at six sites in Eastern Scotland. SMN declined at all sites during the growth of the crop, but reductions in the SMN pool could not always be

accounted for by plant uptake. In these circumstances immobilisation of N was suggested as a possible mechanism.

Sylvester-Bradley *et al.* (2001) concluded that it should not be assumed that SMN is immediately available to the crop and that even where amounts of SMN are sufficient to meet final N uptake by the crop some fertiliser N may be necessary to before equivalent uptake can occur.

Jenkinson *et al.* (1985) observed that experiments with ^{15}N-labelled fertiliser often show that plants given fertiliser N take up more N from the soil than plants not given N, the so-called priming effect or added nitrogen interaction (ANI). It was suggested that this could be a 'real' effect e.g. if fertiliser N increased the volume of soil explored by the plant root system, or an 'apparent' effect by pool substitution (with labelled inorganic N standing proxy for unlabelled inorganic N that could otherwise have been immobilised or denitrified) or isotope displacement.

Powlson *et al.* (1992) showed in experiments on winter wheat on three soils at different sites in Eastern England that application of ^{15}N-labelled fertiliser tended to increase uptake of unlabelled soil N by 10-20 kg N/ha compared to the control receiving no fertiliser. Recovery of fertiliser N by the ^{15}N method ranged from 46-87% (mean 68) compared to 30-96% (mean 74.3%) by the difference method. They concluded that 5-63% (mean 16.5% of the N uptake by the control crop) more unlabelled soil N was taken up by the crop where ^{15}N fertiliser was added. This was attributed to pool substitution. Bhogal *et al.* (1997) reported a positive ANI for winter wheat given less than 175 kg/ha of fertiliser N, but a negative ANI for N applications greater than 175 kg/ha. Thus at the higher N application rates the crop derived more of its total N requirement from fertiliser at the expense of soil derived N.

McTaggart and Smith (1995) found that soil derived N uptake by spring barley was increased from 45 to 80 kg N/ha following the addition of 150 kg N/ha. It was suggested that this effect was caused by more efficient exploitation of soil by the roots, although the effect was not consistently observed at different sites. However, Nielsen *et al.* (1998) found that uptake of soil-derived N by spring barley was not significantly affected by rate of nitrogen fertiliser applied i.e. no priming effect. Recent studies on winter wheat and spring barley as part of HGCA project no. 3084 (unpublished) have indicated that under Scottish conditions, applications of N fertiliser

in excess of the economic optimum dose will not necessarily give rise to higher SMN levels after harvest (and therefore increase the leaching risk). However, an increase in SMN levels with N fertiliser dose was observed with a low yielding, drought-affected spring barley crop on a sandy loam soil, and with a spring barley crop grown after set-aside that had a lower optimum fertiliser N dose.

Legg and Allison (1967) and Westerman and Kurtz (1973) postulated that the priming effect may be due to stimulation of rhizosphere micro-organisms. Supozhnikov et $al.$ (1968) showed in a split root glasshouse experiment that adding ^{15}N labelled NH_4 or NO_3 to roots growing in sand increased uptake of soil N by roots growing in soil by 32 and 11% respectively. However, effects of additional N on root growth are often small compared to top growth. Welbank et $al.$ (1974) found that although fertiliser N increased root density in the top 15cm, it had little effect below 15cm. Hart et $al.$ (1986) suggested that later application of N fertiliser may allow microbial needs to be met by native soil N, so fertiliser N remains available for plant uptake.

Recous et $al.$ (1988a and b, 1992) reported work on the fate of ^{15}N-labelled urea, ammonium and nitrate applied to winter wheat in northern France. The N was applied at 50kg N/ha and 110kg N/ha in early March and mid April. The different forms of N were labelled separately i.e. ^{15}N was applied as either labelled NH_4 or NO_3, or urea. Urea hydrolysis, nitrification and the disappearance of inorganic N was followed at frequent intervals after application. It was found that microbial immobilisation and plant N uptake were major competitors for fertiliser N. Ammonium N was immobilised more readily than nitrate, but the efficiency of N use by the crop was greater for nitrate than ammonium and was greatest at anthesis. However, the efficiency of N use decreased during the grain filling period, indicating turnover of N in the shoot. Thus the estimated annual N use efficiency was dependent on the date of measurement.

2.4.4 Other Fertilisers, Organic Manures and Previous Grass

Glendining et $al.$ (1997) reported ^{15}N balances for experiments in which $^{15}NH_4{}^{15}NO_3$ was applied to spring barley at four N rates (48, 96 144 kg N/ha and Nil N) on plots of contrasting fertility on the Hoosfield continuous barley experiment (FYM, PK, Nil and FYM-residue) in 1986 and 1987. Where crops received adequate P and K recovery of fertiliser N was 51% of that applied, 30% remained in the soil (0-70cm), mostly in the

topsoil (0-23cm) and 19% was lost. Only 4% of the labelled fertiliser N remained in soil in inorganic forms. Where P and K were deficient yields were depressed, recoveries of labelled N were smaller and more labelled N remained in the soil. Similar recoveries of fertiliser N were measured in soils of very different organic matter status, but more soil derived N was taken up by the crops grown on the FYM plots than on the PK plot, indicating greater net N mineralisation in the FYM plot. However, where fertiliser applications exceeded the crop demand the uptake of soil N on the FYM plot was blocked (a negative ANI), especially that present in subsoil (below 23cm).

Powlson *et al.* (1986) reported work in which ^{15}N-labelled fertilisers were applied in spring to selected plots on the Broadbalk wheat experiment. The plots received 48, 96, 144 or 192 kg N/ha. Yields ranged from 1-7 t/ha and in most cases 51- 68% of the applied N was recovered. However, only 40% was recovered when crops were P deficient. Unlabelled N uptake increased with fertiliser uptake from 28 to 62 kg N/ha, presumably due to enhanced N mineralisation of soil organic N from larger residue returns. Under dry conditions uptake of ammonium-N was poorer than nitrate N, but was similar when conditions were wetter. Where wheat was grown on plots which received no mineral fertiliser N for many years the efficiency of SMN use for spring-harvest and autumn-harvest (1995-2001, excluding 1997-1998) ranged from 5 to 60% (mean 28%; unpublished data). However, where FYM only was applied in autumn efficiencies of SMN use by winter wheat (1998-2001) appeared to be greater, ranging from 27 to 89% (mean 64%). This was in part because of the large crop N uptakes on these plots, indicating that the long-term addition of organic manures may have enhanced plant growth and increased the efficiency of SMN use. The mechanism for this is unclear, but may in part be due to greater availability of SMN in the autumn and/or other plant nutrients (e.g. P, K etc) and/or effects on soil physical characteristics which influence germination and nutrient acquisition, perhaps through root growth and development.

Mineralisation of N following cultivation of grass leys or incorporation of N rich crop residues may also affect the efficiency with which subsequent crops utilise SMN. Work reported by Johnston *et al.* (1994) indicates that the efficiency of SMN use by winter wheat on a sandy loam from spring to harvest, following leys of different ages (1-6 years), averaged 262% (range 209-301%). This was probably because of the relatively large crop N uptake compared to the SMN content in spring. In contrast, the

efficiency estimated between autumn and harvest was much smaller, averaging only 87%. This was almost certainly because of the large amounts of SMN present in the soil in autumn after ploughing out the leys, which increased with the age of the previous ley. The substantial crop N uptake between spring and harvest coupled with the relatively small spring SMN content indicates that additional N became available to the crops during the growing season, either by mineralisation or uptake from deeper soil layers (below 90 cm). However, it is also likely that some of the N mineralised following ploughing was lost by leaching during the winter. Therefore, SMN present in autumn may well be used less efficiently than that in spring, especially on well drained sandy soils where significant N losses occur by leaching.

Sieling *et al.* (1998) examined the effects of soil tillage, pig slurry applications, inorganic N fertilisers and fungicides on the yield and grain N uptake of winter wheat (after oilseed rape) and winter barley (after winter wheat), and the relative efficiency of use of slurry N and fertiliser N. Averaged over all factors wheat took up about 50 kg N/ha more than barley and utilised a larger proportion of the N in slurry or mineral fertiliser. Whilst previous cropping may to some extent account for this it was apparent that yields and grain N uptakes of unfertilised winter wheat were only 19-32 kg N/ha greater than for winter barley. Also, when N was not limiting both maximum grain yield and N uptake were greater for wheat than for barley, indicating a greater apparent yield potential and N uptake for wheat compared with barley. Crop N uptake was enhanced more by mineral fertiliser N applied in spring than by autumn or spring applied slurry. However, in two out of three cases wheat yields were increased by autumn slurry applications to a greater extent than spring slurry. This was attributed to more vigorous tillering in autumn leading to greater an increased capacity to utilise available N present in the soil in the subsequent spring. In contrast the development of barley in autumn did not limit subsequent N uptake. Consequently, where substantial quantities of SMN are present in the surface soil in autumn, within easy reach of the crop, the subsequent efficiency of fertiliser N use may be enhanced. Of the mineral fertiliser N applied to winter wheat 40-59% was recovered in the grain, compared with only 19-37% of that applied to winter barley. In both cases the efficiency of fertiliser N use decreased with increasing N application rate and when slurry was applied in spring alone or autumn + spring. For barley even autumn applied slurry decreased the efficiency of use of fertiliser N. In both crops mineral fertiliser N was used more efficiently than slurry N.

2.5 Uncertainties Highlighted by the Literature Review

The literature review revealed a number of important areas where there were gaps or complexities in understanding the key factors that affect the recovery of soil nitrogen:

- The extent to which differences in <u>apparent</u> efficiency of SMN use are the result of changes in the SMN supply (increases through for example net mineralisation and decreases through leaching or other losses) rather than actual differences in recovery. This is important because it influences what might be done to improve the effectiveness with which SMN is taken up. A related factor is the extent to which a single measurement of SMN is indicative of likely net mineralisation over the growing season.

- The validity of a single estimate of SMN use efficiency for all current crop and previous crop types, and for all soil types. The current UK fertiliser recommendation systems make no allowance for soil type as a determinant of efficiency of use of SMN (only amount of SMN), whereas differences in fertiliser N use efficiency are stated for sandy soil, clays/loams/silts and shallow soils.

- The importance of the depth at which SMN is present in determining efficiency of use. Currently, no adjustment is made for N measured at depths between 0 and 90cm. The literature review highlighted contrasting views as to the advantages or disadvantages of SMN being located over a greater depth range, and in some cases interpretation of the likely interaction with presence of fertiliser N appeared to differ.

- The effects of sowing date and length of growing season (or the duration of N uptake) for cereals and oilseed rape, on the recovery of SMN measured in the autumn or spring.

- A concern that recovery of soil N achieved by more modern, shorter wheat cultivars that have been bred to perform best in the presence of N fertiliser, might be less than that achieved with older, taller wheat cultivars.

- The appropriateness of estimates based on unfertilised (zero N) experiments when predicting soil N use efficiency in optimally-fertilised situations, and whether the application of N fertilisers generally increases or decreases efficiency of SMN use.

3.0 Data Compilation and Evaluation

3.1 Approach

Published work and other available data were compiled from several sources (Table 1, Appendix 1: Table 1, and Appendix 2) to examine the relationship between crop uptake of soil-derived N and soil mineral N (SMN, 0-90 cm) present in autumn (or at sowing) and spring under winter wheat, winter barley, spring barley and winter oilseed rape. Data for winter cereals was readily available, but similar data for spring barley and winter oilseed rape was limited. Efficiencies of SMN (0-90 cm) use for each of these crops were calculated according to the method of Wilson and Vaidyanathan (1994), as defined in Equation 2 (page 19). Nitrogen fertiliser response trials which included crop N uptakes in the absence of fertiliser N (Zero-N plots) together with measurements of SMN in autumn and spring were especially useful data sources. However, these trials rarely included comprehensive data for N losses (leaching and denitrification) or N returned to soil in roots and stubble, and did not always include sufficient information to identify all possible interactions between the plant, soil and environment. In particular, crop N uptake data and measurements of SMN in deeper soil layers were sometimes missing. In some cases it was necessary to estimate SMN in subsoil layers (below 30cm) and straw N uptakes.

Table 1. Details of data compiled for analysis of factors controlling the efficiency of SMN use by some commercially important arable crops.

Crop	No of trials	Data[†]	
		Group (factors)	Values (variates)
Winter Wheat	357	Site/location Year Crop variety Previous crop Soil Texture	Autumn SMN (0-90 cm) Spring SMN (0-90 cm) Crop N – spring Crop N – harvest Sowing date Harvest date Rainfall (mm)
Winter Barley	57		
Spring Barley	28		
Oilseed Rape	29		

[†]Published data sources are listed in Appendix 2. Additional unpublished data was supplied by Rothamsted Research, The Arable group (TAG), Scottish Agricultural Colleges (SAC) and the Agricultural and Development Advisory Service (ADAS).

In addition, the efficiency of use of soil derived N by winter wheat and oilseed rape in the presence of fertiliser N was examined using published data from trials on four soil types in SE England established in 1987 (Macdonald *et al.*, 1997). These trials included plots given ^{15}N-labelled fertiliser, as ammonium nitrate, in addition to plots which received no fertiliser N. Efficiencies of SMN use for the fertilised plots were calculated by expressing the uptake of unlabelled (soil-derived) N as a percentage of the SMN measured in autumn or in spring. Total crop N uptake was used to calculate the efficiency of SMN use by the unfertilised crops. Similarly, the efficiency of SMN use by spring barley was calculated using published data from trials in which ^{15}N-labelled fertiliser was applied at rates ranging from 0 to 144 kg N/ha to spring barley in 1986 and 1987 (Glendining *et al.*, 1997).

The zero-N trial data were analysed statistically using Genstat v10 (VSN, Hemel Hempstead, UK) to identify as many of the key factors controlling crop N uptake and efficiency of SMN as was possible (Appendix 1: Table 1 lists the data sub-categories). Preliminary analyses were done using summary statistics to identify general trends in the data. Subsequently, regression analyses were used to examine the relationships between crop N uptake at harvest and SMN in autumn and spring. Further regression analyses were done to examine the relationship between the efficiency of SMN use and SMN present in spring and autumn. The effects of soil texture and previous crop on the amount of SMN present in soil in autumn or spring and its efficiency of use by winter wheat were examined using analyses of variance, including one way analysis of variance on $\log_e$ transformed data. The Microsoft-Excel trend-line facility was also used to examine more general relationships between sowing date, rainfall, SMN distribution, crop N uptake and efficiency of SMN use.

3.2 Crop N Uptake and SMN

3.2.1 Winter Cereals

It was considered that, in general, N uptakes in autumn and spring were similar for both unfertilised winter wheat and winter barley crops. Consequently, because the number of winter barley trials was limited, data for both crops were combined prior to analysing their response to SMN (Fig 1). A linear plus exponential regression model described the relationship between winter cereal crop N uptake and SMN in autumn (Fig 1a) better than a linear model, accounting for 52% of the variance in the data. A

similar regression model accounted for 36% of the variance in the relationship between crop N uptake and SMN in spring (Fig 1b), but was not substantially different from a linear model. A comparison of crop N uptakes for past (1980-1993) and recent (1996-2006) winter cereal trials, in relation to SMN present in spring, was not particularly revealing, largely because of the relative lack of data from recent trials. However, simple linear regressions (not shown) indicated that uptake of N per unit of spring SMN (the slope of the regressions) was similar for both past and recent crops.

(a)   (b)
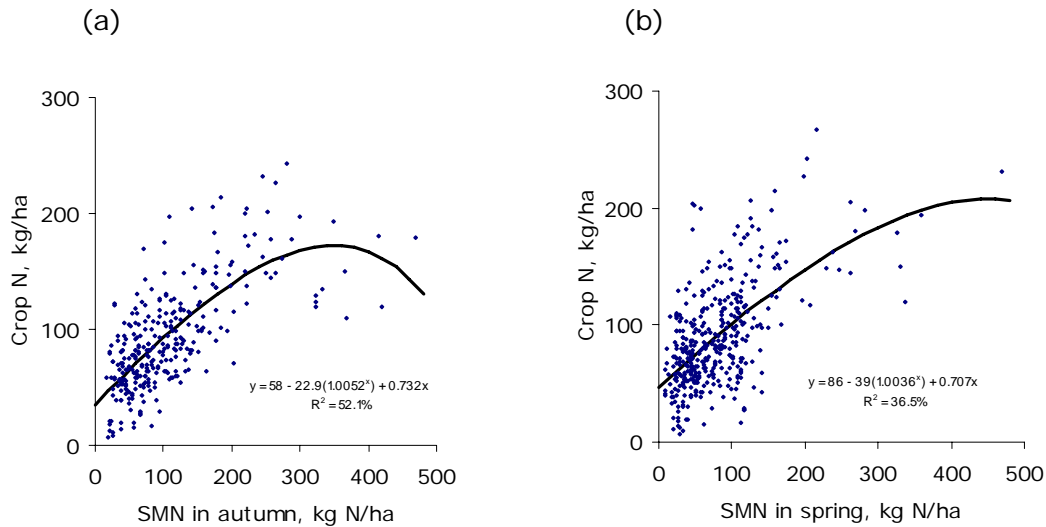
Fig 1. Relationship between crop N uptake at harvest and SMN (0-90 cm) present (a) in autumn and (b) in spring.

