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Establishing best practice for estimation of Soil N Supply

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ABBREVIATIONS USED

AAN	Additionally Available Nitrogen (by GrowHow method)
AN	Ammonium nitrate
CV	Coefficient of variation
DM	Dry matter
FAM	Field assessment method
GAI	Green area index
GNY	Grain nitrogen yield (kg/ha)
ha	Hectare
harvested SNS	Crop N uptake at harvest of unfertilised crop (our definitive measure of SNS)
HCFR	Hill Court Farm Research
Hot KCl	Measure of mineralisation using hot KCl extraction
KCl	Potassium chloride (reagent used in SMN analysis)
N	Nitrogen
NHI	Nitrogen harvest index
Nmin	SNS prediction service offered by GrowHow
PMN	Potentially mineralisable nitrogen
r^2	Coefficient of determination
S.E.	Standard error
SMN	Soil Mineral Nitrogen
SNS	Soil Nitrogen Supply (SMN + Crop N)
t	Metric tonne
TNY	Total nitrogen yield (kg/ha)

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1. ABSTRACT

Estimating soil nitrogen supply (SNS) is an important step in nitrogen (N) decision-making for arable crops. The N that gets into an unfertilised crop by harvest, termed ‘harvested SNS’, can be taken as the most meaningful metric of soil-derived N, as it affects fertiliser N requirements. This report examines past and new datasets to determine how best to predict harvested SNS.

SNS prediction proved worthwhile, whether by a field assessment method (FAM, e.g. RB209) or by soil mineral nitrogen (SMN) measurement, when compared to a simplistic assumption of a fixed value. SMN explained more of the variation in harvested SNS than FAM, but FAM was more accurate on average, unless SMN measures were adjusted for N deposition and recovery. SMN-based predictions performed best on clay and silt soils, in lower rainfall areas and where SNS was expected to be high. In situations where harvested SNS was expected to be moderate or low, SMN did not perform better than FAM, even on clay and silt soils. Overall, there appear to be two ways in which SMN measurement may help to deliver improvements to N management on the farm:

1. to confirm and manage fields where SNS levels are suspected of being very high or are uncertain;
2. as part of a package of measures, including field assessment and monitoring of crop growth, lodging, grain yield and grain protein, used to get average SNS predictions right over large blocks of land, particularly in situations where the management or farming system has changed.

Spring SMN measures explained slightly more of the variation in harvested SNS than autumn measures. Sampling 0-60 cm in autumn was as effective as sampling 0-90 cm, but in spring, sampling to 90 cm was best. Adjustments for deposition and crop recovery of SNS improved accuracy and economic performance of SMN predictions. Mineralisation measures using SOM%, total soil N% or GrowHow additionally available N (AAN) improved the precision of spring (but not autumn) SNS predictions.

Soil sampling and handling studies showed that samples should be kept cool but not frozen, and analysed within three days of sampling. Laboratory standardisation tests showed lab differences to be small, but that ‘ring tests’ between labs should continue.

Studies of oilseed rape showed that crop N and SMN can be considered equivalent in SNS predictions.

2. SUMMARY

2.1. Introduction

2.1.1. Aim and objectives

The use of soil mineral nitrogen (SMN) testing in estimating soil nitrogen supply (SNS) has been the subject of uncertainty in the industry and in recent HGCA reports. This project was set up to address the concerns, provide best practice advice and build confidence in the estimation of SNS.

Overall aim:
To achieve consensus across the industry on best practice for estimation of SNS.

Specific objectives:

1. To collate and consider stakeholder concerns about estimation of SNS and (at the end of the project) to present stakeholders with evidence for best practice.
2. To collate unpublished data on measurements of SMN and prioritise uncertainties.
3. To establish best practice for interpretation of SMN analysis, including sampling depth and assessments of potentially mineralisable N (PMN).
4. To evaluate uncertainties in SMN results, including field sampling methods, sample handling and transfer, and laboratory processing and analysis.
5. To determine the most appropriate method for interpreting over-winter assessments of crop N in oilseed rape.
6. To compare and evaluate approaches for the prediction of SNS both from soil measurements and field assessment methods (FAMs), then to provide guidance on where and when SMN analyses are best used to inform on-farm SNS estimation.

As well as the initial HGCA funding for this project additional funding from GrowHow, HDC and PGRO allowed a larger dataset of SNS measures to be generated, addressing a wider range of situations, with potential for higher levels of SNS to be explored, especially for sites following vegetable crops and pulses.

2.1.2. Background

Of the judgements that farmers make when deciding how much fertiliser N to apply, one of the most important is the amount of N that will be available to the crop from the soil: the SNS. Variability in SNS between different fields, situations and years can be large. Values for a given situation can be judged by a FAM (e.g. as in RB209 or SAC-TN625), but this necessarily gives averages of a wide range of possible values. For the past 20 years the ‘gold standard’ for predicting SNS in most situations has been regarded by many as SMN testing, yet sampling and analytical techniques for the SMN method still vary, and little guidance exists to inform best practice. In recent years some have even questioned its value altogether. In HGCA Research Review 58 Knight et al. (2006) identified various issues that surround the SMN method. These included estimating crop N, best sampling time, depth and intensity; sample storage, transport and processing; and analysis and interpretation. Whilst much work has been undertaken on these issues in the past, this has not always entered the public domain (e.g. Silgram 1997; Silgram & Goodlass 2006). HGCA Research Review 58 highlighted the need for a set of guidelines of best practice for the SMN method, and possible accreditation of practitioners. In addition, practices that could reduce the cost of the SMN method (e.g. using shallower sampling depths) or improve its predictive performance (e.g. estimating potentially available N by incubation or by considering total N%; Bhogal et al. 1999) need to be evaluated.

Subsequently, HGCA Research Review 63 (Richards, 2007) recommended that “The different methods for quantifying soil nitrogen supply, by estimation, measurement or both, need to be validated and compared. The relative contributions of soil mineral nitrogen, N mineralised during spring and N taken up by the crop over winter need to be clarified. Guidance is then needed on the appropriate choice of method for different circumstances taking account of cost and the degree of accuracy required.”

This project sought to address these recommendations in full. Key uncertainties in direct measurement of SMN were identified and recommendations for best practice were developed. On-farm strategies for using direct SNS measurements were then compared with the FAM in The Fertiliser Manual (2010; hereafter referred to as RB209), and best strategies evaluated for different field and farm types.

The expense of SMN sampling means that its use is most likely to be worthwhile where potential fertiliser savings are large i.e. where expected SNS is large or uncertain. There is, however, a need to identify more exactly where and when the SMN method is of greatest benefit, and how results can be used to improve N planning across the whole farm. In addition, rigorous and transparent information is required by the industry to ensure confidence in all of the approaches available to estimate SNS.

This project, involving a broad consortium, drew on previous published and unpublished data and reports, publications, expertise and on-going projects as well as providing new data. It used a robust framework to identify best practice for predicting SNS, using *crop N uptake near harvest without applied N* ('harvested SNS') as the definitive measure of SNS. A cost-benefit analysis of best-practice identified where and when the use of soil measurement should prove worthwhile in farm situations.

2.2. Materials and methods

This project was composed of six tasks to meet the six objectives outlined above.

2.2.1. Task 1: Building consensus through stakeholder engagement

The project aimed to achieve some consensus across the industry on best practice for estimating SNS. To help achieve this a Steering Group met regularly through the project, chaired by Ian Richards and involving representatives from HGCA, ADAS, TAG, SAC, Rothamsted Research, NRM, Hill Court Farm Research, Eurofins, Scottish Agronomy, GrowHow, HDC and PGRO. In addition, well-attended Stakeholder meetings were held at the beginning and end of the project in 2008 (HGCA offices, London) and 2011 (PGRO, Peterborough). Attendees included Defra, government agencies (e.g. Environment Agency), industry bodies (e.g. NFU, AIC), distributors and manufacturers (e.g. Masstock, Hutchinsons, Frontier, Yara), agronomists, laboratories and soil sampling practitioners (e.g. SOYL, Envirofield) and farmers. Stakeholders were given the chance to contribute to the direction of the project at the outset and initial analyses of results were shared at the end of the project where contributions towards final conclusions were sought.

2.2.2. Task 2: Review of past data

Much work has been conducted on SMN methodology since 1980, in the UK and across the world. Not all of the relevant UK information has been fully published. An exercise was conducted at the start of this project to collate as much available past data as possible from all organisations. A dataset was created containing data from all past experiments where SMN had been measured in conjunction with measures of harvested SNS (grain yield and grain N% of unfertilised crop). Where N harvest index (NHI) information was not available this was assumed to be 0.75, so that total N yield could be estimated from grain N yield (TNY = GNY / NHI). The final dataset included over 550 experimental sites; it was used to assess the variability of measured SNS and harvested SNS and the relationship between measured SNS and harvested SNS for a range of soil types and situations.

2.2.3. Task 3: Generating new data for evaluating SNS prediction

In addition to the data collated in Task 2, a new dataset was generated using a total of >180 cereal sites over three years where soil measurements were made in autumn and spring, and crop measures were made at harvest. At each site one 10 metre by 10 metre area was identified for soil and crop sampling, to which no N fertiliser was applied. SMN was measured to 90 cm (or to maximum soil depth where soils were shallow) in 30 cm horizons by bulking nine cores at each date. Crop N at sampling was estimated by visual assessments of growth stage and plant population, as well as ground cover and GAI, and by quadrat samples if crop N was judged to be greater than 30 kg/ha. SMN was measured in autumn (November) and spring (February). In spring additional measures were made on the 0-30 cm samples of soil organic matter (SOM), total soil N%, mineralisation by hot KCl extraction (in 2008 only), and potentially mineralisable N (PMN) by anaerobic incubation. PMN values were converted to ‘additionally available N’ (AAN) by Hill Court Farm Research using the GrowHow method. Field and soil information was obtained for each field including previous cropping, rainfall area, manure history, grass history, soil texture, soil series and stone content. This information was used to determine FAM estimates of SNS index. IRRIGUIDE was used to estimate rainfall and drainage for each site, for the over-winter period as a whole and following autumn and spring sampling. Estimates of N retained after sampling were made using assumptions of soil group and over-winter rainfall category from the approach advocated in the HGCA nitrogen for winter wheat management guidelines.

At harvest, nine 0.25 m^2 quadrats were taken from the unfertilised area, and separately from the surrounding commercially fertilised crop, to allow determination of grain yield, grain protein, straw N%, N harvest index and total N uptake.

Relationships between various SNS predictors (SMN-derived and by the FAM) and harvested SNS were explored for the dataset as a whole, for different soil types and for different situations using a range of regression analyses in Excel and Genstat.

