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Abstract and Summary

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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 $5^{O}C$ and $25^{O}C$)
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 actual efficiency with which this is used, but also the amount of N that becomes available subsequently (mainly by mineralisation), which affects the apparent 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.