A linear regression model indicated that there was a strong positive relationship between the amount of SMN present in soil under winter cereals in spring and autumn (Fig 2a). However, there was a general decline in SMN between autumn and spring, indicating significant losses of SMN in the late autumn and winter, presumably by nitrate leaching (Goulding *et al.*, 2000; Macdonald *et al.,* 2005). Even when accounting for crop N in spring (Fig 2b) apparent losses of SMN were still significant, especially when SMN in autumn was large (>100 kg N/ha).

(a)

(b)
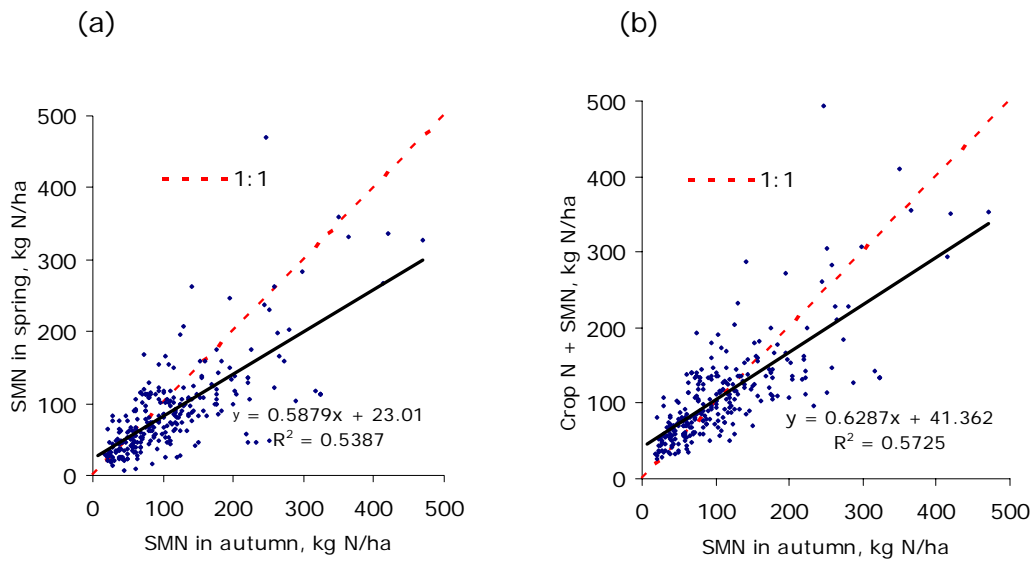
Fig 2. Relationships between (a) SMN (0-90 cm) in spring or (b) spring crop N plus SMN (0-90 cm) and SMN (0-90 cm) in autumn.

A comparison of the change in the quantity of SMN (0-90 cm) between autumn and spring under winter wheat on soils of different textures (Fig 3) indicated that decreases were greater in the sandy loam soils compared with other more nitrate retentive soils.
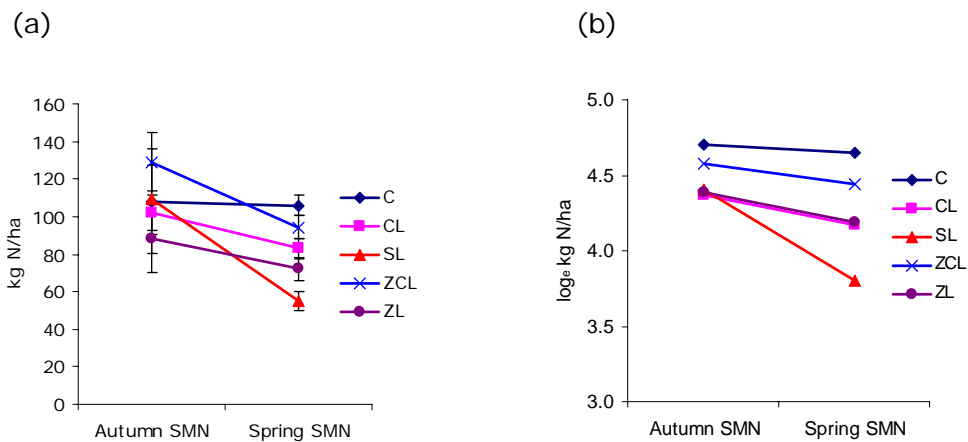

(a)

(b)

Fig 3. Change in mean SMN (0-90 cm) between autumn (sowing) and spring under winter wheat ($\pm$SE) in soils of contrasting texture (Sandy loam (SL), Silt Loam (ZL), Clay Loam (CL), Silty Clay Loam (ZCL), Clay (C)), in (a) kg N/ha and (b) $\log_e$ kg N/ha.

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3.2.2 Winter Oilseed rape

An examination of the limited winter oilseed rape trial data indicated that unlike winter cereals there was no clear relationship between crop N uptakes at harvest and SMN in autumn (Fig 4a) or in spring (Fig 4b). This was almost certainly, in part, because of the narrower range in the quantity of SMN present in the soils under oilseed rape.

(a)   (b)
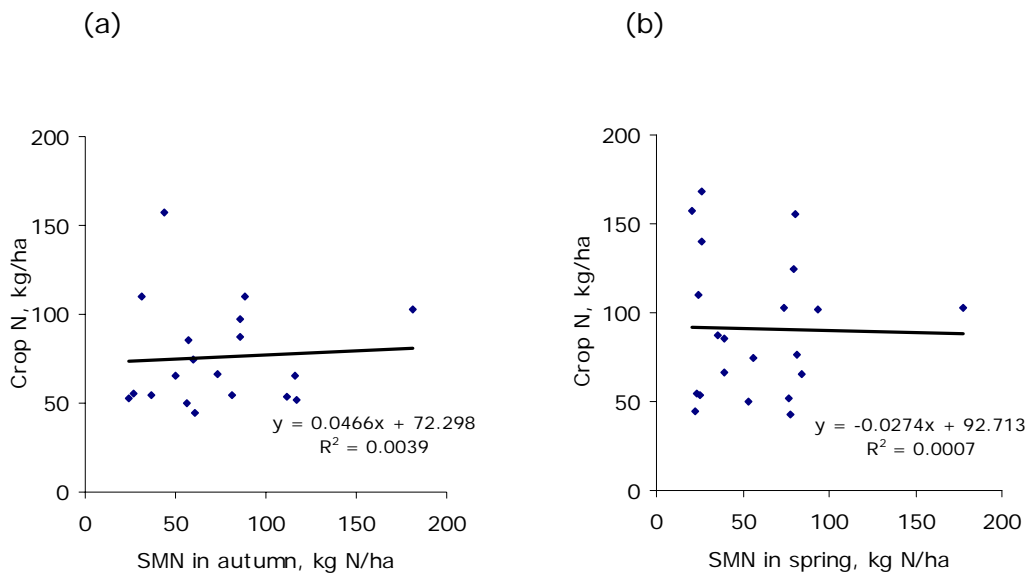
Fig 4. The relationship between winter oilseed rape crop N at harvest and (a) SMN (0-90 cm) in autumn and (b) SMN (0-90 cm) in spring.

There was a positive relationship between SMN present in spring and autumn (Fig 5a), under winter oilseed rape, similar to that found for winter cereals (Fig 2a). The relationship between oilseed rape crop N uptake (autumn-spring) and SMN in spring was close to 1:1 (Fig 5b), indicating that crop N uptake accounted for almost all of the decrease in SMN between autumn and spring, and that SMN was used efficiently.

(a)

(b)
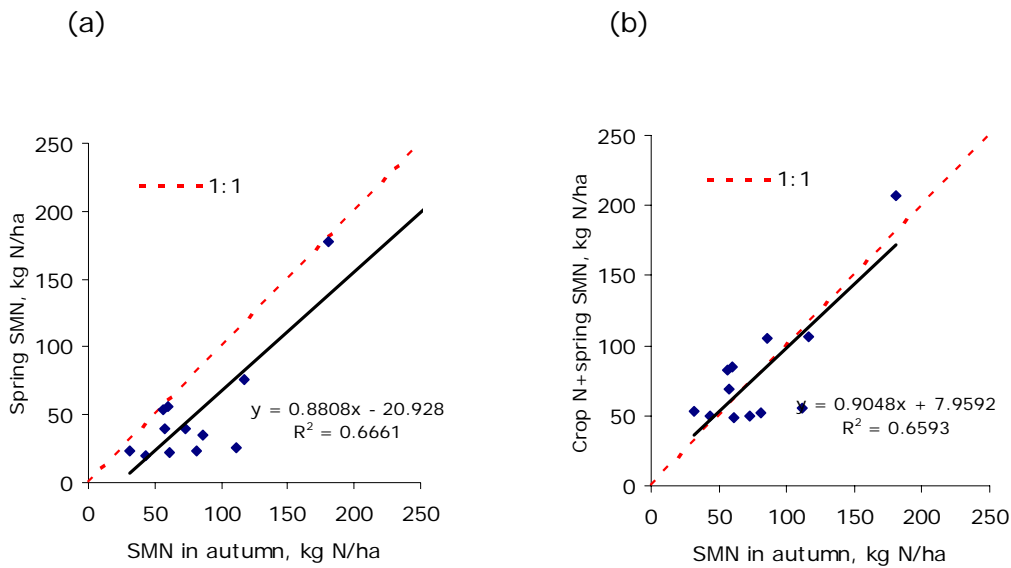
Fig 5. The relationship between (a) SMN (0-90 cm) in spring and SMN in autumn of winter oilseed rape and (b) crop N plus SMN (0-90 cm) in spring and SMN in autumn.

3.2.3 Spring Barley

The range of spring SMN values for the available spring barley data was much narrower than the larger winter cereal dataset. Consequently, it was not possible to compare the two datasets directly. However, over the same range of SMN, the positive linear relationship between spring barley crop N uptake at harvest and SMN in spring (Fig 6a), was similar to that observed for winter cereals in spring (Fig 1b).

(a)

(b)
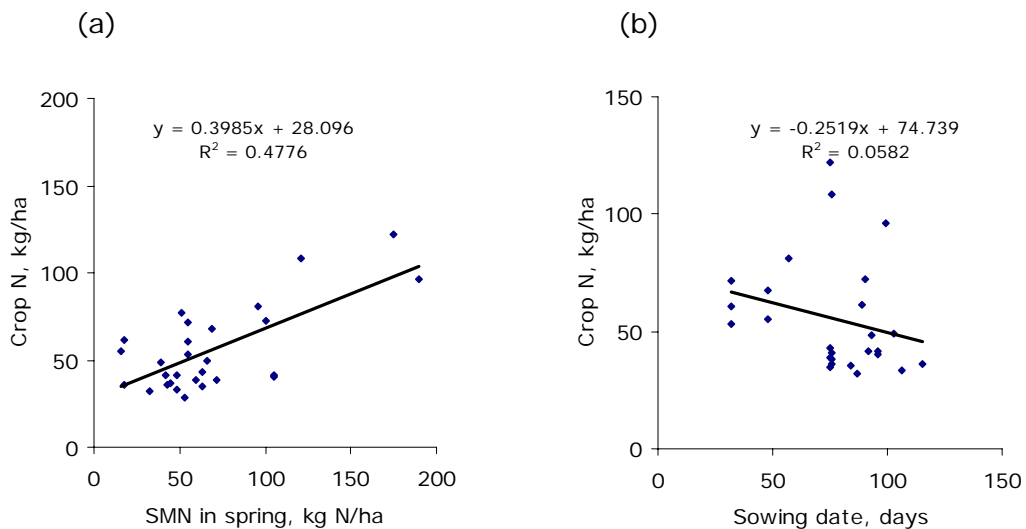
Fig 6 The relationship between spring barley N uptake and (a) SMN (0-90 cm) in spring and (b) sowing date.

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3.3 Effects of Sowing Date

There was a slight negative relationship between spring barley N uptake at harvest and sowing date (Fig 6b). Similarly, there was a negative relationship between crop N uptake in spring and sowing date (Fig 7a) of winter cereals, but there was no clear relationship with crop N at harvest (Fig 7b).
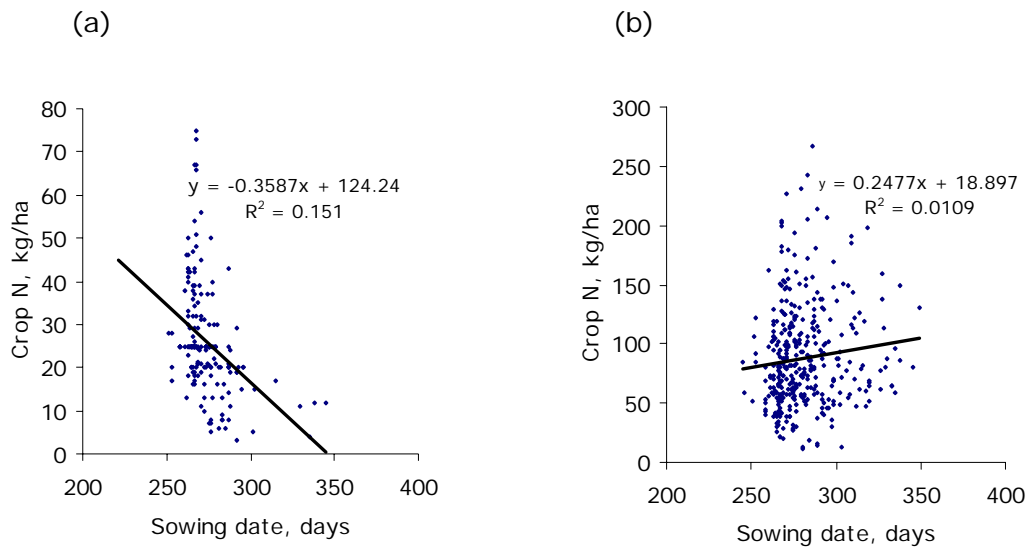
(a) (b)

Fig 7. Relationships between winter cereal (wheat and barley) sowing date and (a) crop N in spring and (b) crop N at harvest.

With oilseed rape it was apparent that early sowing was strongly associated with crop N uptake at harvest (Fig 8a). However, the duration of growth had little effect on the final crop N uptake (Fig 8b), indicating that early uptake of SMN is of more importance for oilseed rape crop N uptake than the length of the growing period.
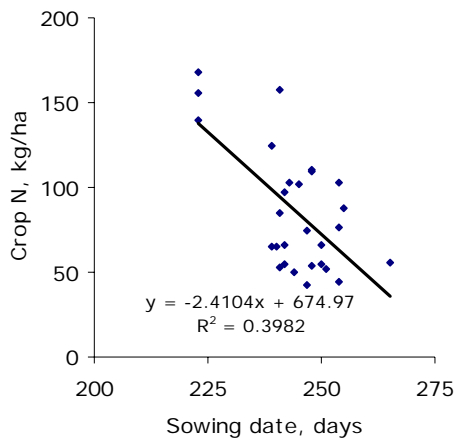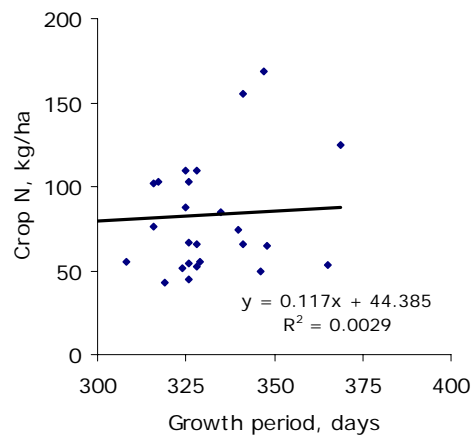
Fig 8. The relationship between winter oilseed rape crop N at harvest and (a) sowing date, and (b) growth period (sowing-harvest).

3.4 Effects of Rainfall

Relationships between winter cereal crop N uptake and rainfall were not strong. However, there was a slightly negative relationship between crop N uptake at harvest with both winter (Fig 9a) and spring rainfall (Fig 9b). There was insufficient rainfall data for the oilseed rape and spring barley trials to examine the effects of rainfall on crop N uptake or efficiency of SMN use.
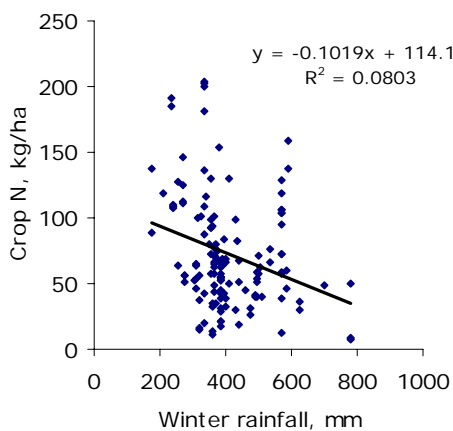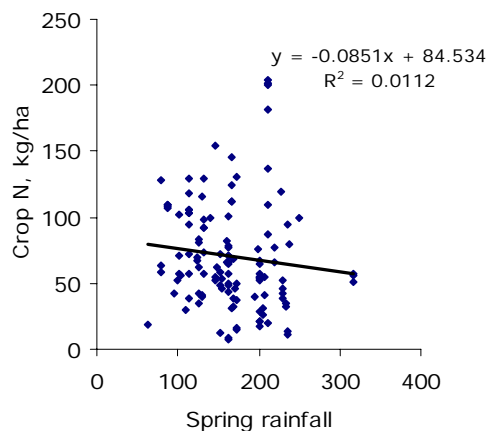

Fig 9. The relationship between cereal crop (winter wheat and winter barley) N uptakes and (a) winter rainfall and (b) spring rainfall.