2.2.4. Task 4: Studies to assess uncertainties in sample handling, storage and analysis

Following the data review in Task 2, specific issues surrounding the measurement of SMN and the prediction of SNS were investigated. Two laboratory standardisation exercises were carried out in spring and autumn 2008. Soil samples of around 3 kg from 0-30 cm cores were collected from ten fields selected to represent a range of expected SNS levels. The samples were thoroughly mixed and six sub-samples of 500g were taken (each made up of 10 portions of 50g soil). Two of the six samples were sent to each laboratory in chilled packs for next day delivery. Temperature sensors were included in each batch of samples so that changes in temperature through transport could be assessed. Samples were analysed for SMN (soil DM%, nitrate-N and ammonium-N; mg/kg) and results compared.

Sample handling and storage exercises were carried out in spring 2009 and 2010. In each study, soil samples were taken from four contrasting fields in each year. For the sample storage studies four separate ~3kg samples from 0-30 cm were obtained by spade from each site. These were thoroughly mixed and sub-samples taken from each, to give samples for eight (2009) or ten (2010) storage treatments with four replicates. In 2009, samples were then stored at 2-4°C for <1.5 days or at room temperature for 7 days; in 2010, samples were stored at 2-4°C for <1, 2, 4 or 7 days or at room temperature for 7 days. In 2009, one treatment also tested samples frozen for 14 days. After storage, samples were extracted with KCl at ADAS Boxworth. Sample extracts were frozen and then sent to the laboratory (HCFR) for determination of nitrate-N and ammonium-N. For the sampling and sample handling exercises samples were generated from each of the four fields in each year by taking soil cores, either within a 10m x 10m area, or a wider 100m x 100m area. From each of four replicates, half of each sample was mixed thoroughly and sub-sampled carefully, the other half was not mixed and sub-samples were taken at random. In 2009, samples were stored at room temperature or 2-4°C for <1.5 or 7 days; in 2010, samples were stored at 2-4°C for <1.5 days before extraction at ADAS Boxworth.

All results were analysed by ANOVA in Genstat to assess treatment differences.

2.2.5. Task 5: Studies of crop N in oilseed rape

In situations that allow substantial growth during autumn and over-winter, oilseed rape crops can take up over 150 kg/ha N by the spring. It is not certain whether all of the crop N in large crops should be subtracted from the target N uptake and should be regarded as equivalent to SMN. This is because oilseed plants may not be 100% efficient at remobilising N from dying leaves. Studies were conducted to investigate this by comparison of small and large crops. Twenty nine ‘paired’ sites were investigated over three seasons (2007/08, 2008/09 and 2009/10). Areas with small and large crops were either selected within adjacent areas of a field or engineered through the use of different sowing dates, seed rates, plant hoeing or the use of fleece covering over winter. N fertiliser was withheld from each plot area so that N uptake of the unfertilised crop could be measured at harvest to give harvested SNS. Soil and crop samples were taken in autumn and spring to measure SMN, crop N and with which to calculate the autumn and spring SNS. Digital photos were also taken at each sampling to allow estimation of GAI using the canopy GAI tool (www.totaloilseedcare.co.uk/GAI/index.html). Crop samples were taken from six 0.5m^2 quadrats before harvest, at the point where N uptake was deemed maximal and before pods started to shatter, in order to calculate final crop N uptake (treated here as ‘harvested SNS’).

2.2.6. Task 6: Cost-benefit analyses to give best practice advice

Three different criteria were used to assess the ‘best’ SNS predictor for a category of crop.

Accuracy

The difference (bias) between the average prediction and average harvested SNS.

Note that, because over-predicting harvested SNS (thus using sub-optimal fertiliser N and incurring yield losses) tends to be more costly than under-predicting harvested SNS, profit from use of any predictor is maximised if it has a small negative bias (zero to -20 kg/ha SNS).

Precision

The extent to which a potential predictor accounted for each value of harvested SNS over a number of sites was assessed using:

- the coefficient of determination (r^2) of the linear regression equation.
- the frequency with which a predictor gave ‘right’ or ‘wrong’ predictions, i.e. the proportion of times that the prediction was within +/- 20 kg/ha or more than +/- 50 kg outside of the harvested SNS.

The combined effects of imprecision and bias were assessed in two ways:

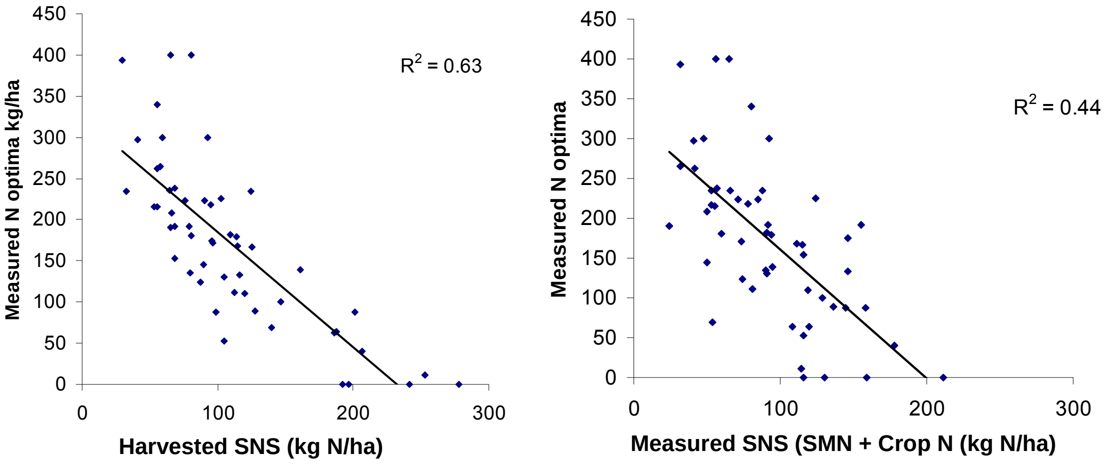
- Statistically: For any prediction, the coefficient of determination (r^2) for y = x shows how much of the variation in harvested SNS was explained by the actual values of any SNS predictor (without an intercept or slope).
- Economically: The effect on margin over N cost ('profit foregone') of using a particular SNS prediction at each site. For this we assumed N was applied according to the SNS prediction and then subtracted the margin over N cost if N had been applied according to actual harvested SNS; we used a typical yield response curve to fertiliser N (taken from HGCA Report PR438), a grain price of £150/t, and an AN price of £300/t.

  Note that large errors in fertiliser N use are disproportionately costly compared to small errors, and average profit foregone (or the frequency of >£40/ha profit foregone) is affected by bias, especially if large (<-20 or >0 kg/ha SNS), as well as by imprecision. Prediction costs e.g. of SMN measurements, were not included in profit calculations.

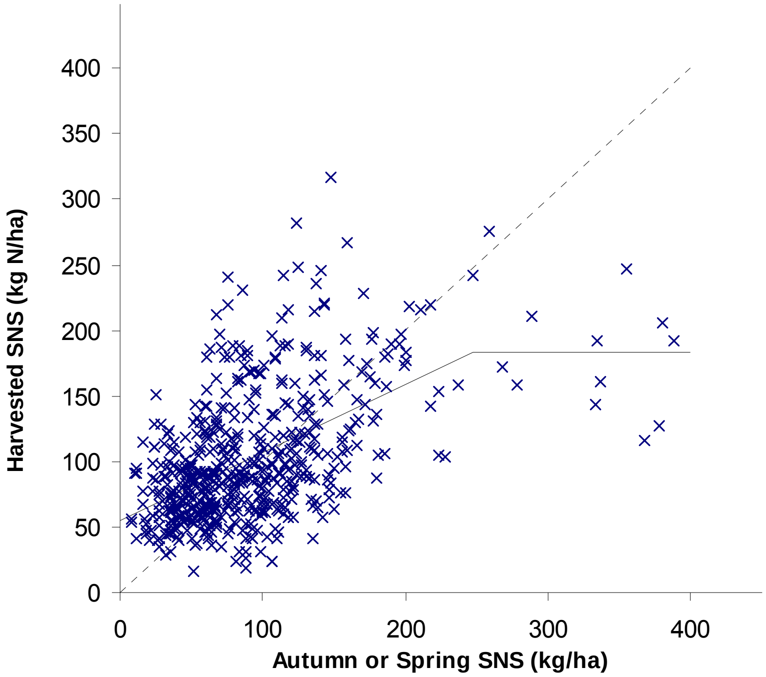
2.3. Key results

2.3.1. Lessons from past data

An analysis of 53 recent N response datasets showed harvested SNS to account for 62% of the variation in N optima across past N response experiments (Summary Figure 1). Harvested SNS was confirmed to be the most important and most predictable component of N requirement when considering sites with a wide range of SNS, even though predictions of harvested SNS are not precise. Unexplained variation in N optima is considerable, especially where harvested SNS is at normal to low levels (below ~100 kg/ha).



Summary Figure 1. Relationship of N optima with a) harvested SNS and (b) measured SNS in autumn or spring (according to whichever data was available).

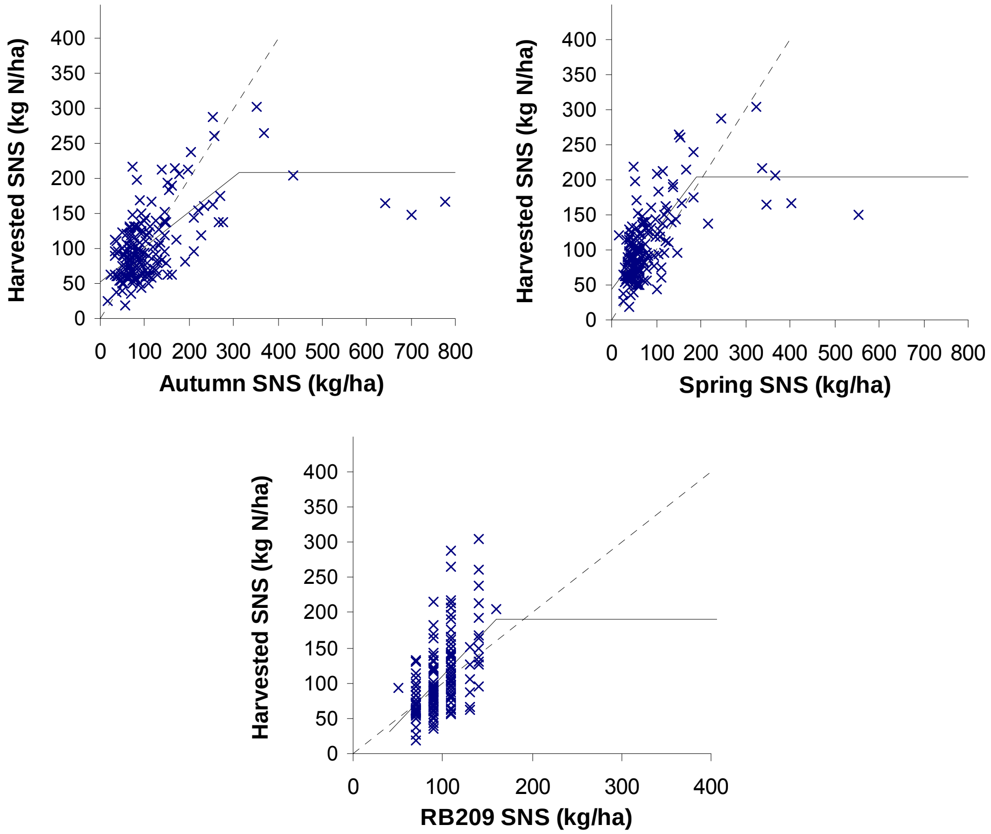


Summary Figure 2. Relationship between measured SNS in autumn or spring and harvested SNS for >550 sites since 1980. Solid line shows fitted broken stick regression model, dashed line shows y=x. Slope of the first line of broken stick = 0.46; variation explained = 38%.