3.5 Efficiency of SMN Use

The efficiency of both autumn and spring SMN use by winter cereals, as defined in Equation 2 (page 19), was inversely related to the quantity of SMN present (Fig 10). Consequently, the efficiency of SMN use (autumn- or spring-harvest) declined with increases in both autumn SMN (Fig 10a) and spring SMN (Fig 10b).

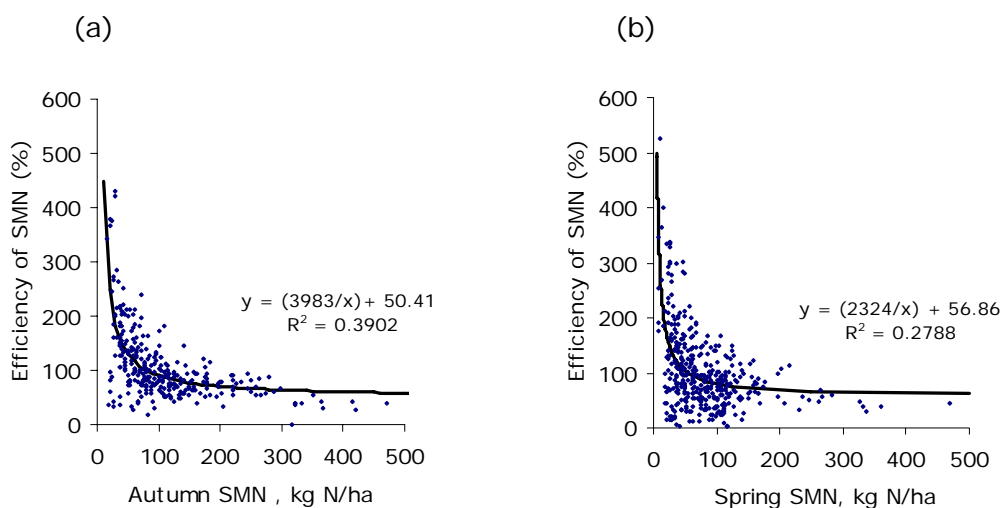(a)   (b)

Fig 10. The relationship between efficiency of SMN use by winter cereals from (a) autumn-harvest and (b) spring-harvest against SMN (0-90 cm) in autumn or spring

Similar inverse relationships between efficiency of both autumn and spring SMN use and quantity of SMN were found for winter cereals grown on a clay loam after cereals, indicating that this relationship was independent of previous crop and soil type.

In contrast to the negative relationship between crop N uptake of winter cereals in spring and sowing date (Fig 7), the relationships between efficiency of autumn (autumn-harvest) and spring (spring-harvest) SMN use and sowing date were relatively weak (R^2 0.0053 and 0.0315 respectively) and slightly positive. Consequently, there was no clear long-term effect of sowing date on the efficiency of SMN use by winter cereals. However, there were strong negative relationships between spring rainfall and efficiency of autumn (Fig 11a) and spring (Fig 11b) SMN use; perhaps indicating enhanced losses of SMN by leaching and/or denitrification in spring when significant rainfall occurs.
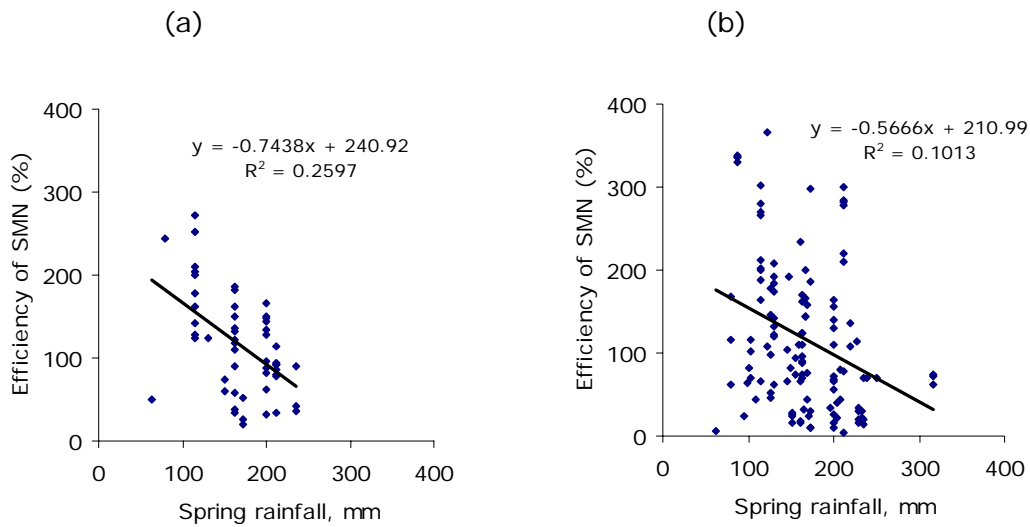
Fig 11 The relationship between efficiency of (a) autumn SMN (0-90 cm) use (autumn-harvest) and (b) spring SMN (0-90 cm) use (spring-harvest) by winter cereals and spring rainfall (mm).

An investigation of the relationship between the efficiency of SMN (0-90 cm) use by winter wheat and its location in the soil profile, using a sub-set of trials, indicated that there was a strong (R^2=0.66) positive relationship (Fig 12a) between the efficiency of use of SMN and the proportion of SMN present in the plough layer (0-23 cm) in autumn. In contrast, the relationship between efficiency of spring SMN use and the proportion in topsoil was poor (Fig 12b). However, efficiencies of spring SMN use were generally greater than those for autumn SMN, indicating that the crop was able to utilise SMN in deeper soil layers more effectively in spring than in autumn.
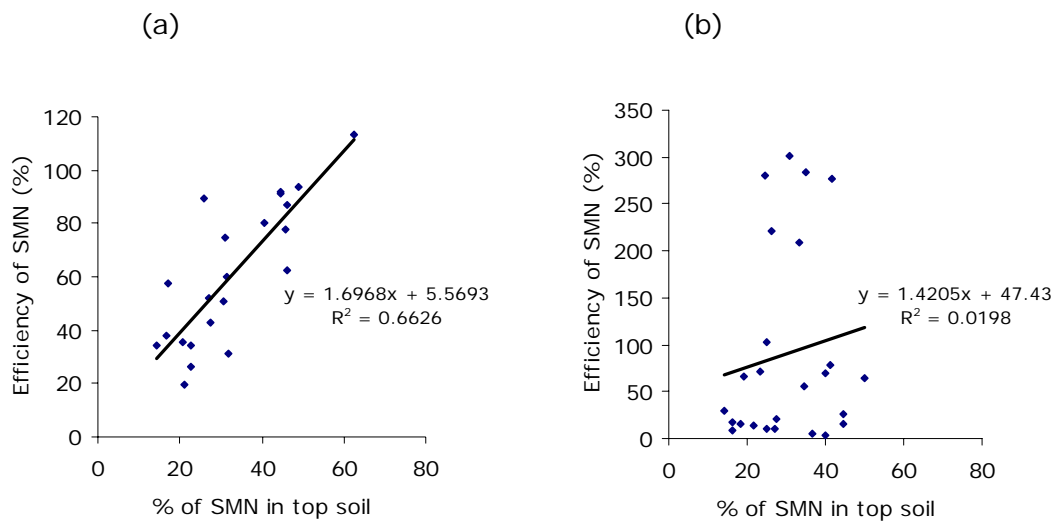
(a)   (b)

Fig 12 The relationship between efficiency of (a) autumn SMN (0-90 cm) use (autumn-harvest) and (b) spring SMN (0-90 cm) use (spring-harvest) by winter wheat and the proportion of SMN present in the plough (0-23 cm) layer.

As with winter cereals, the efficiency of both autumn and spring SMN (0-90 cm) use by winter oilseed rape declined with increasing amounts of SMN (Figs 13a and b) present in autumn.

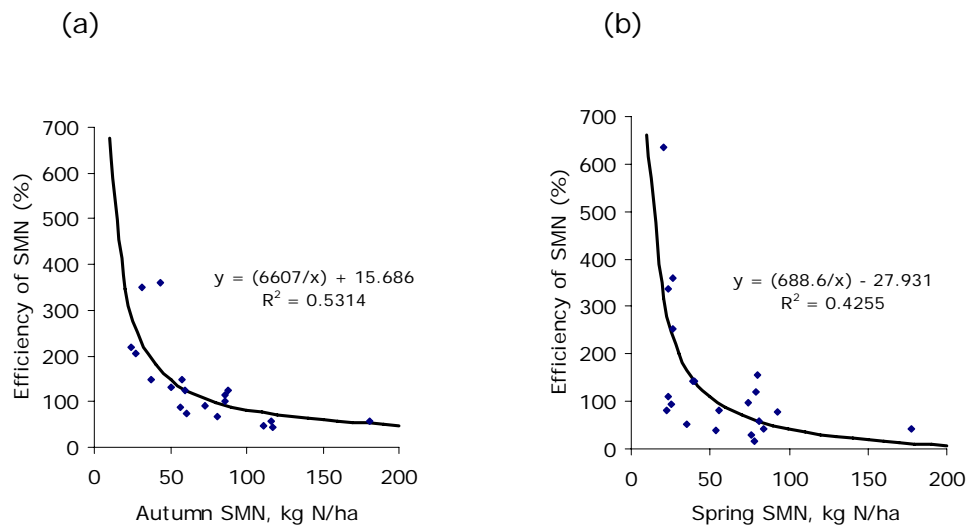(a)   (b)

Fig 13. The relationship between efficiency of SMN (0-90 cm) use by oilseed rape from (a) autumn-harvest and (b) spring-harvest and SMN in autumn or spring.

The inverse relationship between the efficiency of SMN use and SMN (0-90 cm) present in soil in spring under spring barley (Fig 14a) was similar to that for winter cereals and oilseed rape. In addition, the efficiency of SMN use (spring-harvest) by

spring barley showed a negative relationship with sowing date (Fig 14b), similar to that for crop N uptake (Fig 6b), indicating, that later sowing decreased both N uptake and hence efficiency of SMN use by spring barley.

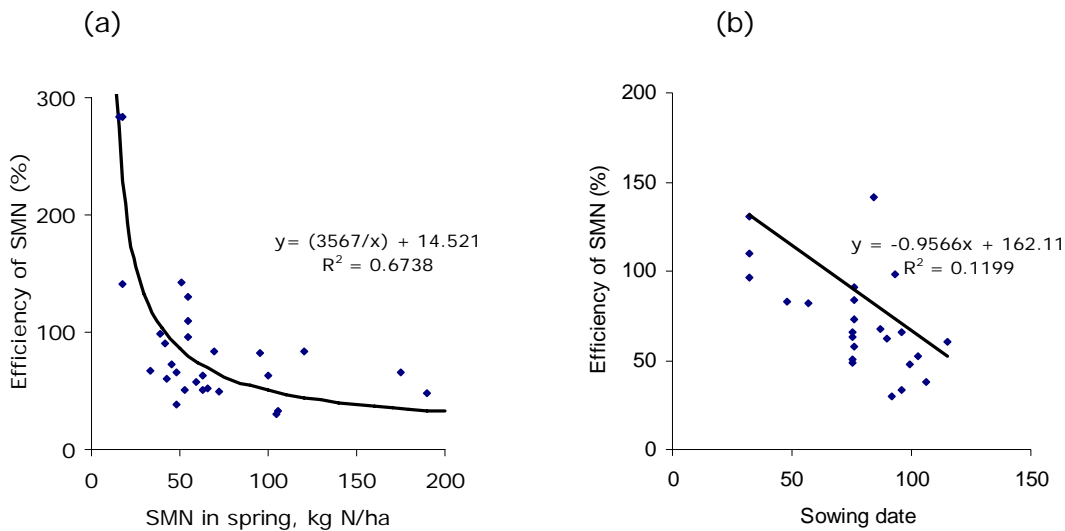(a)   (b)

Fig 14. The relationship between efficiency of SMN use by spring barley (spring-harvest) and (a) SMN (0-90 cm) in spring and (b) sowing date.

In contrast, despite the negative relationships between crop N uptake and sowing date for winter cereals (Fig 7a), there was no strong relationships between efficiency of SMN use and sowing date for these crops; perhaps because their longer growth period provides a greater opportunity for other controlling factors to dominate crop N uptake.

3.6 Effects of Soil Texture

Mean quantities of SMN (0-90 cm) measured in autumn, soon after sowing of winter wheat, ranged from about 80 to 120 kg N/ha (Fig 15) and were similar for most soil types. However, analysis of variance on $\log_e$ transformed data indicated that on average the silty-clay loam contained more SMN than the clay loam. In spring, the mean amounts of SMN present in all five soil categories ranged from 50-100 kg N/ha and in all cases, except for the clay soil, were smaller than those in autumn. The silty-clay loam again contained significantly ($P<0.05$) more SMN than the clay loam, but SMN in the sandy loam was significantly less ($P<0.05$) than in any of the other soil categories. The decrease in SMN over winter was greatest in the sandy loam, indicating that SMN losses during the winter were greatest in free draining sandy soils, as indicated in figure 3.
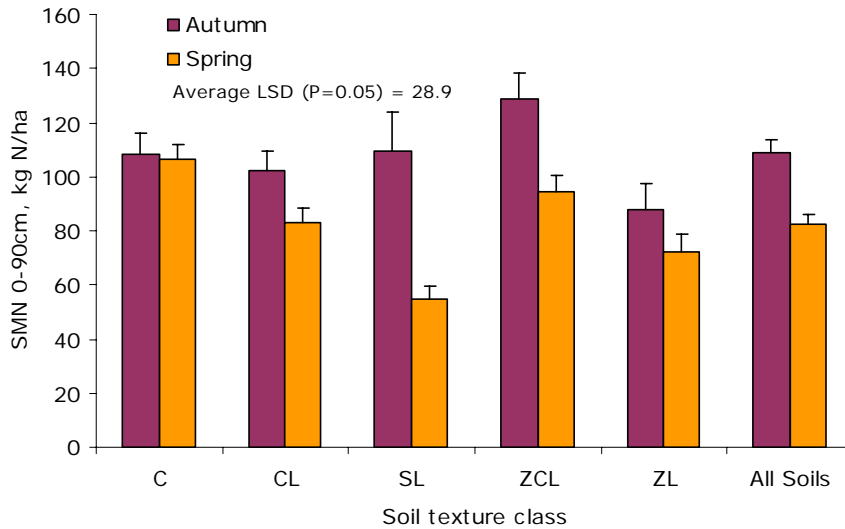
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Fig 15. The effect of soil texture (Sandy loam (SL), Silt Loam (ZL), Clay Loam (CL), Silty Clay Loam (ZCL), Clay (C)) on the mean SMN (0-90 cm, +SE) under unfertilised (Zero-N) winter wheat.

Mean efficiencies of SMN use (autumn-harvest) by winter wheat ranged from 80 to 120%; averaging about 100% over all soils (Fig 16). Efficiencies tended to be greatest where the amounts of SMN were small. Consequently, efficiencies of SMN use were significantly (P<0.05) lower in the silty-clay loam and clay soils compared with the clay-loam and sandy loam soils. Similarly, the SMN in the sandy soils in spring was used with significantly (P<0.05) greater apparent efficiency (spring-harvest) than that in the other soils. Efficiencies of spring SMN use in the clay loam and silt loam soils were intermediate between the sandy loam and the clay and silty-clay loam. The overall mean efficiency of spring SMN use was similar to that for autumn SMN (about 100%). The greater apparent efficiency of use of smaller quantities of SMN was consistent with the relationships between the efficiency of SMN use shown for winter cereals in Figure 10.
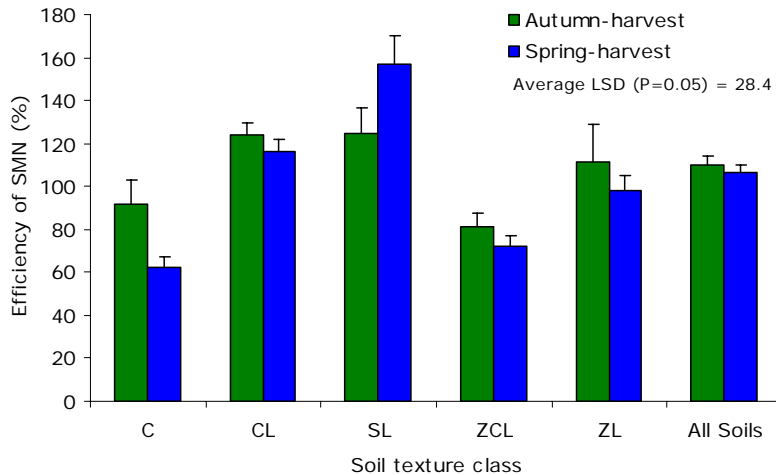
Fig 16. The effect of soil texture on the mean efficiency of SMN (0-90cm) use (+SE) by unfertilised (Zero-N) winter wheat.

3.7 Effects of Previous Cropping

An analysis of the effects of previous crop on the quantity of SMN present in the soil (0-90 cm) in autumn under winter wheat, using log_e transformed data, indicated that significantly smaller (P<0.05) amounts were present following sugar beet compared with all other previous crops (Fig 17).
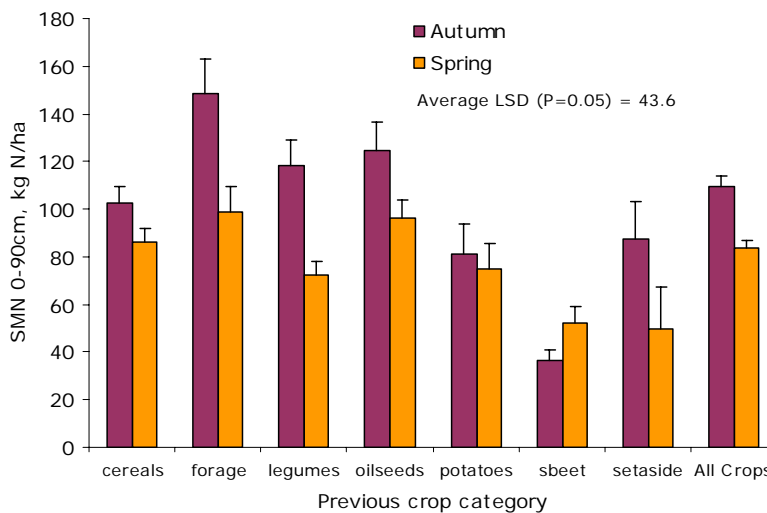

Fig 17. The effect of previous crop on the mean SMN (0-90 cm, +SE) under unfertilised (Zero-N) winter wheat.

Forage and oilseed crops (mostly oilseed rape) left larger amounts of residual SMN compared with cereals. Mean residual SMN following legumes, potatoes and set-aside

were intermediate between those remaining after sugar beet and forage/oilseed crops. In most cases, except after sugar beet, the mean amounts of SMN present following different crops were smaller than those present in the autumn, presumably because some was taken up by the subsequent wheat crops and some was lost. Consequently, differences were less clear cut, but on average residual SMN following sugar beet was still significantly ($P<0.05$) less than that after forage and oilseed crops. Residual SMN in autumn and spring following set-aside were not significantly different from most other arable crops, except sugar beet.

The efficiency of both autumn and spring SMN use by winter wheat when averaged over all previous crops was about 100% (Fig 18). However, efficiency of use of the relatively small amounts of SMN remaining after sugar beet (autumn-harvest) was significantly ($P<0.05$) greater than after other crops. This was consistent with the inverse relationship between efficiency of SMN use and SMN amount (Fig 10); again indicating that efficiency of use of SMN was greater when residual SMN was small. Efficiencies of autumn SMN use following cereals were about 100%; similar to that after oilseeds and set-aside. Efficiency of autumn SMN use following forage and legumes were significantly greater ($P<0.05$) than after cereals, but less than after potatoes and sugar beet. Efficiencies of spring SMN use were generally similar, except following cereals and oilseeds which were significantly lower ($P<0.05$) than for most other previous crops.
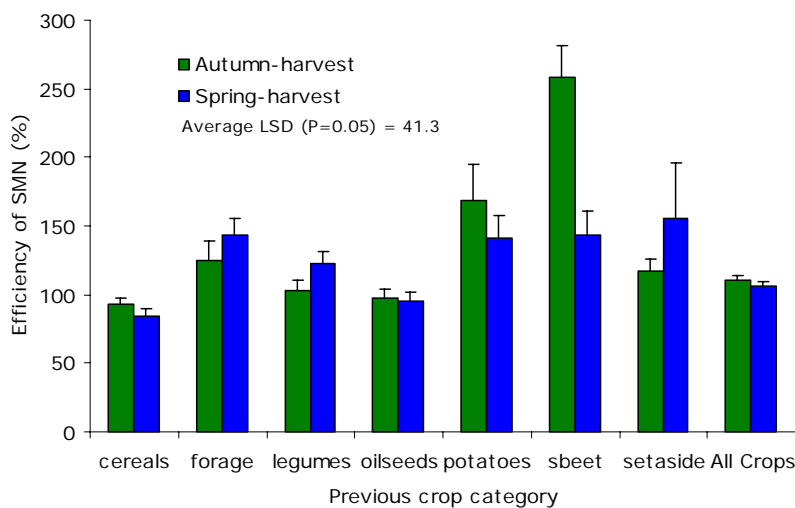

Fig 18. The effect of soil previous crop on the mean efficiency of SMN (0-90cm) use (+SE) by unfertilised (Zero-N) winter wheat.

Efficiencies of use of SMN by unfertilised winter wheat grown on a sandy loam in SE England following ploughing of grass/clover leys of different ages were derived from data published by Johnston *et al.* (1994). Efficiencies of SMN use from spring to harvest ranged from 209 to 301% (Fig 19) and were substantially greater than those estimated from autumn–harvest, which ranged from 78% to 93%. This was largely because crop N uptake as a proportion of the large amount of mineral N present in the soil in autumn was small. In contrast, plant uptake from spring to harvest was large relative to the smaller amount of SMN present in the soils at this time.
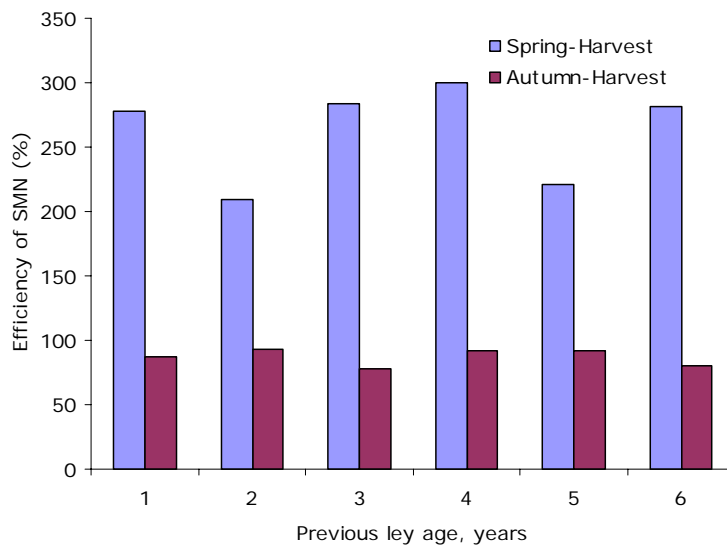

Fig 19. Efficiency of SMN (0-90 cm) use by winter wheat following grass/clover leys of different ages at Woburn (Beds, UK) in 1987.

3.8 Effects of Fertiliser N on Efficiency of SMN Use

The efficiency of use of soil derived N by winter wheat and oilseed rape in the presence and absence of fertiliser N was examined using published data from trials on four soil types in SE England established in 1987 (Macdonald *et al.*, 1997). These trials included plots given ^{15}N-labelled fertiliser (ammonium nitrate) at the recommended rates, in addition to plots which received no fertiliser N. Similarly, the efficiency of SMN use by spring barley was examined using published data from trials in which ^{15}N-labelled fertiliser was applied at rates ranging from 0 to 144 kg N/ha to spring barley in 1986 and 1987 (Glendining *et al.*, 1997).

3.8.1 Winter Wheat

The efficiency of SMN use for winter wheat (with and without fertiliser N) from autumn-harvest and spring-harvest ranged from 3 to 113% (Fig 20). The former was greater than the latter in 6 out of 8 cases, but overall means were not different. Efficiencies of SMN use were generally greater on the silty-clay loam and clay soils compared with the sandy-loam and chalky-clay loam. Grain yields were also greater on the silty-clay loam and clay soils (2.6-7.0 t/ha) compared with the sandy-loam and chalky-clay loam soils (0.4-4.5 t/ha). The low efficiencies of SMN use on the sandy loam were in part because of poor crop growth and N uptake due to severe take-all (*Gaumannomyces graminis*) infection. The lower efficiency of SMN use by unfertilised wheat on the chalky-clay loam was in part a result of pest damage (rabbit grazing). In all cases (except on the clay soil) the apparent efficiencies of SMN use were greater when N was applied.
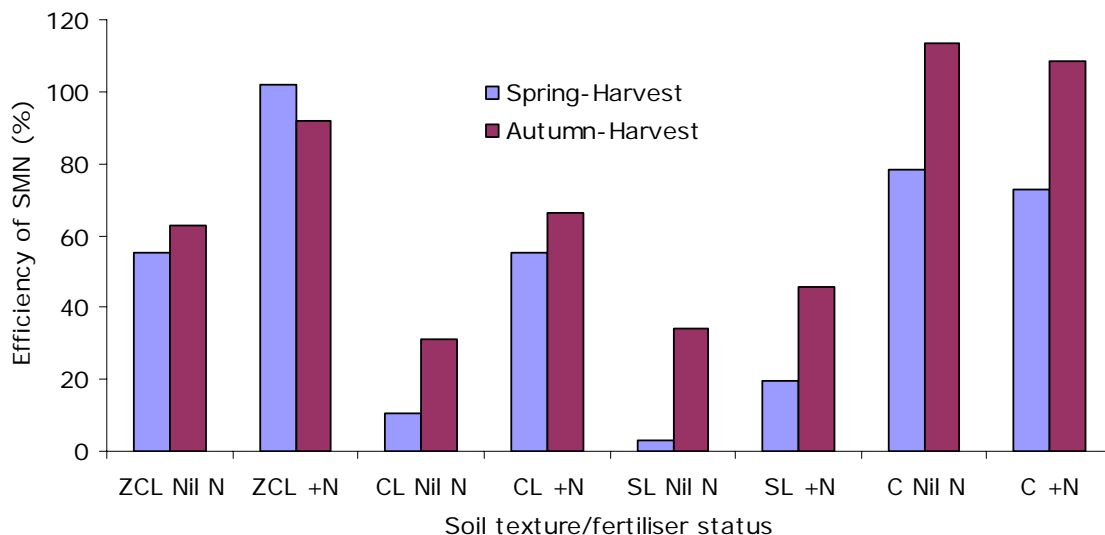
Fig 20. The efficiency of SMN use by winter wheat with (+N) and without (Nil N) recommended rates of ^{15}N-labelled fertiliser at four sites with contrasting soil textures (silty-clay loam (ZCL), chalky loam (CL), sandy loam (SL) and clay (C) soil) in 1987.

The measurement of SMN at harvest in addition to that in autumn, and in spring, was used to calculate an alternative index of SMN use efficiency which expressed crop N uptake as a percentage of the change in the crop N plus SMN content over a given period. This was called the net N efficiency index (Eqn 3). Using this approach

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negative or very large estimates of SMN use efficiency were obtained for unfertilised wheat on the chalky loam, where crop N plus SMN at harvest was smaller than in autumn (at sowing) or in spring, because of pest damage to the crop. Consequently, the estimated net efficiency of SMN at this site was considered unreliable, and was excluded from any analyses (Fig 21a).

$$SMN_{Net} = 100 \times (CN_{T2} - CN_{T1})/((SMN_{T2}+CN_{T2})-(SMN_{T1}+CN_{T1})) \qquad (Eqn\ 3)$$

Where:

SMN_{Net}= Net SMN (0-90 cm) use efficiency by the crop.

CN_{T2}　= Crop N content at harvest

CN_{T1}　= Crop N content at the start of the growth period (autumn or spring)

SMN_{T1} = Soil mineral N content at the start of the growth period (autumn or spring)

SMN_{T2} = Soil mineral N content at the end of the growth period (harvest)

However, for the remaining data, the net efficiency of SMN use ranged from 8 to 317% (Fig 21a) and was least on the sandy soil, where crop N uptake was limited by take-all. In general, efficiencies of use of SMN use for autumn-harvest were greater than those for spring-harvest, because the increase in SMN between the autumn and the SMN plus crop N at harvest was small relative to crop N uptake. However, when an estimate of the SMN leached (SMN_L) in the winter period was include (Equation 4), net SMN use efficiencies from autumn-harvest decreased and were more similar to those for spring-harvest (Fig 21a and b). Nitrate leaching losses on three of the four soils was estimated to be approximately 30 kg N/ha, similar to that reported by Goulding *et al.* (2000), but on the clay soil a value of 15 kg N/ha was used.

$$SMN_{Net} = 100 \times (CN_{T2} - CN_{T1})/((SMN_{T2}+CN_{T2})-(SMN_{T1}+CN_{T1})+ SMN_L) \qquad (Eqn\ 4)$$

Where:

SMN_{Net}= Net SMN (0-90 cm) use efficiency by the crop.

CN_{T2}　= Crop N content at harvest

CN_{T1}　= Crop N content at the start of the growth period (autumn or spring)

SMN_{T1} = Soil mineral N content at the start of the growth period (autumn or spring)

SMN_{T2} = Soil mineral N content at the end of the growth period (harvest)

SMN_L = Estimated SMN leached between $_{T1}$ and $_{T2}$.

Fig 21 Net efficiency of SMN use by winter wheat (a) excluding or (b) including an estimate of N leaching loss over-winter.

3.8.2 Oilseed Rape

Efficiencies of use of SMN by oilseed rape ranged from 53 to 169% (Fig 22) and were generally greater than for winter wheat. However, as with winter wheat, the apparent net efficiency of SMN use tended to be greater for crops given fertiliser N on three of the four soils. Efficiencies from spring-harvest were also greater on these soils than from autumn-harvest. This was most probably a consequence of the relatively large spring/summer N uptake coupled with small spring SMN values.
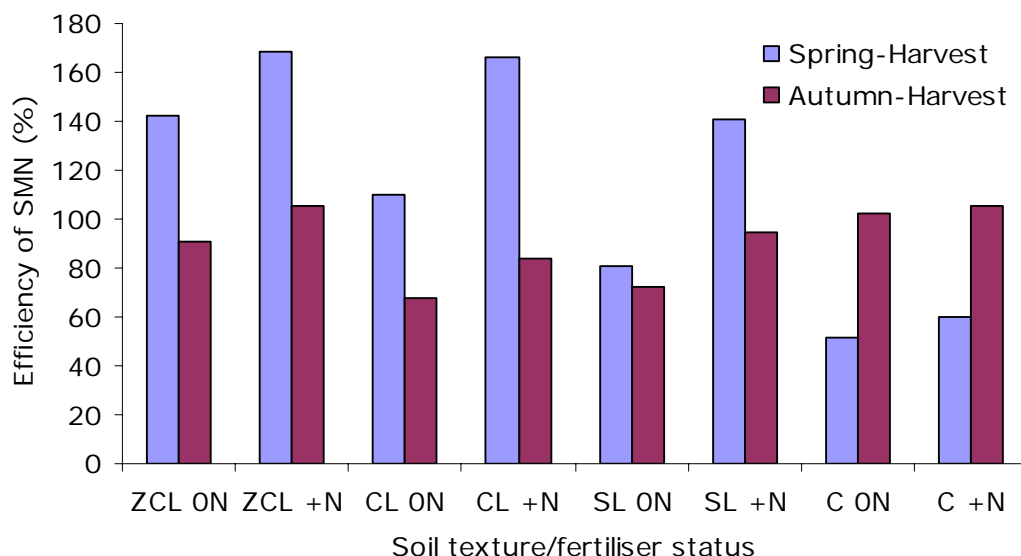
Fig 22. The efficiency of SMN use by oilseed rape with (+N) and without (Nil N) recommended rates of ^{15}N-labelled fertiliser at four sites with contrasting soil textures (silty-clay loam (ZCL), chalky-clay loam (CL), sandy loam (SL) and clay (C) soil) in 1987.