An analysis of a past dataset with >550 comparisons showed that measured SNS related to harvested SNS, but the relationships were not strong, probably due to large spatial and temporal variation in SNS. Some of this variation might be avoided by good practice, but probably not all. The relationship was strongest in the subset of data from uniform, N retentive soils where the spread in expected SNS was high.

2.3.2. Relationships in newly generated data

Analysis of the dataset generated in this project also showed the relationship between measured SNS and harvested SNS to be fairly weak, explaining ~40% of the variation. Measures of SNS explained more variation in harvested SNS than the FAM, but the FAM tended to be more accurate on average (Summary Figure 3; FAM measures are closer to the y=x line) as long as it was estimated with close attention to defining soil type, soil organic matter and field history accurately. On average measured SNS underestimated harvested SNS.



Summary Figure 3. Relationship between SNS measured in autumn, spring or estimated by FAM (RB209) for 164 sites 2008-2010.

The relationships between measured SNS and harvested SNS were best on clay and silt soils, and worst on light and shallow soils. They were also poorer where SNS was expected to be less than 100 kg N/ha (Summary Table 1).

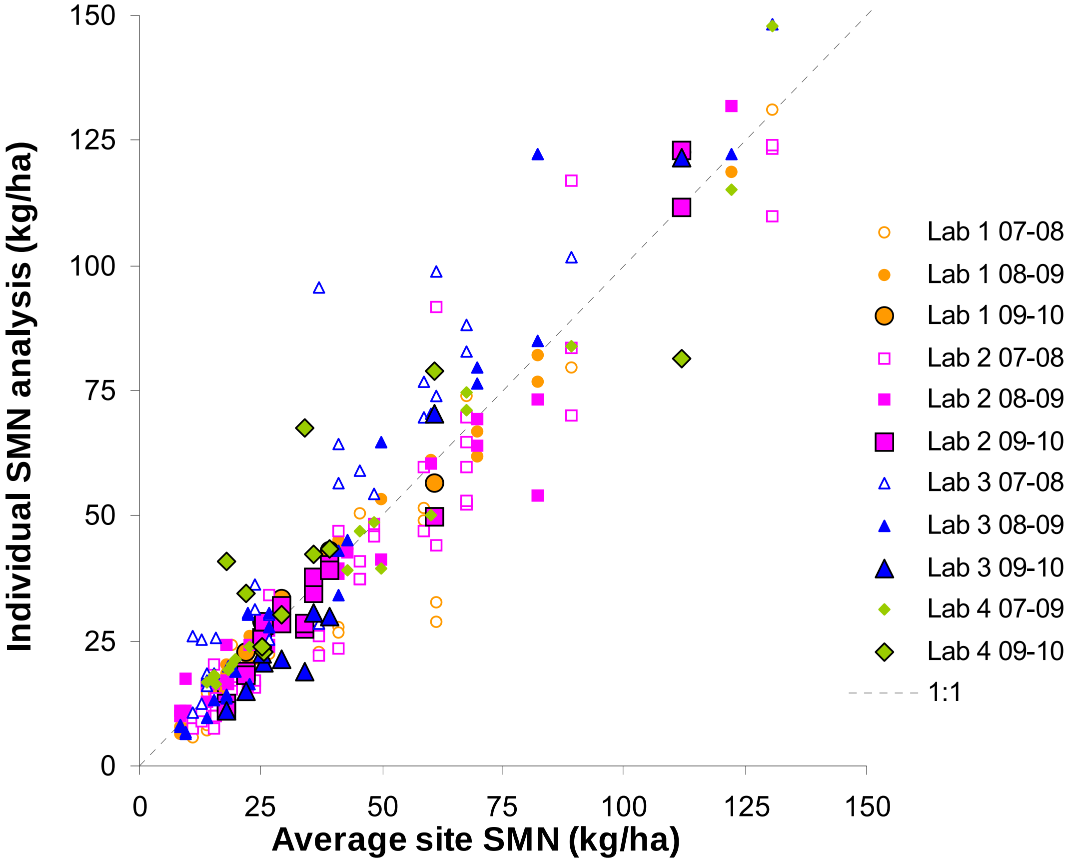
These split line regression analyses, both on past data and new data, show that the relationships between measured SNS and harvested SNS were characterised by intercepts greater than zero, slopes of less than 1 and limits of around 200 kg/ha beyond which harvested SNS did not increase. It was therefore concluded that any prediction of harvested SNS, by whatever method, should be constrained to an upper limit of 200 kg/ha.

Summary Table 1. Percentages of variation in harvested SNS explained by split-line regression of autumn SNS, spring SNS and FAM SNS for the new dataset (2008-2010), for different sub-groups of the data.

		Percentage variation explained		
Group	***Number of sites***	**Autumn SNS**	**Spring SNS**	**FAM SNS**
All	*164*	45	49	31
Silt soils	*34*	52	50	32
Clay soils	*33*	58	62	30
Medium soils	*70*	23	44	9
Shallow soils	*9*	0	0	5
Light sands	*13*	0	23	0
Low rainfall areas	*44*	39	35	27
Moderate rainfall	*75*	48	54	23
High rainfall	*45*	6	36	16
Grass or manure history	*57*	39	47	13
No grass or manure history	*107*	42	48	39
“Normal” arable situations	*52*	22	5	14
Non-“normal” arable situations	*112*	46	59	34
FAM SNS INDEX 0-2	*97*	25	33	5
FAM SNS INDEX 3-5	*67*	43	49	8

2.3.3. Sampling methodology studies

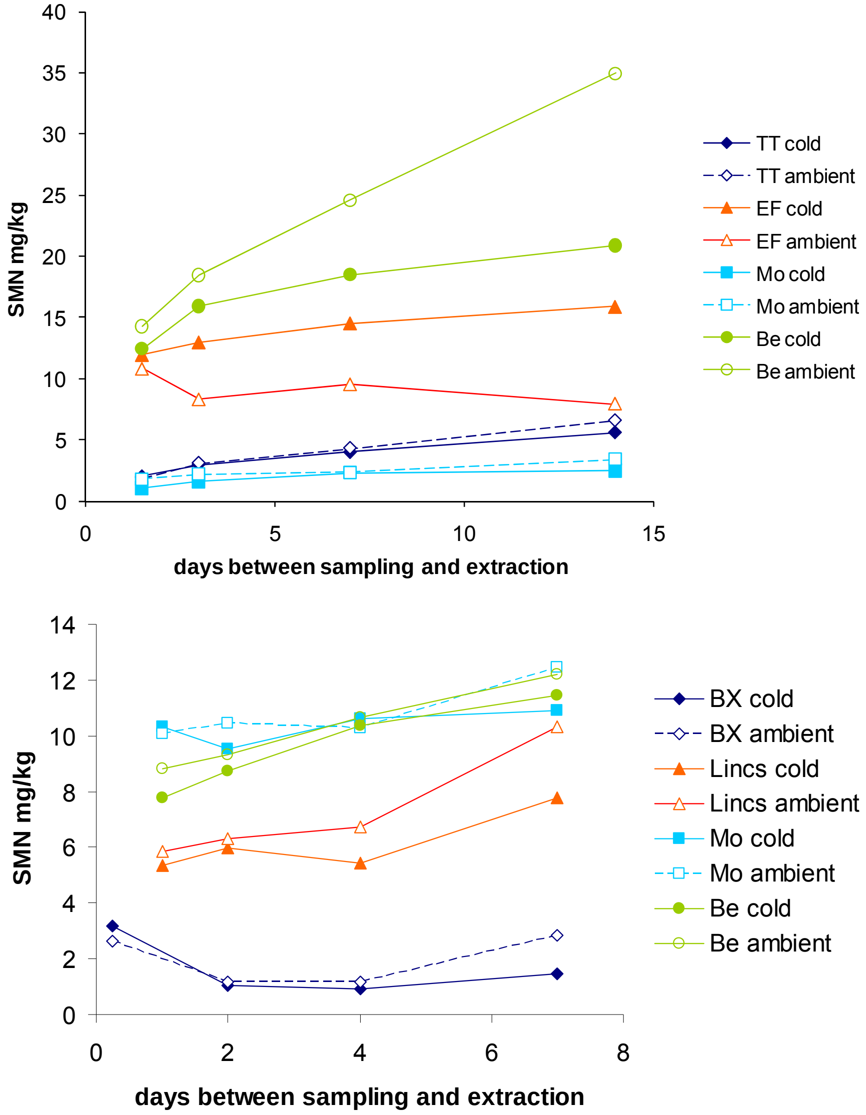
Laboratory standardisation exercises (Summary Figure 4) showed (with a few exceptions) differences between and within laboratories to be relatively small, given the inherent sample variability. The ‘ring-tests’ initiated in this project are now being continued by the major labs. on an annual basis.



Summary Figure 4. Range of SMN values (kg/ha) recorded by different laboratories for individual soil sub-samples from the same field sample, compared to the mean value for those sub-samples. Dotted line 1:1.

Sample storage studies (Summary Figure 5) showed SMN of refrigerated samples to increase steadily with delay in analysis after sampling. Subsoils changed less than topsoils. Average SMN 0-90 cm increased by 2.5 kg/ha per day delay. Increases were larger and more variable at room temperature. It was concluded that samples should be kept cold and storage standardised at 1 to 3 days.

Sub-sampling studies showed that thorough mixing of soil could increase measured SMN. However, mixing also reduced the coefficient of variation (cv) from 36% to 30%. There therefore needs to be a compromise between acquiring representative sub-samples and avoiding stimulation of N mineralisation by excessive mixing.

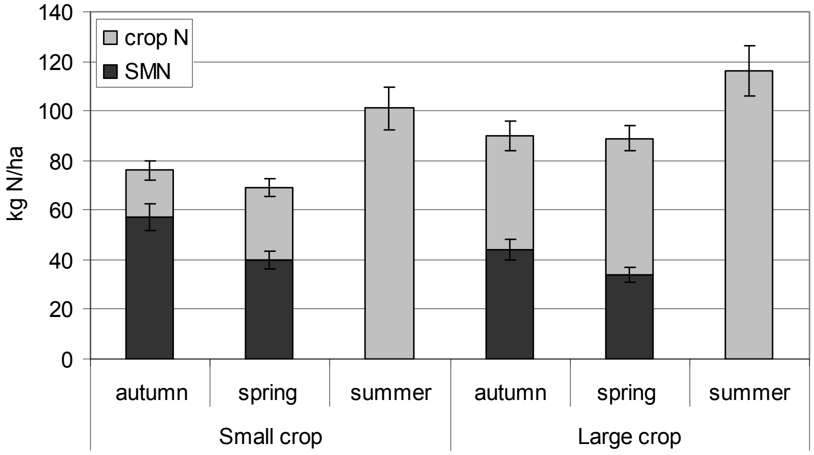


Summary Figure 5. Effect of interval between sampling and extraction on measured SMN for soil samples taken from four fields and stored at two temperatures in 2009 (top) and 2010 (bottom). Abbreviations are site codes; TT= Terrington, EF= Lincs site, Mo = Morley, Be = Beccles, BX = Boxworth.

2.3.4. SMN and Crop N in oilseed rape

In autumn, the average crop N contents were 19 kg/ha for the small crops and 46 kg/ha for the large crops, yet there was no significant difference in total measured SNS because the small crop treatments had more SMN (Summary Figure 6). In spring the small crops contained 29 kg/ha N and the large crops contained 55 kg/ha N. The large crop treatments did have a greater SNS at this stage because there was no difference in SMN due to crop size treatments. Linear regression revealed no significant differences in the relationships of autumn or spring SNS with harvested SNS between the small and large crop treatments.

This was also the case when the regression analyses were performed for individual seasons or across all three seasons. A paired T-test showed no significant difference in the proportion of the autumn or spring SNS that was taken up by summer between the small and large crop treatments, even when the analysis was restricted to the 15 sites with the largest difference between the small and large canopies (average of 24 kg/ha N compared with 66 kg/ha N). These results indicate that SMN and crop N may be considered as equivalent in terms of how they are used to predict harvested SNS.



Summary Figure 6. Effect of crop size on SMN (kg/ha) and crop N (kg/ha) in autumn, spring and summer (harvested SNS) in three years (2007/08, 2008/09 and 2009/10). N=28 ± SEM per crop size.

Relationships for oilseed rape between autumn or spring measured SNS and harvested SNS were very similar to those reported for cereals in Section 2.3.2.

2.3.5. Best and cost-effective predictions of harvested SNS

Correcting bias in a predictor is much easier than improving its precision, yet both bias and imprecision determine its economic performance. Economic outcomes of different predictors are, therefore, best compared with a common small level of bias (-20 to 0 kg/ha SNS).

Almost all SNS prediction methods, including FAM, performed better (by reducing profit foregone) than assuming a fixed SNS of 100 kg/ha (Summary Table 2). However, this should not be taken to represent current practice, and other potential simple methods based on fixed values were not tested. Whilst measures of SNS explained more variation in harvested SNS than FAM, unadjusted SNS measures were often less accurate than FAM (Summary Table 2), even after constraining maximum predictions to 200 kg/ha, so the economic performance of the unadjusted SNS measures (i.e. SMN + Crop N without estimates of mineralisation or recovery) was worse than FAM. This arose because autumn SNS tended to over-predict harvested SNS especially at high SNS levels, and spring SNS under-predicted harvested SNS (by 32 kg/ha on average). In addition, there was greater scope to get predictions very wrong using measured SNS than when using FAM SNS as high (>160 kg/ha) or very low (<50 kg/ha) predictions are not possible with the FAM.

Summary Table 2. For the new dataset, effects on accuracy (mean bias), precision (coefficient of determination; r^2), and profit of using different methods to predict harvested SNS. In each case, maximum predicted SNS was 200 kg/ha.

Prediction approach	Accuracy		Precision			Profit foregone	
	Mean bias kg/ha	slope	r^2 with lin. regres'n	r^2 'as is' i.e. y=x	% errors >50 kg/ha	Average £/ha	% sites >£40/ha
Without adjustment							
Fixed 100 kg/ha	-6	0	0.00	0.00	20%	16.61	10%
FAM	-10	1.27	0.27	0.14	18%	12.20	8%
Autumn SNS 0-90	-6	0.65	0.39	0.27	15%	14.65	7%
Autumn SNS 0-60	-20	0.67	0.41	0.16	27%	14.74	9%
Spring SNS 0-60	-46	0.85	0.39	0.00	40%	22.21	20%
Spring SNS 0-90	-32	0.82	0.49	0.08	30%	14.93	9%
Spring SNS 0-90 + AAN*	-9	0.84	0.52	0.47	14%	9.61	4%
Spring SNS 0-60 + AAN*	-10	0.82	0.44	0.38	16%	11.07	5%
Spring SNS 0-90 + SOM	-29	0.79	0.50	0.14	28%	14.15	9%
Spring SNS 0-90 + 20	-13	0.87	0.49	0.42	17%	10.22	7%
Spring SNS 90+20+SOM	-11	0.83	0.48	0.41	18%	10.53	7%
With slope and intercept adjustment							
Autumn SNS 0-90	-3	0.90	0.42	0.41	21%	11.13	5%
Spring SNS 0-90	-3	1.00	0.49	0.49	13%	9.50	6%
With leaching adjustment							
Spring SNS 0-90 + AAN	- 10	0.87	0.56	0.51	13%	8.63	4%
With leaching, slope and intercept adjustment							
Autumn SNS 0-90	-5	0.88	0.49	0.47	17%	10.06	4%
Spring SNS 0-90 + AAN	-3	0.97	0.57	0.57	12%	8.01	3%

*GrowHow Nmin Method Options

If appropriate adjustments are made to SMN-based predictions to correct for bias, then they could be more worthwhile than predictions from FAM by up to an average £4/ha overall, or up to £10/ha in situations where SNS was expected to be high and uncertain. These benefits, however, were without considering the costs of sampling and analysis. Clearly, costs need to be less than ~£10 /ha for measurements to prove worthwhile. Where SNS is expected to be low (<120 kg/ha) e.g. on light, shallow or medium soils, no average benefit could be shown from SMN-based predictions of SNS.

Comparing SMN-based predictions, sampling in spring explained more of the variation than autumn sampling, and gave a better economic performance, but only if adjustments for deposition/mineralisation (i.e. an intercept) or AAN measures were used. Without these adjustments there was little difference between autumn and spring measured SNS. Sampling in autumn to 60 cm rather than 90 cm depth gave similar results, whereas in spring, shallower sampling was substantially worse at predicting harvested SNS.

Mineralisation measures improved predictive power in spring, but not in autumn. Total soil N% and SOM% give useful information regarding mineralisation potential. The implied relationship within RB209 of 10kg/ha N being mineralised for each 1% increase in SOM% above 4% provides a sensible basis for judging mineralisation, but further calibration is required to provide robust predictions of likely additional mineralisation. GrowHow calibrated AAN measures gave improved prediction of harvested SNS, and reduced the value of slope and intercept adjustments.

Using a mineralisation/deposition estimate of 20kg/ha across the board improves predictions from spring SMN measurements in this dataset. There is some uncertainty whether such an adjustment would still be appropriate following a dry mild winter is spring SMN measures were generally high. The implications for such an adjustment on fertiliser recommendations need to be carefully considered.

Both autumn and spring predictions could be improved by estimating N leaching after sampling, using soil type and rainfall information. Inclusion of estimates of bulk density or soil stone content provided little overall improvement in predictions, and crop N estimation method had little effect.

The analysis suggests that for a benefit to be seen from soil sampling, especially in spring, adjustments are required to account for the difference in the relationship between measured SNS and harvested SNS from 1:1; intercepts were around 40 kg/ha and slopes were around 0.6 for autumn and 0.8 for spring measures. Such adjustments for deposition and recovery have been suggested before by Knight et al. (2008). The relationships found between soil measured SNS and harvested SNS in this project support the concept that an amount of N will become available to the crop through deposition and mineralisation (~40kg/ha), however low the measured SMN, and that only a proportion of the SMN will actually be recovered by the crop (perhaps 70% by harvest, or less before yield is determined). In the past it has been assumed that there is a 100% equivalence between measured SNS and crop N uptake, because it has been assumed for the sake of simplicity that N that becomes available from deposition or mineralisation approximately balances the SMN that is not recovered by the crop. Indeed, on average this is found to be the case, other than in situations where SMN is very high or very low. Given that specific adjustments for intercept and slope, or deposition and recovery, add complexity to the estimation of SNS, and in the majority of cases make relatively little difference to the SNS estimate, further consideration is required before recommending them for widespread use. There is also a risk that the use of inappropriate slope and intercept adjustments risks making predictions worse on average. A simpler approach which would limit the extent of under or over prediction might to fix SNS predictions of <50 or >160 kg/ha at 50 and 160 kg/ha respectively except for situations where there is confidence based on past experience that harvested SNS will really be very low or very high. However, this approach would need wider discussion before it could be advocated generally.

2.4. Discussion and key conclusions

Data examined in this project (from previous research) show that estimating SNS is an important part of N decision-making. Harvested SNS explained around 60% of the variation in fertiliser N optima (the N requirement); the other components of N demand and fertiliser recovery had less influence on N requirements and were less predictable. Thus all SNS prediction methods, whether cost-free (i.e. FAM), or based on soil and crop measurements, had clear advantages over ignoring variation in SNS altogether (i.e. fixed SNS in Summary Table 2) when deciding on N use. However, the range of SNS values encompassed within this project was much wider than would be typical of most ‘normal’ arable farms, and it was clear that our current ability to predict harvested SNS is (scientifically) weak. The best adjusted SNS prediction methods explained about half of the variation in harvested SNS, and only one quarter of variation was explained by the FAM (Summary Table 2). Nevertheless, it is doubtful whether the more sophisticated and costly prediction methods could be justified economically, except in a minority of circumstances, e.g. high grain and fertiliser prices, and large, uniform areas with high expected SNS.

This conclusion arose because (although they explained more variation than the FAM overall) SNS predictions from soil measures could include larger errors and bigger inaccuracies than the FAM. FAM approaches could never hope to explain all the variation seen in harvested SNS across different farm situations, but FAM performed surprisingly well in predicting harvested SNS on average. However, getting good value from the FAM clearly depended on its careful use; inaccurate assessments, especially of organic soil status, and grass and manure history, could substantially reduce the value of FAM predictions.