The efficiency of SMN use by oilseed rape in 1987 (spring-harvest) estimated using the net N mineralisation approach (Equation 3) ranged from 25% to 99% (averaging 67% overall). However, the net efficiency of SMN use between autumn and harvest ranged from 87% to 660% (averaging 262% overall) and in most cases was much greater than that estimated using the conventional approach (Equation 1). The uptake of large amounts of mineralised N in surface soil, or from below 90cm, may also have contributed to these large estimates of efficiency. However, as with wheat, when an estimate of over-winter N leaching losses was included (Equation 4) the efficiency of SMN use agreed more closely with that estimated from spring to harvest, and those estimated using the conventional method (Fig 23 a and b).
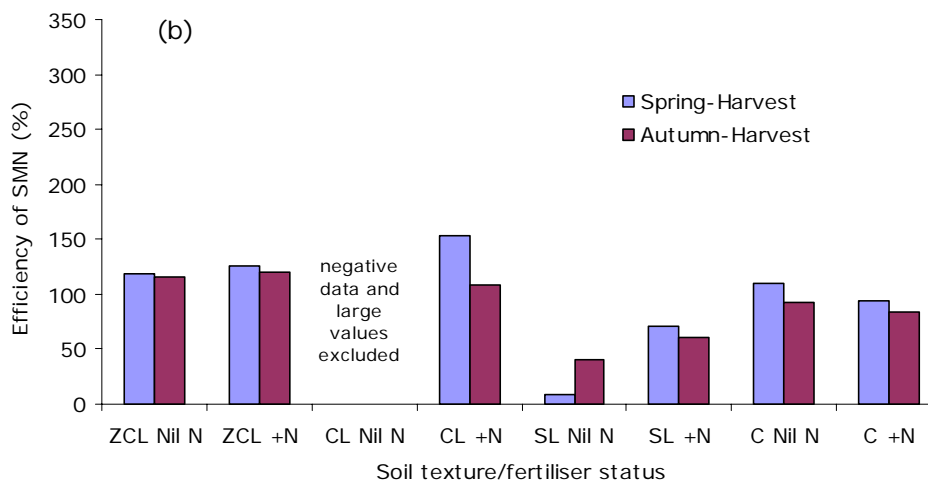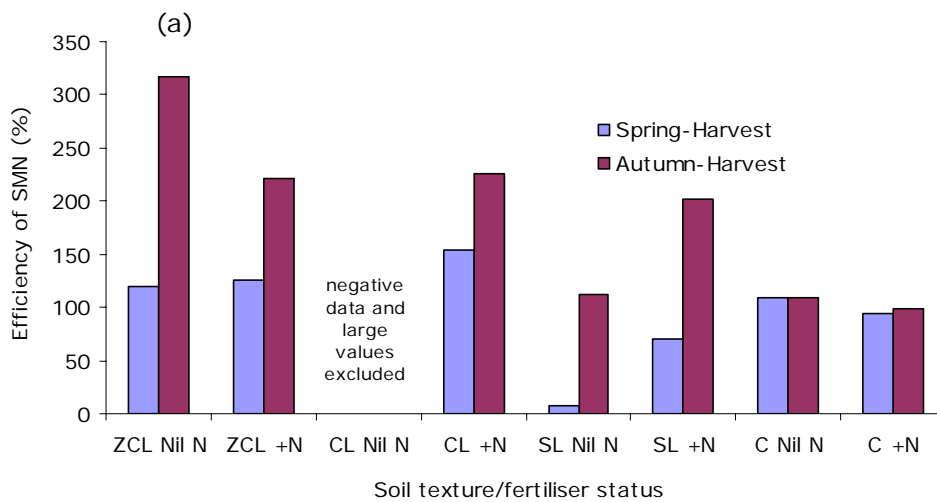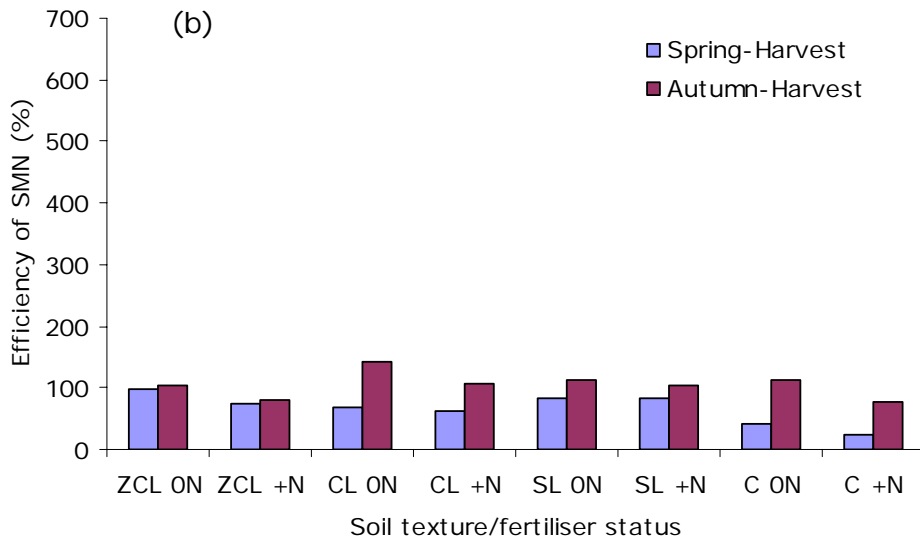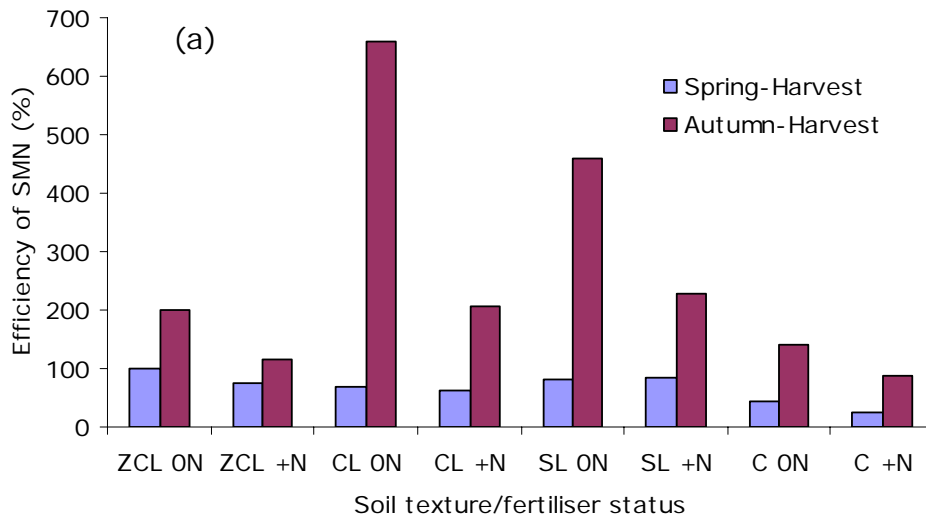
Fig 23. Net efficiency of SMN use by oilseed rape (a) excluding or (b) including an estimate of N leaching loss over-winter.

3.8.3 Spring Barley

Efficiencies of SMN use by spring barley (spring-harvest) grown on plots with contrasting fertiliser/manure treatments in 1986 and 1987 (Fig 24) increased with N fertiliser application rates up to 96 kg N/ha, but declined thereafter (Glendining *et al.*, 1997). In both cases the efficiency of SMN use followed a trend similar to that for grain yield, indicating that efficiency of SMN use declined when the N supply from fertiliser and soil derived N exceeded crop demand. There was evidence to suggest that N applications in excess of crop demand blocked uptake of soil-derived N from deeper soils layers.
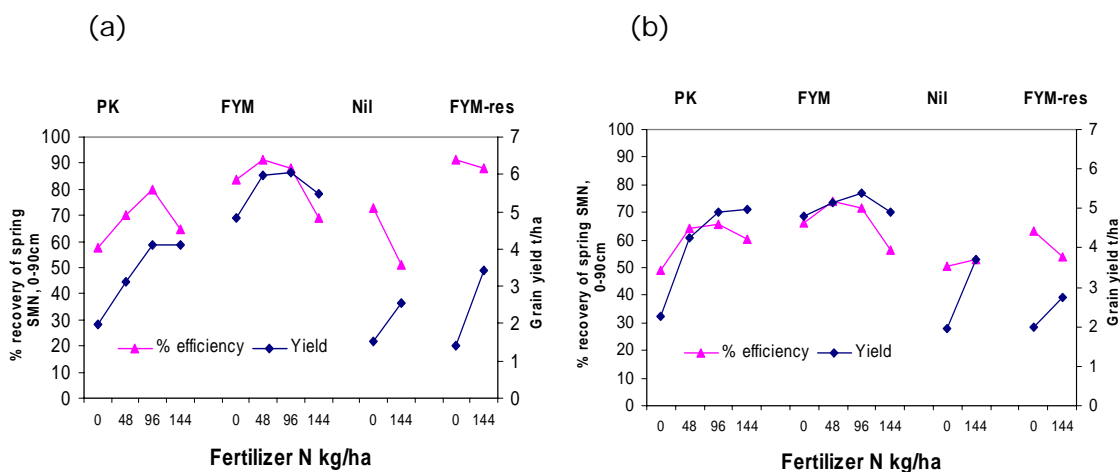
Fig 24. Grain Yield and recovery of SMN (% Efficiency of SMN, Spring-Harvest)) by spring barley on plots with different long-term manure histories at Rothamsted in (a) 1986 and (b) 1987.

4.0 Model Simulations of SMN Uptake by Arable Crops

Model simulations, using the nitrogen turnover model SUNDIAL (Bradbury *et al.*, 1993; Smith *et al.*, 1996), were done to examine in more detail the impact of factors that might affect the efficiency of SMN use in the presence of fertiliser N. SUNDIAL specifically takes in to account post application processes such as denitrification and mineralisation and can thus estimate efficiency in a more complete fashion. In this way an understanding can be gained of the relative importance of processes in soil that determine the efficiency of use of both fertiliser and soil-derived N. Firstly, however, SUNDIAL was tested against a number of experimental datasets from which it was also possible to derive estimates of the efficiency of SMN use in the field. With SUNDIAL validated in this way it was possible to investigate the detail of processes that would be difficult if not impossible to measure.

In addition, model simulations were done with standard datasets using SUNDIAL (Smith *et al.*, 1996) to further examine the likely impact of these factors on crop uptake of SMN and to help identify management practices that could enhance the efficiency of SMN use by arable crops.

4.1 Model validation

The SUNDIAL model is a dynamic model, incorporating descriptions of the major processes of Nitrogen (N) turnover in the soil/crop system on a weekly basis (Figure 25). N dynamics in SUNDIAL are driven by the carbon (C) cycle. Nitrogen may be added to the soil/crop system as inorganic fertiliser, organic manure or by atmospheric deposition. Nitrate and ammonium are taken up by the crop in proportion to the expected yield of the crop and driven by the cumulative temperature since sowing. N and C are returned to the soil, at harvest as stubble and straw, and also throughout the growing season as root exudates, dead leaves and fragments of roots. Partitioning of the C and N from crop debris into biomass and humus during decomposition takes place according to the soil type. The C:N ratios of these organic matter pools are assumed to remain constant. If the C:N ratio in the debris rises, N is immobilised first from ammonium and then from nitrate in the soil. If the debris C:N ratio falls, N is mineralised to ammonium. Ammonium may then be nitrified to nitrate, and nitrate may be lost by denitrification or leaching. SUNDIAL is not a crop growth model and it requires a realistic estimate of crop yield as a model input.
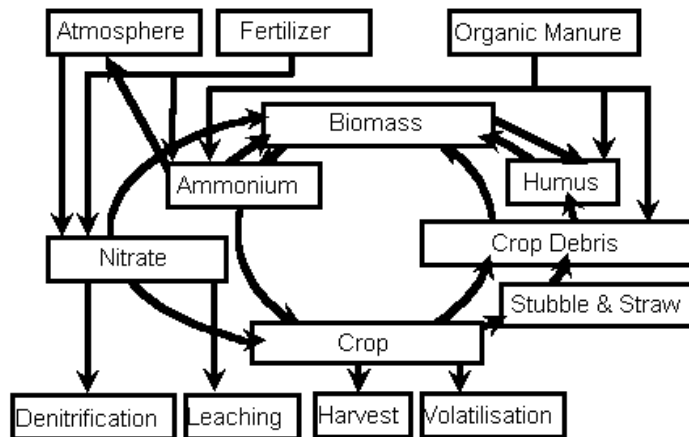
Figure 25. Flow diagram showing the processes in the soil-plant nitrogen cycle simulated by SUNDIAL

SUNDIAL was validated against experimental data from four experiments in which fertiliser N labelled with ^{15}N was applied. In the first three experiments, fertiliser was applied at different rates to experiments on spring barley, winter OSR and winter wheat. In the last experiment, ^{15}N-labelled fertiliser was applied at different depths to winter wheat.

4.1.1 Uptake of soil N at different rates of fertiliser N by Spring Barley

[15]N-labelled fertiliser was applied to spring barley grown at Rothamsted in 1986 and 1987, at four N rates (Glendining *et al.*, 1997; see also section 3.8.3 and Fig 24, page 54). SUNDIAL was used to simulate crop uptake of unlabelled (soil-derived) N, using the actual crop yields as model inputs for the plots with adequate P and K. There was general agreement between measured and modelled N uptake (Figures 26a and 26b), with a maximum difference of 18 kg N/ha. There was a general trend of increasing uptake of unlabelled N with increasing yield, but a decline in uptake at the highest N rate, where there was no further yield response to N. SUNDIAL overestimated the decline in N uptake at the highest N rate in 1986 (Figure 26a).
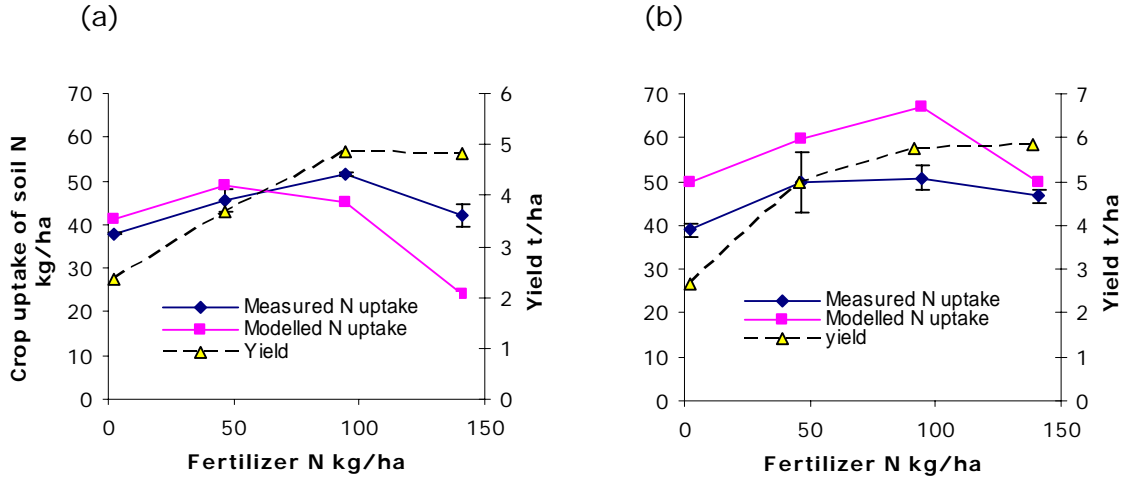
Figs 26a and 26b. Measured and modelled N uptake of soil derived N by Spring
Barley in 1986 (a) and 1987 (b).

4.1.2 Uptake of soil N at different rates of fertiliser N by WOSR

[15]N-labelled fertiliser was applied at two rates (157 and 235 kg N/ha) to WOSR grown
at four contrasting soils in SE England in 1988 (Macdonald *et al.*, 1997). The soil
textures ranged from a sandy loam to a heavy clay. SUNDIAL was used to simulate
the uptake of crop N derived from the soil (i.e. uptake of unlabelled N) at harvest,
using actual crop yields as model inputs. There was very good agreement between
measured and modelled crop uptake of soil derived N at all sites and N rates, with a
maximum difference between measured and modelled of 5 kg N/ha or 3% (Figures
27a and 27b). It can be seen that a greater proportion of the N taken up by the crop
is derived from soil N at the lower fertiliser N rate, across all the sites (Figure 27b).