This is perhaps a more challenging conclusion than in some previous studies (e.g. Sylvester-Bradley et al., 2008), but it concurs with others (e.g. Orson, 2010). The strength of the relationship between measured SNS and harvested SNS was greatest on silty and clayey soils where the spread in expected SNS values was large. It was weakest on light and shallow soils and where the spread in expected SNS values was modest, e.g. <~120 kg/ha.

It seems likely that the weakness of SNS predictions is largely due to inherent spatial variability of soil properties and temporal variability of many processes (N inputs crop uptake, immobilisation, mineralisation, deposition and N leaching). However, variability in measured SNS can be minimised by:

- ensuring sufficient cores are taken to give a representative sample;
- judicious sample mixing and sub-sampling;
- keeping samples cool (but not frozen) once taken;
- minimising sample storage before analysis;
- regularly standardising lab tests; and
- assessing crop N appropriately at the time of sampling.

Autumn SNS predictions based on SMN measures risk over-predicting harvested SNS on average, especially where 0-90 cm measures rather than 0-60 cm measures are made. Leaching adjustments based on soil type and rainfall, and / or slope (recovery) adjustments are required to mitigate this risk.

Spring SNS predictions based on SMN measures risk under-predicting harvested SNS on average. Measures of likely mineralisation, or inclusion of a ‘deposition / mineralisation’ estimate help to mitigate this risk.

While benefits could accrue from use of slope and intercept adjustments to measured SNS, differences to the SNS predictions used would be small except at the extremes. Further investigation is needed to assess the potential to make such adjustments as they would add complexity and could risk causing confusion.

Given the relatively small (or even negative) economic benefits found from knowledge of SMN to inform SNS predictions over FAM, even before the costs of sampling are accounted for, consideration needs to be given to where and how SMN sampling should be advised.

It is clear that in normal situations SMN sampling cannot be advocated as a tool to be used to determine N recommendations for every field in every year; as well as being expensive this would probably also lead to spurious minor adjustments to N use which would risk delivering worse average financial returns than following the FAM or ‘farmer experience’. It seems that SMN testing cannot be advised for profitable use in minor ‘fine-tuning’ of N use on a field by field basis.

It appears that there remain two situations in which SMN testing may prove useful in informing N management on the farm:

- In helping to ascertain average levels of SNS for a farm, or for blocks on a farm with different soil types, rotational positions and management, and in showing how these relate to FAM estimates for those situations. Whilst information on seasonal variability may be provided, the biggest benefit may derive from understanding SNS levels on the farm on average. This use of SMN testing will mainly arise when a grower initially assumes responsibility for land. The benefit of such SMN testing is likely to diminish with time, unless substantial changes are made to the farming system.
- In helping to identify and manage individual fields where expected SNS levels are very different to the average for the farm, especially where SNS is very high or uncertain.

2.5. Key messages and recommendations

2.5.1. Assessment of harvested SNS

- A prediction of harvested SNS should always be made as part of decision making on N for arable crops, whether by FAM or by soil sampling.
- It should be appreciated that all current prediction methods for harvested SNS have poor precision, so the decision-making process should employ appropriate caution, including double-checking.
- The Field Assessment Method described by RB209 or SAC-TN625 should be used with care, paying particular attention to accurate description of soil type, assessment of soil organic matter content if this is likely to be moderate or high, and acknowledgement of field history, especially if grass or manures have been involved at least in the last decade.
- FAM predictions of SNS are best used where SNS is likely to be moderate or small (<120 kg/ha, below SNS Index 4) e.g. on mineral soils with arable crops without grass or manures in a field’s history. In most arable situations FAM is the most cost effective method for estimating SNS.
- Measuring SMN becomes progressively more worthwhile as SNS (as predicted by the FAM) increases beyond 120 kg/ha, or where SNS is uncertain. This includes situations where organic manures have regularly been used in the past, where there is a history of long term grass and following vegetable crops which have left N-rich

residues. SMN testing gives best predictions on deep retentive (clay and silt) soils in low rainfall areas. Conversely, SMN measurement can give poor predictions of harvested SNS on light and shallow soils, or where SNS is expected to be small.

- SMN measurement may prove useful as part of a more comprehensive N monitoring approach (e.g. including FAM, crop growth, lodging, grain yield and grain N%) applied to large areas across a farm, and especially as a grower seeks familiarity with new blocks of land. In particular, SMN measures can provide a check of how SNS levels on the farm compare to RB209 expectations.

2.5.2. Sampling methods for SMN determination

When to sample

- Sampling in spring (February) gives slightly better predictions of harvested SNS than sampling in autumn (November), though the difference on clay and silt soils is small.
- Autumn SMN measurements have the advantage that soils only need to be sampled to 60 cm, whereas spring sampling should be to 90 cm.

How to sample

- The number of samples per field that should be taken depends upon the level of SNS expected, the variability expected and the size of the field. Generally 10-15 samples is sufficient; taking more than this is unlikely to be cost effective, except where fields are highly variable or are large (<20ha) and SNS is expected to be high (<160kg ha).
- Sampling in a W pattern (as opposed to more complex arrangements) is adequate to give representative samples.
- Ideally sub-sampling in the field should be avoided. If bulk samples are too large for dispatch to the labs, then representative sub-sampling is required. Excessive mixing of samples should be avoided as this can stimulate mineralisation. The best approach is to take many small portions of soil from the bulk sample to form the sub-sample.

Transport and analysis

- It is crucial that samples are kept cool during storage and transport, to the laboratory, and they should be analysed within three days. Samples should not be frozen except for research purposes.
- Continued annual ring-tests are important to ensure that any systematic differences between analytical laboratories are identified and corrected.
- A standard bulk density (1.33 kg/l) is adequate to predict harvested SNS; bulk densities specific to soil type and depth give little improvement in predictions.

- No evidence has been found to show value in adjusting for stone content. If adjustments are made, care is needed to ensure that stone contents are not over-estimated.
- It is important that crop N at the time of SMN sampling is estimated and included in the estimate of SNS. Visual estimation methods are usually adequate. A number of approaches for estimating crop N in wheat and oilseed rape are available, estimates from shoot counts of GAI in wheat are satisfactory, in oilseed rape assessment of GAI gives the best estimate of crop N. There is no evidence that crop N in oilseed rape should be treated differently to that in other crops when estimating SNS.

2.5.3. Mineralisation tests

- Indicators of mineralisation do not seem to add predictive power to SNS estimates made in autumn.
- Measures of AAN (PMN estimated by a proprietary calibration from anaerobic incubation) improve predictions of SNS in spring.
- Measures of total soil N (%) and SOM (%) are also useful indicators of mineralisation, and they might overcome the need for annual measurements of AAN, but they have not yet been calibrated to give predictions of AAN. The implied relationship within RB209 of 10kg/ha N being mineralised for each 1% increase in SOM% above 4% provides a sensible basis for judging mineralisation, but does not perform as well as a predictor of mineralisation as AAN.
- Using a mineralisation/deposition estimate of 20kg/ha across the board improves predictions from spring SMN measurements in this dataset. There is some uncertainty whether such an adjustment would still be appropriate following a dry mild winter is spring SMN measures were generally high. The implications for such an adjustment on fertiliser recommendations needs to be carefully considered.

2.5.4. Interpretation issues

We suggest that organisations offering N advice based on SMN testing could jointly consider the following points in order to standardise their approaches and hence improve the confidence of their clients in SMN testing:

- Estimates of SNS from large SMN values can seriously over-predict harvested SNS. It may be sensible to treat SNS estimates exceeding 160 kg/ha as predictions of 160 kg/ha and no more, unless field experience has shown that greater amounts of soil N can confidently be expected to be taken up by the crop.

- Estimates of SNS from small SMN values can under-predict harvested SNS. It may be sensible to treat SNS estimates of less than 50 kg/ha as predictions of 50 kg/ha, not less, unless field experience can be used to confidently expect that very little N will become available.
- Where SNS predictions are very high, and fertiliser N rates are cut back, growers could be advised to monitor the crop closely through spring for signs of N deficiency. Then where necessary, adjustments to the planned N strategy could be made as appropriate.
- SMN measures in autumn tend to over-predict harvested SNS, so they may require adjustment to give predictions better accuracy on average. Possible adjustments are for over-winter rainfall, or for SNS recovery.
- SMN measures in spring tend to under-estimate harvested SNS. This could be rectified by adding a fixed amount (representing N deposition or mineralisaton) and/or by including a measure of mineralisable N. Consideration is needed as to whether such adjustments are appropriate in all situations, and whether such adjustments are really appropriate in the context of current recommendation systems.

2.6. Recommendations for future work

Given the estimate that a combined use of FAM on most fields (and SNS measurement on a minority) can achieve ~98% of fields with margins over N cost within £40/ha of the maximum possible, it is questionable whether further experimentation specifically on SNS measurement will be worthwhile. This is not to say that SNS prediction using FAM could not be improved, and confirmation of maximum harvested SNS uptake on light and shallow soils would be valuable to growers with potentially high SNS on these soils.

There is possible scope for further analysis and modelling of the extensive and valuable new dataset generated here, e.g. developing predictions of AAN from soil N%, or refining predictions of N retention after sampling in autumn or spring. However, it is doubtful whether extensive further research specifically on SNS prediction systems, which could only save an average of ~£10/ha, could be considered worthwhile.

What may prove more beneficial is the development and validation of a more holistic approach to managing N fertiliser decision-making on the farm, which acknowledges farm to farm differences separately from within-farm aspects of farming systems. We suggest a ‘Farm N profiling’ approach should be tested that would integrate a wide range of information sources, including farmer experience as well as soil and crop assessments, to build a picture of how current N use on a farm relates to optimal N management. This could identify and resolve the farm to farm differences that are seldom explicit in multi-site experimentation but which some allied research projects have shown to be important. Thus, future work should address prediction of crop N requirements holistically, by assessing all its components together (harvested SNS, crop N demand, and fertiliser N efficiency), not just SNS (as here). This work should examine variation in crop N requirements at different levels separately: farm to farm, between rotational positions, between years, between fields and within fields; and it should develop and evaluate targeted approaches for predicting and managing each level of variability.

3. TECHNICAL DETAIL

3.1. Introduction

3.1.1. Project objectives and background

The use of soil mineral nitrogen (SMN) in estimating soil N supply (SNS) has been the subject of uncertainty in the industry and in recent HGCA reports. This project was set up to address these uncertainties, provide best practice advice and build confidence in the estimation of SNS.

3.1.2. Project objectives

Overall aim

To achieve consensus across the industry on best practice for estimation of SNS.