(a)

[Chart (a): Y-axis "Modelled crop N from soil kg/ha" (35 to 55), X-axis "Measured crop N from soil kg/ha" (35 to 55), with N1, N2 and 1 to 1 line]

(b)

[Chart (b): Y-axis "Modelled % crop N from soil" (20 to 40), X-axis "Measured % crop N from soil" (20 to 40), with N1, N2 and 1 to 1 line]
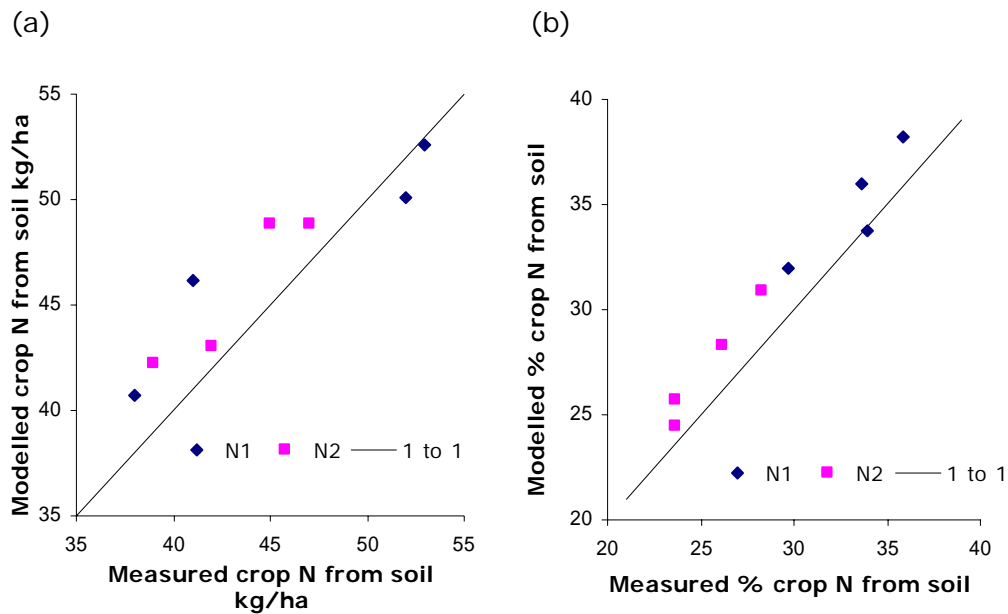
Figs 27a and 27b. Measured and modelled WOSR crop N uptake derived from soil N (0-150cm) at 2 fertiliser rates (N1 = 157, N2 = 235kgN/ha), from four contrasting sites (a) crop N uptake derived from the soil kg/ha (b) % of crop N uptake derived from the soil.

Thus it was apparent that, providing realistic crop yields were used, SUNDIAL was able to accurately simulate the recovery of soil N for oilseed rape given fertiliser N.

4.1.3 Uptake of soil N at different rates of fertiliser N by winter wheat

In 1984 the first crop of winter wheat following six different rotations on the Woburn Ley-Arable experiment received ^{15}N-labelled fertiliser at four different rates (nominally 0, 70, 140 and 210 kg N/ha) to examine the effect of fertiliser N and previous rotation on crop recovery of fertiliser N and soil derived N. Experimental details are given by Macdonald *et al.* (1989); crop yields and N uptakes are provided by DS Powlson (unpublished data). SUNDIAL was used to simulate the uptake of soil N, at a range of fertiliser N rates, and with different soil organic matter contents, as determined by the previous rotation. The soil is a sandy loam, with approximately 0.8% C for the continuous arable rotations and 1.2% C for the three year grass ley / two year arable rotation (Rothamsted Research, 2006). Crop recovery of ^{15}N-labelled fertiliser at the different N rates ranged from 65 to 82%, with a further 9-21% remaining in the soil at harvest.

SUNDIAL was run with a preceding crop of winter wheat at all rotations, to allow the model to stabilise, before the application of the labelled fertiliser N. This preceding crop would be expected to have only a marginal effect on the fertility of the soil. Measured crop yields and total crop N uptake were used as inputs to the model.
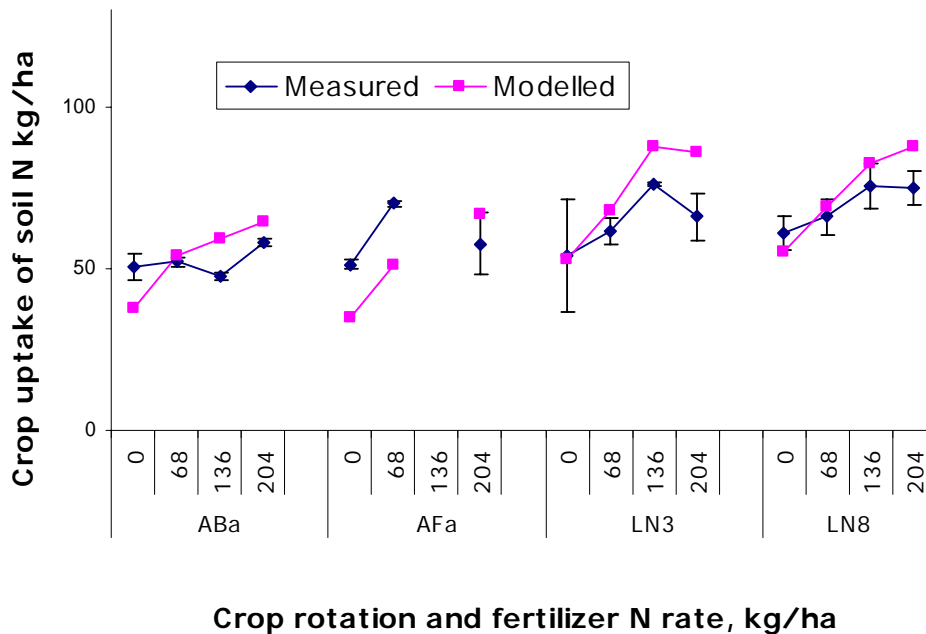
Fig 28. Measured and modelled crop N uptake of soil derived N by winter wheat at the Woburn Ley-arable Experiment, 1984 (measured data from DS Powlson, unpublished). Bars show standard errors of the mean.

There was good agreement between measured and simulated crop uptake of soil N after the two arable rotations ABa and AFa (barley/barley/beans and fallow/fallow/ beans) and after the three and eight year grass leys given fertiliser N (LN3 and LN8). The maximum difference was 20 kg N/ha. For all rotations, measured crop uptake of soil N increased with fertiliser N rate as yields increased, until there was no further response to fertiliser N. There was a decline in soil N uptake at the highest fertiliser N rate after the LN3 and AFa rotations. The SUNDIAL simulations also showed this trend. SUNDIAL considerably underestimated the uptake of soil N after the two grass-clover based rotations (three and eight year grass/clover leys, data not shown). This is not surprising, as SUNDIAL was designed to predict N turnover under annual arable crops. Further adaptation would be required to enable the model to simulate the turnover of N under perennial forage legumes, which was outside the scope of this project.

4.1.4 Recovery of soil mineral N from different depths

Winter wheat on Hoos Field, Rothamsted, received ^{15}N-labelled fertiliser, applied as KNO_3 in May 1983. It was applied at a depth of 0, 60 and 120cm, at an equivalent rate of 40 kg N/ha (DS Powlson, unpublished data). Labelled N was applied beneath the crop by augering three holes from outside the sample area at an angle and injecting ^{15}N-labelled KNO_3 solution. Earlier in the spring 100 kg N/ha of unlabelled fertiliser N was applied to the surface. At harvest, the crop recovered 68% of the surface-applied ^{15}N-labelled fertiliser. The proportion of the labelled nitrate recovered by the crop decreased with increasing depth (Fig 29). Recovery of nitrate placed at 60cm depth was only 79% of that recovered from surface applied N, and recovery of nitrate at 120 cm depth was even less, only 68% of that applied to the surface.

SUNDIAL was used to simulate the recovery of labelled N at different depths, by modifying the model to allow the addition of labelled inorganic N to the 0-50, 50-100 or 100-150cm soil layers. For convenience, the recovery of this labelled N is shown at the mid-points of these layers, i.e. at 25, 75 and 125 cm, which are comparable to the depths used in the field experiment (Fig 29). Measured total crop N uptake was used as an input to the model.
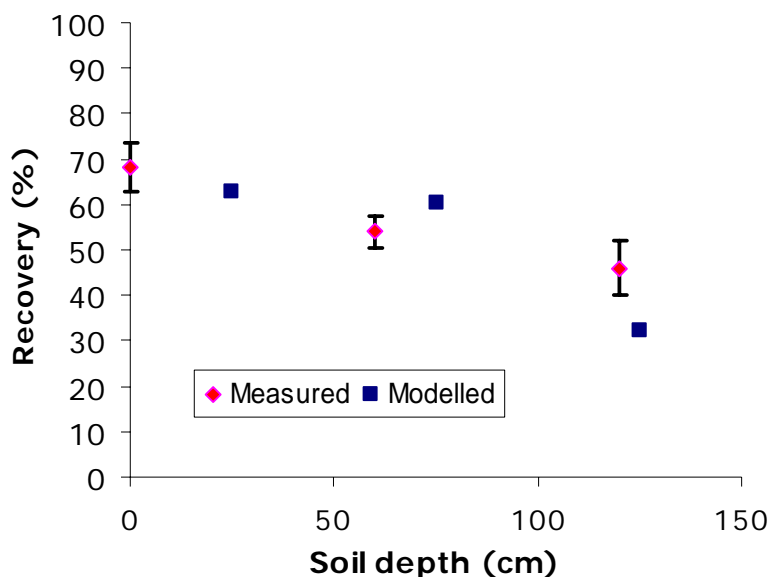
Fig 29. Measured and modelled % crop recovery of labelled N placed at different depths (measured data from DS Powlson, unpublished). Winter wheat, 1983, Rothamsted. Bars show standard errors of the mean.

There was reasonable agreement between the SUNDIAL simulations and the measured data, with the simulations confirming that the proportion of fertiliser N recovered by the crop declined with increasing depth of placement. The results of this simulation give us some confidence that we can use SUNDIAL to investigate the effect of depth of SMN on the efficiency with which it is used by the crop.

4.2 Investigation of factors that might influence efficiency of SMN use

The SUNDIAL simulations of ^{15}N-labelled fertiliser in section 4.1 confirmed the ability of the model to predict the crop uptake of soil-derived N when fertiliser N is applied. As there is very little data which allows the effects of fertiliser N on the efficiency of use of SMN to be directly investigated, the SUNDIAL model was used to investigate some of the main factors involved using standard datasets. These included crop type, SMN amount and distribution, soil type (texture and organic matter content) and rainfall.

All runs were initialised with four years of continuous winter wheat, with standard inputs (Rothamsted conditions). Fertiliser N applications were optimised by the model, to ensure the expected crop yields were achieved (Table 2), without allowing SMN to accumulate. Soil Organic Matter (SOM) was set at the start of the run; otherwise conditions were only varied for the one test year. Note that the SUNDIAL simulations were for 0-150cm, rather than the 0-90cm usually measured for SMN.

Table 2. Crop yields used in the SUNDIAL simulations (t/ha at 85%DM):

	Sand	Loam	Clay
Winter Wheat	8.0	9.0	9.0
Spring Barley	5.5	6.5	6.5

4.2.1 Model Comparisons
1) Two crop types - winter wheat and spring barley
2) Three soil types - sand, loam and clay
3) Two SOM levels - low and normal. Low SOM is 2/3 x normal
4) Three rainfall classes - wet, normal and dry: normal is Rothamsted (685mm, 30 year mean), dry is Rothamsted/1.25 (548mm), wet is Rothamsted x 1.25 (855mm).
5) Four SMN profile distributions (NO_3 + NH_4): Large, small, topsoil and subsoil. Large and small are uniformly distributed down the profile (0-150cm) – small is 80kgN/ha, large is 150 kg N/ha. Topsoil and subsoil are both 150 kg N/ha unevenly distributed down the profile: Topsoil: 100kg 0-25cm, 50kg 25-150cm; subsoil: 35kg 0-50cm, 115kg 50-150cm.
6) Two times of setting the amount of SMN in the profile – autumn and spring. Autumn is October 1st, spring is February 1st (before any fertiliser N is applied).

In total 288 simulations (2 crops x 3 soil types x 2 SOM x 3 rain x 4 SMN distributions x 2 timings) were done. Output from all of the model simulations was used to make comparisons between specific factors, unless stated otherwise, e.g. soil type effects were the mean of all crop x SOM x rain x SMN distributions. In all cases timings of setting the amount of SMN in the profile (October or February) were considered separately.

4.2.2 Calculation of Efficiency of Recovery of SMN

Sundial has the facility to trace ^{15}N-labelled nitrogen applied to the soil. This has proved very useful in the interpretation of experiments where fertiliser N was so labelled. Here we use this facility to distinguish between native and applied N and extend the facility to trace the fate of other (non-fertiliser) N in the soil by labelling other nitrogen pools. In this project SUNDIAL was modified to include the facility to 'label' all the SMN in the profile on October 1st or February 1st.

1) Fertiliser N is labelled, crop uptake of **unlabelled** N is taken as a proxy for the uptake of SMN (as in many of the experiments we have looked at). SSMN use efficiency is calculated as:

$$SSMN_{eff} = 100 \times (CNU_{T2} - CNU_{T1})/SMN_{T1} \qquad \text{(Equation 5)}$$

Where:

$SSMN_{eff}$ = Efficiency of SMN (0-150 cm) use by the crop as calculated by SUNDIAL

CNU_{T2} = Crop N content of unlabelled N at harvest

CNU_{T1} = Crop N content of unlabelled N at the start of the growth period (autumn or spring)

SMN_{T1} = Soil mineral N content at the start of the growth period (autumn or spring)

Unlabelled N is all of the soil N which is not derived from fertiliser – i.e. SMN in October or February, plus any more N mineralised.

This gives two measures of efficiency:

a) SMN set in October, crop uptake of unlabelled N October-harvest (Winter Wheat only)

b) SMN set in February, crop uptake of unlabelled N February-harvest (Winter Wheat and Spring Barley).

2) **SMN is labelled** in October or February. Crop uptake of labelled N is taken as a proxy for the uptake of SMN. SSMN use efficiency is calculated as:

$$SSMN_{eff} = 100 \times (CNL)/LSMN \quad \text{(Equation 6)}$$

Where:

$SSMN_{eff}$ = Efficiency of SMN (0-150 cm) use by the crop as calculated by SUNDIAL

CNL = Crop N content of labelled N at harvest

LSMN = Labelled soil mineral N at the start of the growth period (autumn or spring)

This is different to the measurements of the uptake of N by zero-N treatment crops or by the uptake of unlabelled N by crops given ^{15}N-labelled fertiliser, because it excludes N mineralised after sampling.

This gives two measures of efficiency:

   c) LSMN set in October, efficiency October-harvest (Winter Wheat only)
   d) LSMN set in February, efficiency February-harvest (W Wheat and Spring Barley)

Results

4.2.3 Effects of Crop Type and Method of Calculating %SSMNeff

Overall, there was little difference between winter wheat and spring barley in the SMN use efficiency, measured in the period February–harvest (Fig 30). Using the method given in equation 5 (uptake of unlabelled N when fertiliser N is applied), the mean % SSMNeff was 55% for winter wheat and 61% for spring barley, within the range calculated from field measurements (see figs 20 and 24 for winter wheat and spring barley respectively). Note that the efficiency has been calculated over 0-150cm, so would tend to be lower than that calculated over 0-90cm. The % SSMNeff was much lower when calculated by the method given in equation 6 (uptake of labelled N when labelled SMN is applied), as this is a direct calculation of efficiency, based only on the SMN present at a particular time in spring and does not include subsequent mineralisation of soil N. With this method the mean values were 31% for spring barley and 28% for winter wheat (0-150cm). Whilst this approach may provide estimates of efficiency of SMN use closer to the 'true' value of the efficiency of use of SMN for a given instant in time, they are almost certainly subject to wide variation.
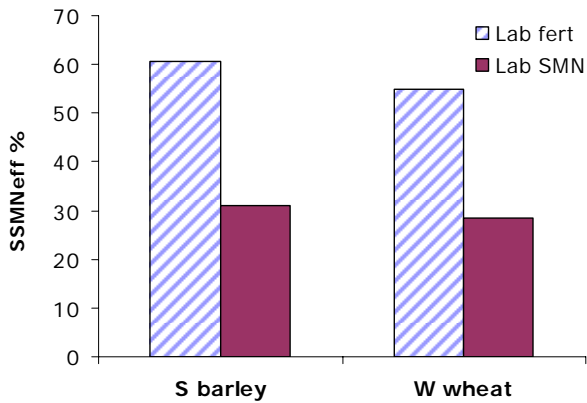
Fig 30. SUNDIAL simulations of % SMN use efficiency (SSMNeff %) for winter wheat and spring barley, February-harvest, showing the two different methods of estimating SSMNeff %.

4.2.4 Effects of Soil Type

The SUNDIAL simulations showed a decline in % SMN use efficiency with decreasing clay content, with clay soils being most efficient and sandy soils least. This effect was greatest when calculating efficiency from October-harvest (Fig 31). In both wheat and spring barley, mean SSMNeff % was 20% less in sandy soils than clay soils, spring-harvest. There was little difference between clay and loam soils. Trends were similar when SSMNeff% was calculated by labelling the SMN (Eqn 6; data not shown).

Fig 31. SUNDIAL simulations of the effect of soil type on % SMN use efficiency (SSMNeff %) for Winter wheat (WW) and Spring barley (SB). Efficiency is calculated as the uptake of unlabelled N when labelled fertiliser N is applied. Efficiency is calculated over two periods, October-harvest (WW only) and February-harvest.

This was due to greater losses of N from the sandy soil, e.g. for winter wheat, October-harvest, 20 kg N/ha more N was lost (by leaching and/or denitrification) from

the sandy soil than the clay soil, mean of all simulations. When the SMN was labelled, total losses of labelled N from the sandy soil were 12 kg N/ha greater than from the clay soil, February-harvest (winter wheat, mean of all simulations).