Specific objectives

1. To collate and consider stakeholder concerns about estimation of SNS, and (at the end of the project) to present stakeholders with evidence for best practice.
2. To collate unpublished data on measurements of SMN and prioritise uncertainties.
3. To establish best practice for interpretation of SMN analysis, including sampling depth and assessments of potentially mineralisable N (PMN).
4. To evaluate uncertainties in SMN results, including field sampling methods, sample handling and transfer, and laboratory processing and analysis.
5. To determine the most appropriate method for interpreting over-winter assessments of crop N in oilseed rape.
6. To compare and evaluate approaches for the prediction of SNS both from soil measurements and field assessment methods (FAMs), then to provide guidance on where and when SMN analyses are best used to inform on-farm SNS estimation.

As well as the initial HGCA funding for this project additional funding from GrowHow, HDC and PGRO allowed a larger dataset of SNS measures to be generated, allowing a wider range of situations to be explored, especially for sites following vegetable crops and pulses.

3.1.3. Background

The decisions that farmers make when deciding how much fertiliser N to apply are primarily, though not exclusively, founded on the amount of N that will be available to the crop from the soil; the SNS. Variability in SNS between different fields, situations and years can be large. Values for a given situation are given by a field assessment method (FAM e.g. as in The Fertiliser Manual, Defra, 2010; hereafter referred to as RB209), but these are necessarily averages of a wide range of possible values. For the past 20 years the ‘gold standard’ for predicting SNS in most situations has been SMN sampling, yet sampling and analytical techniques for the SMN method still vary, and little guidance exists to inform best practice. Some in the industry have even questioned its value altogether in recent years. In HGCA Research Review 58 Knight (2006) identified various issues that surround the SMN method. These included estimating crop N, sampling time, depth and intensity; sample storage, transport and processing; and analysis and interpretation. While much work has been undertaken on these issues in the past, this has not always entered the public domain (e.g. Silgram 1997; Silgram & Goodlass 2006). Research Review 58 highlighted the need for a set of guidelines of best practice for the SMN method, and possible accreditation of practitioners. In addition, practices that could reduce the cost of the SMN method (e.g. using shallower sampling depths) or improve its predictive accuracy (e.g. estimating potentially available N by incubation or by considering total N%; Bhogal et al. 1999) need to be evaluated.

Subsequently, HGCA Research Review 63 (Richards, 2007) recommended that
“The different methods for quantifying soil nitrogen supply, by estimation, measurement or both, need to be validated and compared. The relative contributions of soil mineral nitrogen, nitrogen mineralised during spring and nitrogen taken up by the crop over winter need to be clarified. Guidance is then needed on the appropriate choice of method for different circumstances taking account of cost and the degree of accuracy required.”

This project seeks to address these recommendations in full. Key uncertainties in direct measurement of SMN are identified and recommendations for best practice are given. On-farm strategies for using direct SNS measurements will then be compared with the FAM from RB209, and best strategies evaluated for different field and farm types.

The expense of SMN sampling means that its use is likely to be most worthwhile where potential fertiliser savings are large i.e. where expected SNS is large or variable. But there is a need to identify more exactly where and when the SMN method is of greatest benefit, and how results can be used to improve N planning across the whole farm. In addition, rigorous and transparent information is required by the industry to ensure confidence in all the approaches available to estimate SNS.

This project, involving a broad consortium, draws on previous published and unpublished data and reports, publications, expertise and on-going projects as well as providing new data. It uses a robust framework to identify best practice for predicting SNS, using *crop N uptake near harvest without applied N* as the definitive measure of SNS i.e. harvested SNS. A cost-benefit analysis of best-practice identifies where and when the use of soil measurement is worthwhile in farm situations.

Defining Soil N Supply

SNS is defined in RB209 as:

> "The amount of nitrogen (kg/ha) in the soil (apart from that applied for the crop in manufactured fertilisers and manures) that becomes available for uptake by the crop in the growing season, taking account of nitrogen losses"

Thus here, as in most recommendation systems world-wide, SNS is defined by N uptake of the mature crop grown without fertiliser (Sylvester-Bradley *et al.* 2001), and we describe it by the term: 'harvested SNS'.

Predictions of harvested SNS may be made at any time throughout the preceding growing season in which case predicted SNS may be derived from estimates (sometimes but not always measurements) of N already in the crop plus the N that will come from the soil (i.e. not from fresh fertiliser). Over winter, the bulk of measured SNS is SMN (nitrate N plus ammonium N which are readily available to the crop). As growth proceeds through the winter and spring increasing amounts of measured SNS are found in the crop. There are also contributions to harvested SNS from spring and summer mineralisation of soil organic matter and from atmospheric N deposition, so these may be included within SNS predictions.

Harvested SNS can be measured directly by maintaining a crop without fresh fertiliser N until harvest, then measuring its grain yield, the grain N content (%) and the N harvest index (ratio of grain N to total crop N, excluding roots), and calculating as follows:

$$\text{Harvested N (kg/ha)} = \frac{\text{grain yield (t/ha at 85\%DM) x grain N (\% DM) x 8.5}}{\text{N harvest index (ratio e.g. 0.75)}}$$

In this project this measure of harvested SNS is used as the ‘best’ estimate of SNS, as it affects requirements for fertiliser N.

Clearly, this measure of harvested SNS will not necessarily reflect the quantity of soil-derived N that is taken up by a crop receiving N fertiliser. For instance acquisition of soil N may increase under stress, or conversely fertiliser N will increase growth and rooting so increasing uptake of soil-derived N. However, harvested SNS is the measure adopted here because it is easily and commonly used, and it is orthogonal with measurements of crop N demand (uptake of N by optimally fertilised crops), and hence estimates of apparent recovery of fertiliser N.

RB209 and the Scottish fertiliser recommendations (SAC TN625) classify SNS using index systems, as follows:

SNS (kg/ha)	Fertiliser Manual SNS Index	SAC SNS Index
< 60	0	1
61 – 80	1	2
81 – 100	2	3
101 – 120	3	4
121 – 160	4	5
161 – 240	5	6
> 240	6	6

However, units of kg/ha SNS are used throughout this report. Where necessary, SNS Index is converted to kg/ha by assuming a mid-point in the relevant range.

SNS as a component of N decision making

The N requirement of a crop is the amount of fertiliser N that proves optimal from an economic perspective; i.e. the rate which gives the highest profit. The accuracy of any system for predicting optimum fertiliser N is notoriously imprecise (Sylvester-Bradley, 1993; Delgado, 2002) and several studies have showed only weak relationships between SNS and N optima (Harrison et al., 1995; Sylvester-Bradley et al., 2008; Orson, 2010). However, it has become conventional to predict N fertiliser requirements from three components, as set out in the HGCA nitrogen for winter wheat management guidelines (Sylvester-Bradley, 2009):

- Crop N Demand
    - The amount of crop N that is taken up when the optimum amount of fertiliser N is applied.

- Soil N Supply
- Fertiliser N recovery
    - The efficiency with which applied fertiliser N is taken up by the crop

The crop N requirement equals:

$$\frac{\text{(Crop N Demand – SNS)}}{\text{Fertiliser recovery.}}$$

In most recommendation systems SNS is the most important of the three components because it tends to be the most variable, and this variability is to some extent predictable (or measurable).

Analysis of 53 N response experiments in the UK since 2000 shows the strong negative relationship between SNS and N requirement (Figure 1). If harvested SNS could be predicted perfectly, around 60% of the variation in N optima would be explained (Figure 1A). Predicting SNS by measuring SMN can explain around 40% of the variation in N optima (Figure 1B). By contrast, variation in crop N demand or fertiliser recovery explains very little of the variation in N optima (data not shown; 15% for crop N demand, 0% for fertiliser recovery). So it is differences in SNS that constitute the major predictable differences in N fertiliser requirements.

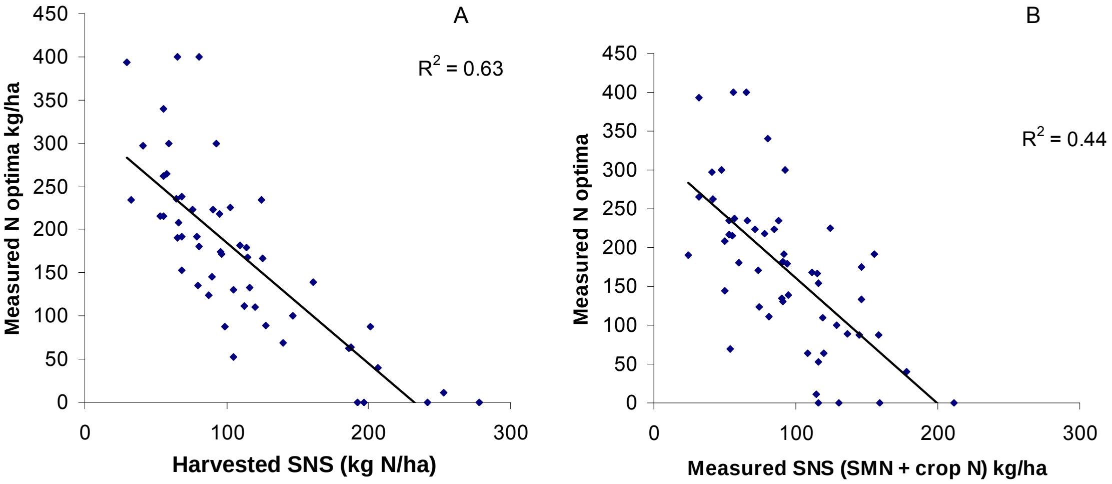


Figure 1. Relationship between SNS and measured N optima for 53 UK N response experiments since 2000. A) shows the relationship with harvested SNS (the definitive measure of SNS); B) with measured SNS by SMN sampling in autumn or spring.

Ways of predicting SNS

Predicting SNS before fertiliser decision-making can be achieved by (i) FAMs based on previous cropping, soil type and over-winter rainfall (e.g. RB209 or SAC-TN625), (ii) measurement of various N forms in the soil and crop, or possibly (iii) assessing crop N status remotely. A further approach that has been advocated by Orson (2010) is to ignore variation in SNS altogether in situations where SNS is likely to be low (eg long term arable rotations without additions of organic manure).

Field Assessment Method (FAM)

Soil N supply in fertiliser recommendations is generally based on some form of FAM, whereby information on soil type, over winter rainfall and previous cropping is used to estimate SNS. Whilst RB209 (or PLANET) is perhaps the most commonly used form of FAM, it is not the only source as different countries, and many fertiliser and distributor companies have their own recommendation systems (e.g. SAC TN625, GrowHow N-Calc, Yara N Plan).

Soil Mineral N testing

It is estimated that around 20,000 SMN samples are analysed by UK labs each year, relating to ~8000 fields being tested each year for SMN, predominantly in spring. Assuming an average field size of 10ha this represents less than 3% of the arable area, although SMN samples in many cases are used to inform a much bigger area. It is normally recommended (e.g. in RB209) that soils are sampled in 30 cm horizons to 90 cm depth in spring, 60 cm in autumn or 30 cm for shallow rooted crops. The fresh soils are then sent to the laboratory for analysis of ammonium-N and nitrate-N.

SMN Analysis Methods

The standard procedure for the analysis of SMN is described in MAFF Reference Book 427, The Analysis of Agricultural Materials (Anon., 1986). In summary, 40g subsamples of soils are extracted in 200ml 2M KCl for 2 hours, the extract is separated from the soil by centrifuge, decanting or filtering and the extract is then analysed for ammonium-N and nitrate-N concentration by rapid flow analyser, spectrophotometer or flow injection analyser. The dry matter content of the soil is determined by weighing and drying in order to calculate concentrations on a per kg soil basis from the per litre extract basis.

Measuring mineralisable N

In addition to SMN testing some labs offer tests to estimate likely mineralisable N in the soil.

There have been a number of methods suggested for estimating mineralisable N, including the Hot KCl technique (McTaggart, 1992; Bhoga et al., 1998; Fisher et al., 1996) which is not commercially available at present.

Anaerobic incubation is the most commonly used measure of mineralisation, as used by Hill Court Farm Research for GrowHow. Soil mineral N (ammonium and nitrate) measures are made before and after incubating the wetted soil in a sealed flask for seven days (Keeney & Bremner, 1966). After incubation ammonium is extracted with 2 M KCl. The N released by anaerobic incubation is calculated as the difference between the mineral N present before and after incubation.

The total amount of N mineralised by anaerobic incubation is termed *Potentially Mineralisable N (PMN)*. This is often much larger than the amount of N that is normally observed to become available to a growing crop. A prediction of the amount of N that will become available has been made by Hill Court Farm Research for GrowHow from calibrations (see Annex 4) and is termed *Additionally Available N (AAN).* Commercially, this has been offered as the Grow How N-Min® service which includes 3 options: 1) Spring SNS 0-90 + $AAN_{90;}$ 2) Spring SNS 0-60 + $AAN_{60;}$ 3) Spring SNS 0-30 + estimate of N in the 30-60 cm + AAN_{60}. In the last option, where samples are only taken to 30cm, the N in the 30-60cm profile is estimated from 200 regional calibration measures taken each year. The AAN measure in the N-Min prediction may also account for some N in the 60-90cm profile, so a different AAN calculation is used for 0-60cm measures (AAN_{60}) than 0-90cm measures (AAN_{90}). In this study we therefore consider AAN_{90}, AAN_{60}, SNS 0-60 (measured) and SNS 0-60 (calibrated) separately.

In addition to direct measurements of potential mineralisation, measures of soil organic matter and soil total N% can be indicative of likely mineralisation (Sylvester-Bradley et al., 2008). SOM fractions have been widely investigated in the literature for their differing relationships with mineralisation, though Ros *et al*. (2011) have recently concluded that no single organic matter fraction can be adequately used to predict mineralisation. Organic matter fractions are not considered further in this project.

A relationship between SOM and likely mineralisation is implied in RB209 and the HGCA N management guide of roughly 10 kg/ha per 1% increase in SOM above 3-6%. This is only meant to be indicative and has not previously been tested.

Remote sensing

Differences in SNS can be detected by crop sensors such as the Yara N sensor, Crop Circle, Greenseeker, or by satellite imagery (Sylvester-Bradley et al., 2009). However, whilst it is possible to detect spatial differences, it is not yet proven that such technologies can be used to predict SNS on an absolute basis. This is being investigated in HGCA project 3530 (LINK project 09134) and is not explored further here.

Issues to resolve

Causes of variation in measured SNS and harvested SNS

Systematic variation

A large number of factors influence the supply of N from the soil, which, as these factors vary between and within fields, will cause differences in SNS between fields and years. Differences in rotation reflect differences in N inputs (by fertilisers, manures or N fixation by legumes) and N off-takes (N in the harvested products – grain, seeds, tubers, roots, straw and residues) cause differences in the residual N in soil and crop residues in autumn. Differences in soil type and soil texture cause differences principally through the amount of N lost through leaching over winter and in early spring. Differences in over-winter rainfall do likewise. Differences in soil organic matter can also give differences in the amount of mineralisation before and during the growing season.

To the extent that the above factors are known they can be used to predict differences in SNS; these factors form the basis of FAMs.

The extent of spatial variation will depend on the extent to which these factors also vary; principally soil texture, organic matter and the balance of past N inputs / N off-takes.

To the extent that we cannot accurately and precisely know these factors (due to the resources required to capture the spatial and temporal variability) and because they are influenced by processes that vary with weather (e.g. temperature for mineralisation / immobilisation), and because the processes themselves are not understood in enough detail to give accurate quantitative predictions, there will always be substantial uncertainties on any predictions of SNS with or without direct measurement.

To be able to improve our predictions of SNS we need to evaluate the importance of the above factors in determining final harvested SNS, in order to guide future systems for predicting SNS in the most promising direction.

'Errors' in soil measurement

When undertaking soil sampling to measure the amount of available N in the soil (nitrate-N and ammonium-N in the soil solution) there will be spatial (horizontal and vertical) and temporal variability that we must accept will cause variability in any relationship between SNS measured at a given time and final harvested SNS. But in measuring SNS at any given time there are five issues that can potentially cause substantial deviation from the 'true' SNS at that time:

- Representative sampling (number of measures, sampling pattern etc)
- Constitutive changes in the sample between sampling and analysis (storage and handling)
- Systematic and random variability in laboratory analysis
- Conversion from laboratory results of soil N concentration (mg/kg) to a quantity per area (kg/ha), affected by bulk density and soil stoniness
- Estimation of N already in the crop

Each of these issues is considered in some detail in this report.

Predicting final SNS

Once a measure or estimate of SNS has been made at a given time in autumn or spring, even if perfect, we cannot expect this to relate perfectly to final harvested SNS because of the multitude of soil and crop processes that occur through the subsequent life of the crop. Prediction of final harvested SNS may be improved by accounting for N losses (leaching and immobilisation) and N additions (deposition and mineralisation) that are likely to occur after soil sampling, and these are examined in the report. However, many other factors have not been examined, and must remain contributors to the unexplained error in prediction of harvest SNS.

3.2. Project approach

3.2.1. Task 1: Building consensus through stakeholder engagement

This project aimed to achieve some consensus across the industry on best practice for estimating SNS. To help achieve this, a Steering Group met regularly through the project involving Ian Richards as chair with representatives of HGCA, ADAS, TAG, SAC, Rothamsted Research, NRM, Hill Court Farm Research, Eurofins, Scottish Agronomy, GrowHow UK Ltd, HDC and PGRO. In addition, well-attended Stakeholder meetings were held at the beginning of the project in 2008 (HGCA offices, London) and at the end in 2011 (PGRO, Peterborough). Invitees included Defra, government agencies (e.g. Environment Agency), industry bodies (e.g. NFU and AIC), distributors (e.g. Masstock, Hutchinsons, Frontier and Yara), agronomists, laboratories and soil sampling practitioners (e.g. SOYL and Envirofield). Stakeholders were given the chance to contribute to the direction of the project at the start, and initial analyses of results were shared at the end of the project when views on final conclusions were sought.

3.2.2. Task 2: Review of past data

Much work has been conducted on SMN sampling and SNS since 1980, in the UK and across the world. Not all of the relevant UK information has been fully published. An exercise was conducted at the start of the project to collate as much available data together as possible from all organisations. A dataset was created containing all available data where SMN had been measured in conjunction with measures of harvested SNS (grain yield and grain N% of unfertilised crop). If N harvest index (NHI) information was not available this was assumed to be 0.75 so that crop total N yield could be estimated from grain N yield (TNY = GNY / NHI).

An exploration of the variation in these estimates of harvested SNS is described in section 3.3. Information collated in this exercise was also used where appropriate through each other chapter of this report.

3.2.3. Task 3: Generating new data for evaluating SNS prediction

In addition to the data collated in Task 2, a new data set was generated using a total of >150 sites over three years where soil measurements were made in autumn and spring, and crop measures made at harvest, to allow different approaches to SNS prediction to be evaluated. This exercise is reported in section 3.6.

3.2.4. Task 4: Studies to assess uncertainties in sample handling, storage and analysis

Following the data review in section 3.1, specific issues surrounding the measurement of SNS were investigated. This included laboratory standardisation exercises and studies investigating the effects of sample handling and storage. These are reported in section 3.4.

3.2.5. Task 5: Studies of crop N in oilseed rape

In years which allow substantial growth over-winter, oilseed rape crops in spring can contain over 100 kg/ha N. Including all of this within an estimate of SNS, together with SMN, can lead to very small recommendations for fertiliser N. There has been concern from industry over whether this N should truly be seen as equivalent to soil N. Studies were conducted to investigate this, and these are reported in section 3.7.

3.2.6. Task 6: Cost-benefit analyses to give best practice advice

Analyses of the ‘best’ approaches for SNS prediction, including financial analyses, have been made in section 3.8.

3.3. Exploring past data to assess variability in harvested SNS and soil measurement

Many factors affect SNS and its uptake by the crop, so there can be great variation in SNS temporally and spatially. SNS is increased by processes which add available N to the soil, such as:

- Addition of mineral N fertilisers and organic manures to previous crops
- Defecation and urination by livestock (this can be spatially very variable)
- Annual deposition of N from rain and the atmosphere
- Return of high-N crop residues to the soil
- N fixation by legumes as previous crops
- Ploughing out of long term grass can release a lot of N over a long period as organic matter from old roots and leaves is mineralised
- Mineralisation of soil organic matter tends to be greatest where;
    - SOM levels are high
    - C:N ratios are low (leafy residues not straw residues)
    - Temperatures are warm
    - Soils are moist

SNS is reduced by processes that remove N from the soil, or convert available mineral N into unavailable (organic) forms:

- Crop N uptake and removal in harvested products and straw.
    - High yielding crops tend to take up more N than lower yielding crops
- Immobilisation of N by soil flora and fauna is increased where:
    - Mineral N levels are high (i.e. after fertiliser application)
    - C:N ratios of added OM are high (eg after incorporation of cereal straw)
- (The N immobilised by soil microbes is often mineralised later in the season, so is often available to the succeeding crop)
- Leaching of mineral N from the soil is greatest where:
    - Soils are coarse in texture, or highly fissured so not retentive of water (e.g. sands and not silts)
    - Rainfall over-winter is high, so drainage is high
- Volatilisation of N can lead to significant losses of N (as ammonia from mineral fertiliser and organic manures) to the atmosphere before the N is incorporated into the soil. Volatilisation is not a major loss pathway for N already in the soil.
- N can also be volatilised to the atmosphere as nitrous oxide formed through denitrification where soils are moist and warm with concentrated nitrate. However, quantities lost are generally small.
- Processes such as drought and compaction may restrict uptake of available N. These are not normally considered in assessments of SNS, but may affect harvested SNS via differences in recovery.