4.2.5 Effects of Soil Organic Matter Content

The SUNDIAL simulations suggest that SMN is used less efficiently under conditions of low soil OM than normal OM (Fig 32), when SSMNeff% is calculated according to equation 5 (uptake of unlabelled N, ^{15}N-labelled fertiliser applied). In these simulations, 'normal' soil OM is the standard value for long-term arable soils, as used by SUNDIAL (Smith *et al.*, 1996: 25, 36 and 44 t C/ha for sand, loam and clay, respectively). Low is 2/3 x normal. The effect is more pronounced when SSMNeff% is calculated October-harvest than February-harvest. In both winter wheat and spring barley, mean SSMNeff % was 8% less in low OM soils than standard OM soils, February-harvest, compared to 15% less for winter wheat, October-harvest. The reason for the lower efficiency with low OM soils is that less N is mineralised, so less unlabelled N is available to be taken up by the crop. SSMNeff% is calculated from the crop uptake of all unlabelled N, both SMN and mineralised soil N.
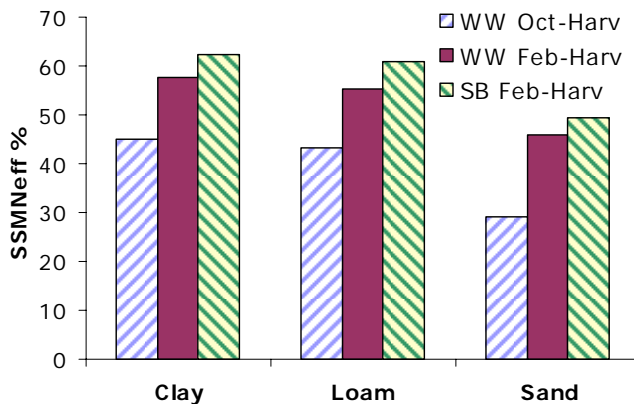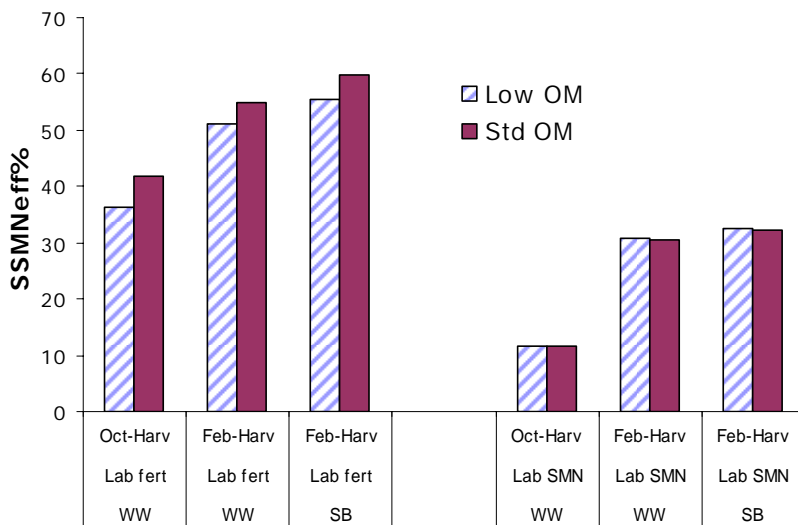

Fig. 32. SUNDIAL simulations of the effect of soil organic matter content on % SMN use efficiency (SSMNeff %) for Winter wheat and Spring barley. Efficiency is calculated as the uptake of unlabelled N when labelled fertiliser N is applied, or as the uptake of labelled SMN. Efficiency is calculated over two periods, October-harvest and February-harvest.

When SSMNeff% was calculated using Eqn 6 (labelled SMN), there was very little difference between low and standard SOM content (Fig 7). With this method,

SSMNeff% is calculated from the uptake of labelled SMN only. Soil OM content had no effect on the crop uptake of the labelled SMN.

4.2.6 Effects of Rainfall

The SUNDIAL simulations show an interaction between rainfall and the amount of SMN, with wet conditions leading to a reduction in SMN use efficiency under conditions of high SMN content (Fig 33). This is most pronounced in the period October-Harvest for winter wheat (Fig 33a), with a smaller effect between February and harvest. Spring barley shows a similar reduction in efficiency with wet conditions over the period February-harvest (Fig 33b). There is a similar trend of a reduction in the efficiency of use of SMN with wet conditions when efficiency is calculated by equation 6, i.e. uptake of labelled SMN. This is due to larger losses from the high SMN treatment under wet conditions. On average, total N losses October-harvest under winter wheat from the high SMN treatment were 67, 48 and 23 kg N/ha more than from the low SMN treatment from the wet, medium and low rainfall treatments, respectively. Under spring barley, February-harvest, the corresponding total N losses were 10, 2 and 4 kg N/ha more from the high SMN treatment, from the wet, medium and low rainfall treatments, respectively.

(a)   (b)
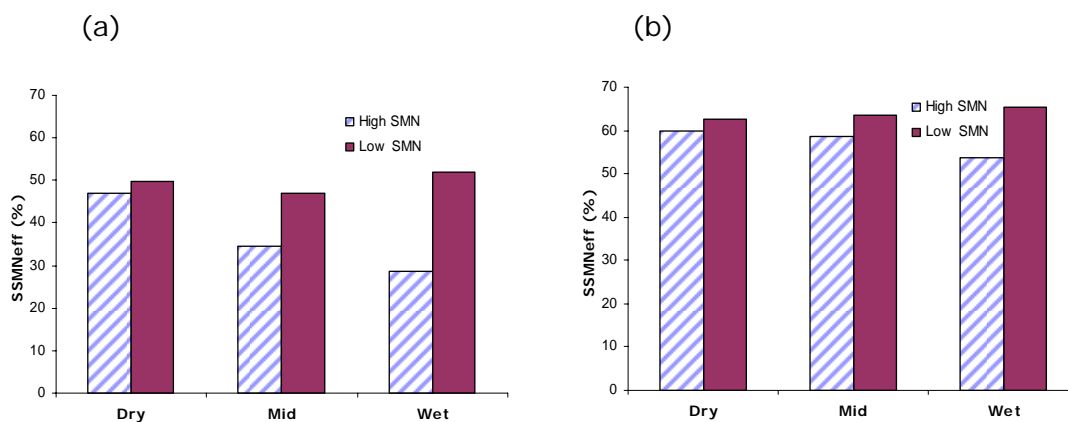
Fig 33. SUNDIAL simulations of the effect of rainfall on % SMN use efficiency (SSMNeff %) for Winter wheat, October-harvest (a) and Spring barley, February-harvest (b). Efficiency is calculated as the uptake of unlabelled N when labelled fertiliser N is applied.

4.2.7 Effects of SMN Amount and Distribution

a) Large vs small amounts of SMN

The SUNDIAL simulations suggest that larger amounts of SMN are used less efficiently than small amounts, when SSMNeff % is calculated according to equation 5 (Fig 34).

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This is particularly apparent for winter wheat, October-harvest and spring barley, February-harvest. This supports the experimental evidence, when %SMNeff is calculated from zero-N trials, (Fig 10 for winter wheat, Fig 14a for spring barley) or as the uptake of unlabelled N when labelled fertiliser N is applied. However, when SSMNeff % is calculated according to equation 6, the reverse appears to occur, with the larger amount of SMN being used more efficiently than the small amount. Equation 6 calculates SSMNeff% from the crop uptake of **labelled** SMN. The pool of labelled SMN is diluted by (unlabelled) mineralised soil N and fertiliser N. The dilution effect is greater for the smaller amount of SMN than the larger amount, thus the efficiency of use is smaller. In contrast, in Equation 5, SSMNeff% is calculated from the uptake of **unlabelled N**, so the (unlabelled) mineralised N increases the size of this pool proportionally more for the low SMN compared to the high SMN.
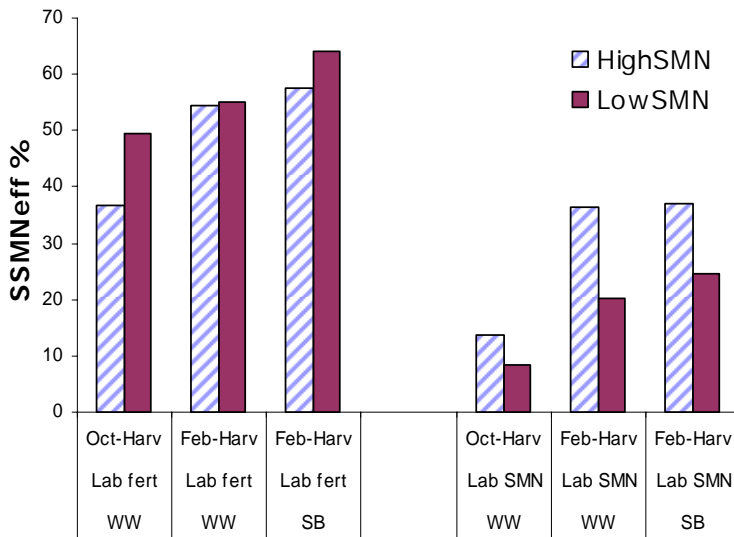
Fig 34. SUNDIAL simulations of % SMN use efficiency for Winter wheat and Spring barley, showing the two different methods of estimating SSMNeff, with low and high SMN contents (80 and 150 kg N/ha, 0-150cm). SSMNeff is calculated for February-harvest for both crops, and also for October-harvest for winter wheat.

b) Topsoil vs Subsoil SMN

The SUNDIAL simulations included investigating the effects of placing the majority of SMN (150 kg N/ha) either in the topsoil (0-25cm) or in the subsoil (50-150cm). SMN mainly in the topsoil was used a little more efficiently by winter wheat than that mainly in the subsoil (35.7 and 34.3 % respectively) October-harvest. When calculated from February-harvest, the difference was much greater with a clear

indication that SMN mainly in the subsoil was used less efficiently than that mainly in the topsoil. This effect was greatest in sandy soils (Fig 35a) or under wet conditions (Fig 35b), for both winter wheat and spring barley, situations when leaching losses were greatest. When SMN use efficiency was calculated by labelling the SMN, the same trend was apparent.
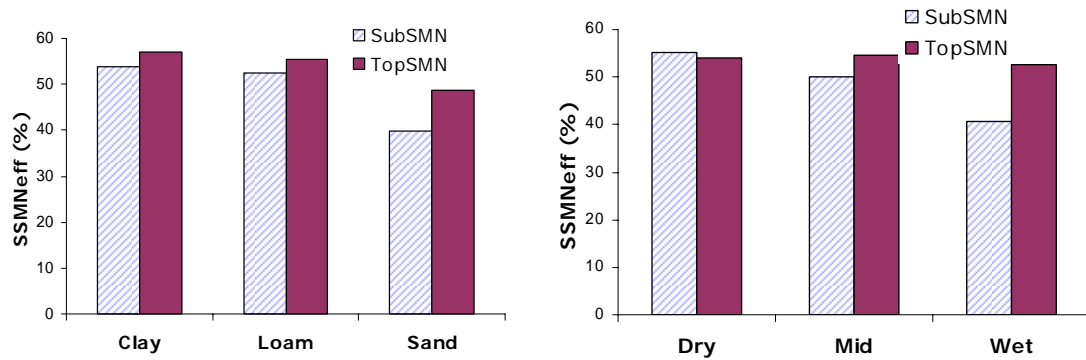
Fig 35. SUNDIAL simulations of % SMN use efficiency for winter wheat, with SMN (150kgN/ha, 0-150cm) either mainly in the topsoil or subsoil, showing the effect of soil type (a) and rainfall (b). SSMNeff is calculated for February-harvest, by labelling the fertiliser N.

The modelling results appear to disagree with the findings in the data compilation (Fig 12), where placement of SMN in the profile appeared to have a greater influence in autumn than spring. However, the model simulations required large amounts of SMN in the profile in October, (150 kg N/ha, 0-150cm), to ensure that there was sufficient SMN present in the spring. If less SMN had been available in the autumn, then depth of SMN may have had a greater effect. Only 20 kg N/ha of crop N uptake came from SMN present in October, compared to 55 kg N/ha from SMN present in February. SUNDIAL simulated that losses of SMN (by leaching and denitrification) were greater from SMN mainly in the subsoil than the topsoil October-harvest (75 and 65 kg N/ha, respectively). Total losses February-harvest were much lower, but with a greater difference between subsoil and topsoil SMN (45 and 25 kg N/ha, respectively).

5.0 Discussion

Crop N uptake and Efficiency of SMN Use by Winter Cereals

The linear plus exponential regression model which described the relationship between winter cereal crop N uptake and SMN in the autumn (Fig 1a) indicated that for winter cereals uptake of SMN per kg of SMN was relatively constant up to about 200 kg/ha of SMN, but that as SMN increased uptake declined. In contrast, the regression model describing the relationship between crop N uptake and SMN in spring (Fig 1b) showed that uptake of spring SMN was relatively constant up to about 300 kg N/ha, indicating that spring SMN may have been used with greater efficiency than that present in autumn, perhaps because of the greater potential for N losses over-winter. The SUNDIAL simulations also showed that spring SMN was used more efficiently than autumn SMN, especially under conditions of high SMN content (150 versus 80 kg N/ha, Fig 34). The greater decline in SMN between autumn and spring on the sandy soils (Fig 3) indicates that nitrate leaching losses over winter were greatest on sandy soils and almost certainly decreased the efficiency of SMN use. Whilst nitrate leaching accounts for a substantial proportion of the SMN lost from arable soils in winter, gaseous N losses by denitrification may also account for some of this N loss, particularly in the early autumn when the soil temperatures are still relatively high.

The SUNDIAL simulations showed a decline in SMN use efficiency with clay content, with clay soils being most efficient and sandy soils the least, due to greater losses of N from the sandy soils, especially over winter (Fig 31). The generally smaller crop N uptakes in spring, associated with later sowing (Fig 7a), was presumably a result of greater N leaching losses prior to crop establishment (Macdonald *et al.*, 2005). Conversely, early sowing tended to enhance crop N uptake. Consequently, early sowing may help minimise losses of SMN in the early autumn. However, sowing date had little effect on N uptake at harvest, indicating that N uptake later in the season was controlled by factors which became more dominant during the rapid growth phase of the crop in spring/summer (e.g. temperature, rainfall, pests, disease, weeds etc). In addition, the negative effects of increasing winter and spring rainfall on crop N uptake (Fig 9) may also have been the result of enhanced SMN losses by leaching and denitrification. High rainfall may have been associated with poor growth conditions, such as lower temperatures and/or higher disease pressures, but data were not available to verify this. A comparison of cereal crop N uptake by past and recent crops

did not reveal any clear differences in the efficiency of SMN use between old and newer cereal cultivars.

The relative importance of possible mechanisms underlying the inverse relationship between amount and efficiency of SMN use by winter cereals (Fig 10) are not certain, but decreasing efficiency of SMN use with increasing SMN is likely to be associated with a greater risk of SMN losses when large amounts of residual SMN are present, and also uptake being limited by crop demand, especially in the early winter when the risk of nitrate leaching is greatest. The greater efficiencies of SMN use observed where SMN was small might reflect crops being able to assimilate small quantities of SMN relatively quickly, whilst the risk of large SMN losses is small. This is consistent with the negative relationship between efficiency of SMN use and spring rainfall (Fig 11), presumably because of enhanced SMN losses by denitrification and/or movement of SMN below the crop rooting depth. Gaseous N losses in early autumn and spring are almost certainly enhanced where SMN is large (Addiscott and Powlson 1992; Smith *et al.*, 1997). The SUNDIAL simulations suggest that rainfall has a greater effect under conditions of high SMN content, as more of the SMN is lost (Fig 33, page 67).

However, it should also be remembered that efficiency of use of SMN (as shown by Fig 10) has been determined from the overall uptake of N from the soil. As noted earlier, the soil N supply consists not only of SMN but also of mineralised N, and at low SMN levels mineralised N may constitute a higher proportion of the soil N supply, giving higher apparent SMN use efficiencies. If the amount of mineralised N does not increase in proportion to the SMN, then apparent efficiency of SMN use may decrease, even if the efficiency of use of the SMN itself is unchanged or even increasing. This effect was demonstrated by the model simulations (Fig 34).

The strong positive relationship between the proportion of the SMN (0-90 cm) present in the plough layer (0-23 cm) in autumn and the efficiency of SMN use indicates that the capacity of winter cereal crops to utilise SMN is related not only to the amount of SMN, but also to its location in the soil profile. The SMN present in the soil surface (0-23 cm) in autumn was used more efficiently than that in subsoil layers. Presumably, limited root development in autumn prevents uptake of SMN at depth. In contrast, the deeper root system present in spring facilitates greater uptake of SMN from the subsoil horizons. Consequently, SMN present in subsoil in autumn under winter cereals is almost certainly at greater risk to leaching than that in topsoil in spring. In

contrast, the SUNDIAL simulations suggest that the position of the SMN in the profile had little effect on its uptake, October-harvest, but that in the spring, SMN in the topsoil was used more efficiently than that in the subsoil. This was due to greater losses of SMN from the subsoil, spring-harvest, the effect being greatest under wet conditions or sandy soils (Fig 35). It should be noted that the SUNDIAL simulations assumed larger amounts of SMN, and greater depths (down to 150cm rather than 90cm).

Crop N Uptake and Efficiency of SMN Use by Winter Oilseed Rape

Whilst for unfertilised winter oilseed rape there was no clear relationship between crop N uptake and SMN in autumn or spring (Fig 4) the strong relationship between crop N+SMN in spring and SMN in autumn (Fig 5b) indicated good recovery of autumn SMN. In part, this may well be due to earlier sowing. On average oilseed rape was sown about one month (32 days) earlier than winter cereals. Consequently, it often had a greater opportunity to utilise SMN mineralised in the early autumn compared with winter cereals. In addition, evidence in the literature indicates that the early root growth of Brassicas is more rapid than for grasses (Thorup-Kristensen, 2001) and for this reason may be more effective cover crops to help decrease nitrate leaching (Macdonald *et al.*, 2005). This was supported by the strong negative relationship between sowing date and N (Fig 8) uptake by oilseed rape, indicating that early sowing may further enhance its capacity to take up SMN and hence its efficiency of SMN use.

The inverse relationship between efficiency of SMN use by oilseed rape and SMN in autumn and spring (Fig 13) indicated that when SMN exceeds the crop N demand it may be subject to greater losses, as with winter cereals. Whilst nitrate leaching often accounts for a substantial proportion of the SMN lost from soil in winter, leaching losses in spring are generally smaller because of increased losses of water to the atmosphere by evapo-transpiration, and hence decreased drainage. Consequently, gaseous N losses by denitrification may account for much of the SMN loss in spring (Addiscott and Powlson, 1992). Significant rainfall events in spring may enhance such gaseous losses, but rainfall data were not sufficient to examine this.

Crop N Uptake and Efficiency of SMN Use by Spring Barley

The linear relationship between spring barley crop N uptake and SMN in spring (Fig 6a) over a narrow range of SMN was consistent with the relationship between winter cereal crop N uptake and spring SMN over a similar range (Fig 1b). The inverse relationship between efficiency of SMN use and spring SMN (Fig 14a) was consistent with that for winter cereals and oilseed rape (Figs 10b & 13b). Again, the SUNDIAL simulations with crops given fertiliser N supported the observations from zero-N plots, when estimated as the uptake of non-fertiliser N. Similarly, the slight negative relationship between crop N uptake and sowing date was also consistent with that found for spring N uptake by winter cereals (Fig 7a) and oilseed rape N uptake (Fig 8b). This indicates that in general the factors controlling N uptake and efficiency of SMN use (e.g. risk of N loss, sowing date and location of SMN in the profile) may well be similar for all three crops. However, for spring barley in particular there was a strong negative relationship (R^2=0.73) between sowing date and its total growth period, indicating that late sowing was associated with a shorter growth period and smaller crop N uptakes.

Effects of Soil Texture and Previous Crop on SMN and Efficiency of SMN Use

The generally greater quantities of SMN present in the silty-clay loam and clay soils (Fig 15) compared with the other soils textures (clay-loam, silty-loam and sandy-loam) indicates that these soils are more effective at retaining SMN. In contrast, the substantial decreases in SMN between autumn and spring on the sandy loams indicate that they are particularly vulnerable to SMN loss over winter, presumably as a result of nitrate leaching (Fig 3). However, despite the apparently greater susceptibility to N loss in sandy soils the average efficiency of use of SMN (autumn–harvest and spring–harvest) exceeded 100% and was similar or greater than in the other soils (Fig 16). This was consistent with the inverse relationships between SMN and efficiency of SMN use (Fig 10), but appears to be at odds with the apparently greater risk of SMN losses on this soil. The efficiency of use of the relatively small amounts of residual SMN left by sugar beet also exceeded 100%, and was generally greater than that after forage and oilseed crops (Fig 18).

Efficiencies of SMN use (spring-harvest) estimated following ploughing out of grass/clover leys were 209-301% (Fig 19). This was almost certainly due to plant uptake of the large quantities of N mineralised from the incorporated grass/clover residues in spring. The incorporation of large quantities of N in readily decomposable

sugar beet tops may also result in significant net N mineralisation (Macdonald *et al.*, 1997). Thus it is apparent that on average there is a tendency for the relatively simple index of SMN use efficiency (Equation 2) to overestimate the efficiency of SMN use. This is in part because it does not account for increases in SMN (by N mineralisation) in soil following its measurement in autumn or spring, nor does it account for subsequent losses of SMN by leaching and/or denitrification. SUNDIAL simulations with crops given fertiliser N showed a decline in SMN use efficiency with clay content, with clay soils being the most efficient and sandy soils the least. This was most apparent in the period Oct-harvest, due to greater losses of N from the sandy soils. The SUNDIAL simulations also considered the effect of soil OM on SMN use efficiency. When SMN use efficiency was calculated as the uptake of non-fertiliser N, SMN appeared to be used less efficiently under conditions of low OM, because less N was mineralised, and less non-fertiliser N was available for uptake. However, when SMN use efficiency was calculated as the uptake of labelled SMN, soil OM had no effect on efficiency, as mineralised soil N was not included in the uptake of labelled N by the crop. These simulations illustrate that the method of calculating SMN use efficiency can have a profound effect on the results.

Effects of Current Crop

The generally smaller estimates of the efficiency of SMN use by winter wheat (Fig 20) compared with oilseed rape (Figs 22), together with the apparently small N losses between autumn and spring under oilseed rape (Fig 5b), indicates that efficiency of SMN use by oilseed rape may well be greater than with winter wheat. The inclusion of an estimate of nitrate leaching loss in the calculations of the <u>net</u> efficiency (Equation 4) of SMN use for winter wheat and oilseed rape improved the agreement between estimates of efficiency for autumn-harvest and spring-harvest (Fig 21b and Fig 23b). The inclusion of an estimate for N leached seems valid on the basis that any true estimate of SMN use efficiency should aim to take account of all potentially available sources of SMN for plant uptake. Consequently, where efficiencies are estimated using measurements done in early winter a correction for N losses in drainage should be included. Similar corrections for N losses by denitrification and N production by mineralisation should also help improve estimates of efficiency of SMN use.

It was apparent that severe take-all infection of wheat can adversely affect SMN use efficiency. Take-all is a soil-borne fungal pathogen of cereals and is usually more prevalent in second and third wheats. It damages the plant root system and in severe

cases greatly decreases the capacity of the plant to absorb water and nutrients, resulting in poor growth and diminished efficiency of use of both fertiliser and soil derived N (Macdonald *et al.*, 1997). Consequently, its impact on yield is often worse on free draining sandy or shallow soils where moisture may become limited in the late summer. In situations where severe take-all is anticipated modifications to rotations may help minimise the impact of take-all and maintain the efficiency of use of both fertiliser and soil-derived N.

Effects of Fertiliser N on Efficiency of SMN Use

Experiments using ^{15}N-labelled fertilisers indicated that fertiliser N applications to winter wheat and oilseed rape enhanced the uptake of SMN and hence its efficiency of use (Figs 20 & 22). Similarly, the apparent efficiency of SMN use by spring barley increased with increasing rates of fertiliser N until it exceeded crop N demand (Fig 24). However, there was also an indication that at the highest N application rates the uptake of SMN from subsoil was suppressed (Glendining *et al.*, 1997). Analogous trends were seen for winter wheat in the Woburn Ley-arable experiment (Fig 28). As discussed earlier, the application of fertiliser N may result in a real added nitrogen interaction (ANI), in which the crop's capacity to recover soil-derived N is enhanced by increased crop growth and root development. However, apparent ANIs may also occur as a result of pool substitution, in which fertiliser N is either immobilised or denitrified in place of soil N, resulting in greater crop uptake of soil-derived N in place of the fertiliser N. These so called "apparent ANIs" tend to be greatest when both fertiliser N and soil N are intimately mixed (Jenkinson *et al.*, 1985).

6.0 Conclusions

Analysis of crop N data for winter cereals, spring barley and winter oilseed rape has shown that the uptake of soil N between autumn and harvest or spring and harvest can vary widely. Unfertilised crops will typically take up an amount of N by harvest that ranges above and below 100% of the amount of SMN that is measured in autumn or spring. However, model simulations suggest that if net mineralisation is excluded, estimates of the efficiency of use of the measured SMN itself would be lower than those indicated by simple methods that express N uptake as a proportion of the SMN present in either autumn or spring. The simulations indicated that, if mineralised N is excluded, estimates of SMN use efficiency might be about 60% of those obtained when mineralised N is not excluded. In other words, where apparent efficiencies of around 100% are observed, actual efficiencies might be closer to 60% (and therefore similar to typical efficiencies with which fertiliser N is used).

The net mineralisation method (which expresses N uptake as a proportion of the change in SMN plus crop N between the autumn or spring and harvest) gives a measure of efficiency of soil N use relative to the net amount of N mineralised during that period. Where allowance is made for estimated N losses (e.g. due to leaching) estimated efficiencies by the simple and net mineralisation methods have been similar. However, it was apparent that the simple approach tends to overestimate SMN use efficiency where losses of SMN are significant or large amounts of SMN are mineralised after SMN is measured in autumn or spring. Consequently, an improved estimate of SMN use efficiency should include estimates of both N mineralisation and losses, especially nitrate leaching. In some circumstances it may also be important to account for denitrification losses in early autumn and spring.

Higher SMN levels in the autumn or spring appear to be associated with lower efficiencies of use in winter cereals, spring barley and winter oilseed rape. Evidence for winter cereals suggests that this is a general trend that is independent of previous crop and soil type. Efficiencies below 100% have often been obtained with SMNs above about 100 kg N/ha for winter cereals and oilseed rape, and with SMNs above about 50 kg N/ha for spring barley. This trend towards lower efficiency is likely to be the result of decreasing uptake as supply meets and exceeds crop demand coupled with the increasing risk of SMN loss, especially at sowing. However, it will also be a

consequence of the fact that efficiencies are calculated from uptake of crop N as a proportion of the amount SMN present at one point in time, whereas the N supply is a combination of the SMN plus the N that becomes available subsequently over time, notably due to mineralisation.

Crops (such as sugar beet) that leave smaller amounts of SMN, and leaching-prone sandy soils which have low levels of SMN, may give apparent efficiencies of use that are higher. However, this is likely to be because mineralisation after the measurement of SMN represents a larger proportion (as a percentage) of the soil N supply. Leaching-prone sandy soils, and high rainfall situations, are likely to give lower efficiencies of SMN use, especially between autumn to harvest, when compared to clay soils or low rainfall situations respectively with the same amount of SMN present.

Losses through leaching (and/or denitrification) and gains through net mineralisation or other processes therefore appear to be the two main uncertainties when estimating efficiency of soil N use. Both of these factors are partly dependent on weather (rainfall and temperature), which cannot be predicted with certainty. The combination of higher concentrations of soil organic matter, cooler wetter summer conditions, delay in mineralisation in spring and a longer period of N uptake over the summer justify the current low use of the SMN approach to fertiliser recommendations in Scotland.

For winter cereals in the absence of fertiliser N, the depth at which SMN is present in the autumn may be an important determinant of its efficiency of use, with higher efficiencies where a higher proportion is located in the topsoil. This is likely to be because crop rooting is mainly restricted to the topsoil in the autumn, and N present below topsoil depth in the autumn is also more likely to have been moved down beyond effective rooting depth by the spring. Depth at which SMN is present appears (for winter cereals) to be less important in the spring (at least within the range 0-90cm), as by this stage roots will be able to access N from depth. In the presence of fertiliser N however, model simulations have suggested that efficiency of SMN use might be reduced in wet seasons where a high proportion is present at greater depth (50-150 cm) in the spring. This was consistent with the negative relationship between winter cereal crop N uptake and both winter and spring rainfall.

Early sowing of oilseed rape maximises recovery of available soil N in the autumn, and can improve efficiency of SMN use between autumn and harvest by reducing leaching

losses over the winter. Earlier sowing of spring barley also increases the efficiency of use of SMN measured in the spring, by extending the duration of crop growth and therefore crop N uptake. For winter cereals, although earlier sowing tends to increase recovery of SMN present in the autumn, sowing date does not appear to be a primary determinant of crop N uptake by harvest (and therefore overall efficiency of use). High levels of disease (e.g. take-all) that limit crop growth and therefore N uptake are likely to result in lower efficiencies of use between spring and harvest in particular.

Although variety is by no means the only factor that would have changed over this period, a comparison of N uptake for past and recent winter cereal trials did not reveal a difference in efficiency of SMN use between older and more modern cereal cultivars.

The application of N fertiliser tended to increase the apparent efficiency of use of SMN in all three crops. There was evidence on spring barley that efficiency increased up to a point near where crop demand was met (as indicated by yield response to N dose), above which efficiency of use decreased. If it is assumed that efficiency of fertiliser N use is unaffected by the dose applied (at least for doses below maximum yield), then calculated efficiencies for winter cereals indicate a similar increase then decrease in efficiency, with the highest value reached at a point near to where N uptake began to plateau. Evidence from the literature suggests that the apparent increase in efficiency may, in some cases at least, be due to pool substitution, with fertiliser N replacing soil N that would otherwise have become unavailable for uptake or been lost. Hence, the application of N fertiliser may not increase efficiency of use of the total N supply compared to when soil N alone is present. However, this does suggest that estimates of SMN use efficiency derived from zero-N trials are not necessarily higher than would occur in an optimally-fertilised situation.

Specific management practices that may help enhance the efficiency of SMN use include early sowing of winter crops, especially in high rainfall areas on sandy soils where significant nitrate leaching occurs. Alternatively, the use of early sown cover crops on sandy soils prior to sowing spring crops may help minimise leaching losses of SMN. In the longer-term the N derived from the decomposition of cover crop residues may contribute to subsequent crop N uptakes. Early sowing of spring crops to maximise the length of the growing season (and therefore N uptake) should also improve SMN use efficiency. The more frequent use of break crops to combat the build up of take-all may also help enhance efficiency of SMN use in arable crop

rotations. In addition, full account should be taken of the N supply from recent organic manure applications and/or the release of SMN after ploughing out grass and grass/clover leys when calculating the required N fertiliser application rate.

7.0 Recommendations for Further Work

The analyses of crop N uptake and efficiency of SMN use for unfertilised winter cereal crops were characterised by significant variation, highlighting the complexities involved in estimating the amount of N that an individual crop will recover from the soil. This review has identified the main processes and factors that are involved, and their likely impact in either increasing or decreasing the uptake of N from the soil. However, further improvements in estimating the efficiency with which soil N is used and understanding the impact of crop management practices and other factors would be facilitated by additional work in the following areas:

i. Better estimates of the principal processes that control soil N availability (in particular mineralisation and losses by leaching) are required to develop a more accurate estimate of the efficiency of SMN use. The evaluation of indicators of these processes against experimental data is required to help develop look-up tables or other simple models to more accurately estimate both the soil nitrogen supply and the efficiency of SMN use on a field specific basis.

ii. Additional N response trials with new cultivars of winter wheat, oilseed rape and spring barley (including trials using ^{15}N-labelled fertilisers) are needed to provide more data on fertiliser N requirement and its relationship with the soil N supply. These trials need to include a full spectrum of soil and crop N measurements in order that the balance between soil N supply and crop N uptake over the period from autumn to harvest can be examined.

iii. Further examination of the effect of take-all infection in cereals on N uptake is required in order to evaluate the impacts of crop rotation and disease management on the efficiency of use of both soil and fertiliser N.

iv. Uncertainties remain over the effect that the depth at which SMN is present in the spring has on its efficiency of use, when large amounts of fertiliser N are present in the soil surface layers. Studies that involve placement of ^{15}N labelled fertiliser at different depths in the soil might be helpful in understanding this.

v. A related uncertainty is whether or not the timing of fertiliser N applications has an effect on efficiency of SMN use. Central to this is whether or not early spring applications can increase rooting and potentially improve the recovery of SMN from depth later in the spring, or whether they are beneficial only in meeting initial crop need when the amount of SMN present in the topsoil is low. The most appropriate fertiliser N strategy might then depend on the distribution of SMN down the soil profile, as well as the amount of SMN that is present.

8.0 Acknowledgements

9.0 References

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10. Appendices

Appendix 1: Table 1. Data sub-categories

Data categories	Sub categories
Previous crop	Cereals, forage, legumes, oilseeds, potatoes, sugar beet, set-aside
Soil Texture	Sandy loam (SL), Silt Loam (ZL), Clay Loam (CL), Silty Clay Loam (ZCL), Clay (CL)
SMN (0-90 cm)	0-30, 30-60 and 60-90 cm
Crop N – spring	
Crop N – harvest	Above-ground crop (grain plus straw)
Sowing and Harvest date	Julian days
Rainfall (mm)	Annual, Spring, Harvest, Autumn.

Appendix 2: Published sources of data

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