The balance of the processes above determines the SNS for any given area of soil at any given time, and ultimately the SNS taken up by harvest by an unfertilised crop. Figure 2 shows the distribution of harvested SNS for UK cereals from over 550 experiments conducted across a wide range of soil types, farming systems and geographic locations since 1980. This shows a wide spread in harvested SNS, ranging from less than 20 kg/ha up to 350 kg/ha. The majority of harvested SNSs were less than 100 kg/ha (corresponding to SNS Index 0, 1 or 2) although 40% of sites in this dataset have harvested SNS greater than 100 kg/ha (SNS Index 3 or higher) and 21% greater than 150 kg/ha. Mean harvested SNS is 102 kg/ha, the median is 90 kg/ha. Harvested SNS is not widely measured on-farm, but SMN is widely measured. Figure 3 shows a similar distribution for SMN measures as was seen with harvested SNS. Again, the majority of fields measured less than 100 kg/ha, with 35% of sites greater than 100 kg/ha. On average, 10 kg/ha less N was measured in the soil than got into the crop; mean soil-measured SNS was 91 kg/ha and median SNS was 80 kg/ha. Despite this, there are slightly more fields giving very high measured SNS by soil measurement (>250 kg/ha) than was seen taken up by the unfertilised crop (2% vs 0.5% >250 kg/ha respectively).

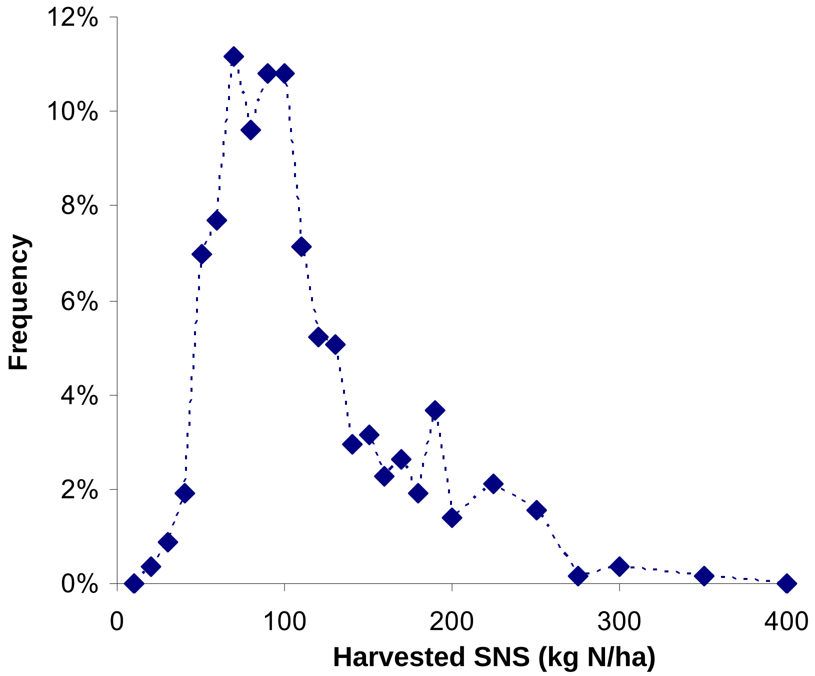


Figure 2. Frequency distribution of harvested SNS for >550 experimental sites in UK since 1980

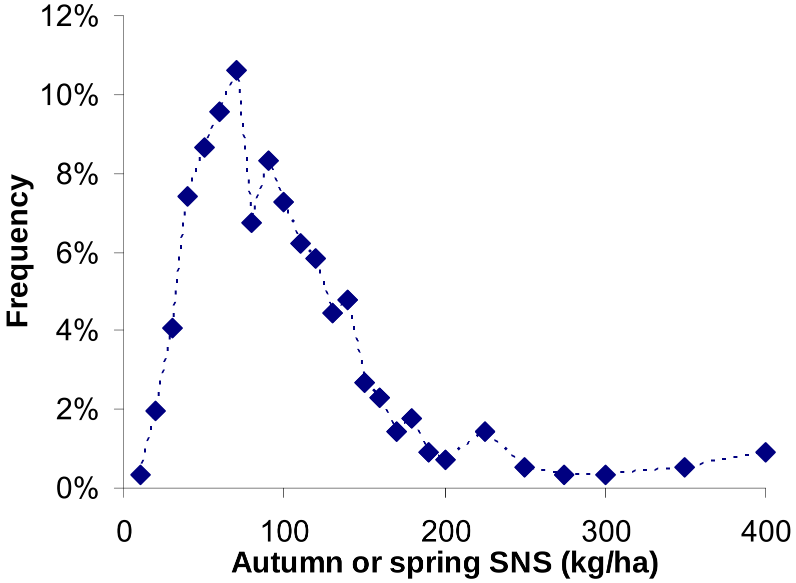


Figure 3. Frequency distribution of measured SNS for >550 experimental sites in UK since 1980

Systematic differences would be seen in the levels of harvested SNS in different situations (soil type, rainfall area, previous crop etc). However, there was still considerable variability within each situation (Figs 4 to 12).

3.3.1. Systematic differences in SNS

Differences in SNS due to soil type

The following frequency distributions show differences in distribution of harvested SNS and soil measured SNS between soil types (Figure 4 and 5). Very high levels of both soil measured SNS and harvested SNS were much less common on light and shallow soils than on the more retentive soil types.

Crop rotation

It can be seen in Figures 6 and 7 that harvested SNS and measured SMN tended to be low following cereal or sugar beet as a previous crop. Differences in harvested SNS following different crops reflect the differences in RB209, i.e. harvested SNS is greater following oilseed rape than following cereals.

Rainfall area

Where rainfall over winter is high as described by RB209 (over 700mm annual rainfall or over 250mm excess winter rainfall), losses of N to leaching are expected to be greater. Figures 8 and 9 show that a greater proportion of sites had harvested SNS of less than 100 kg/ha in high rainfall areas than in low (500-600mm annual rainfall or <150mm excess winter rainfall) or moderate rainfall areas.

History of manure use and grass

Where manure had been used in the past few years, or the field had been in grass in its recent history, there was a greater spread in harvested SNS, with more sites giving very high levels of measured SMN and final harvested SNS (Figures 10 and 11).

Soil organic matter

Partly linked to past manure use and grass history, sites with higher organic matter also tended to give high SNS levels (Figures 12 and 13).

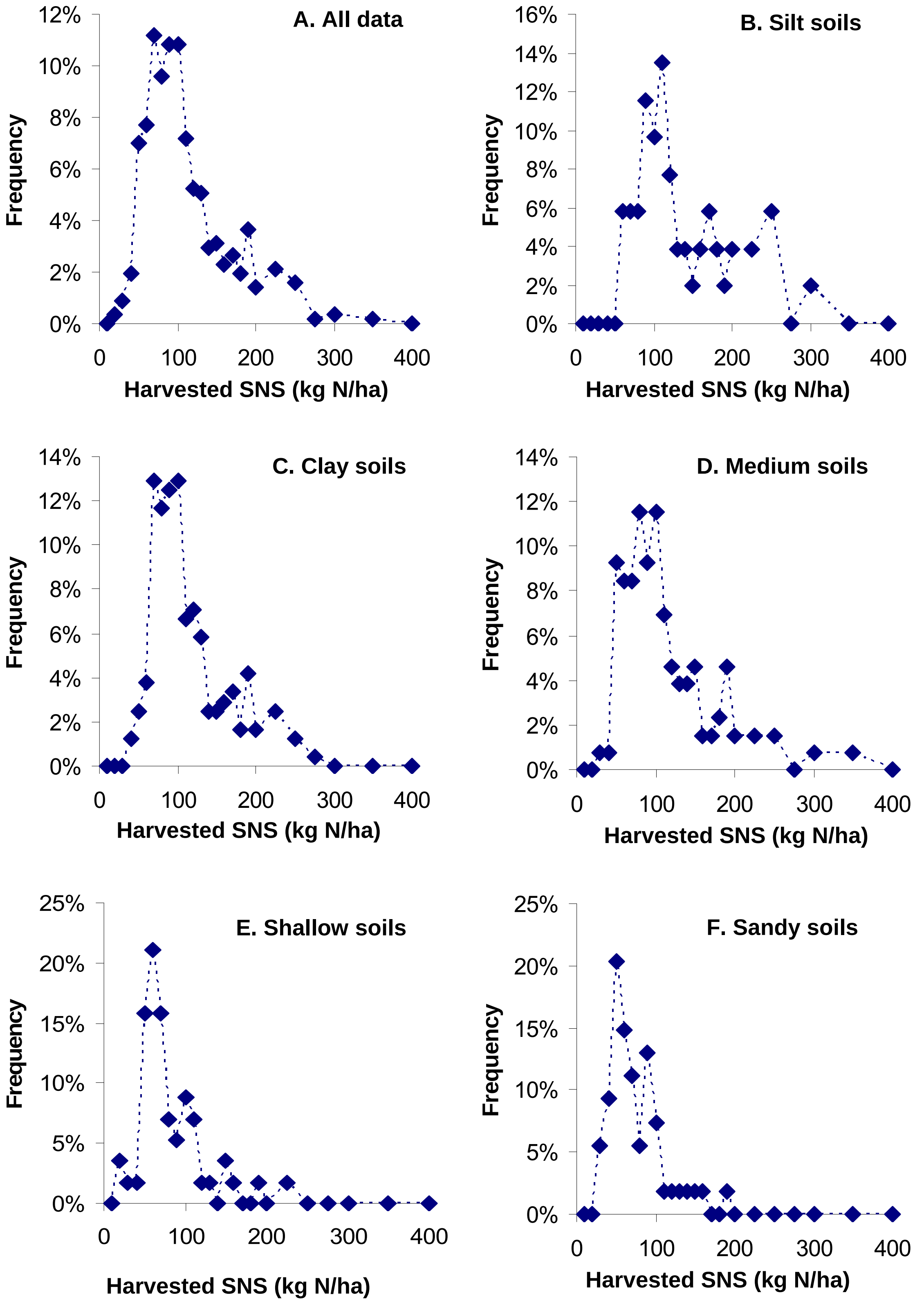


Figure 4. Frequency distribution of harvested SNS for >550 experimental sites in UK since 1980, for all data (a) and divided into different soil types, (b-f).

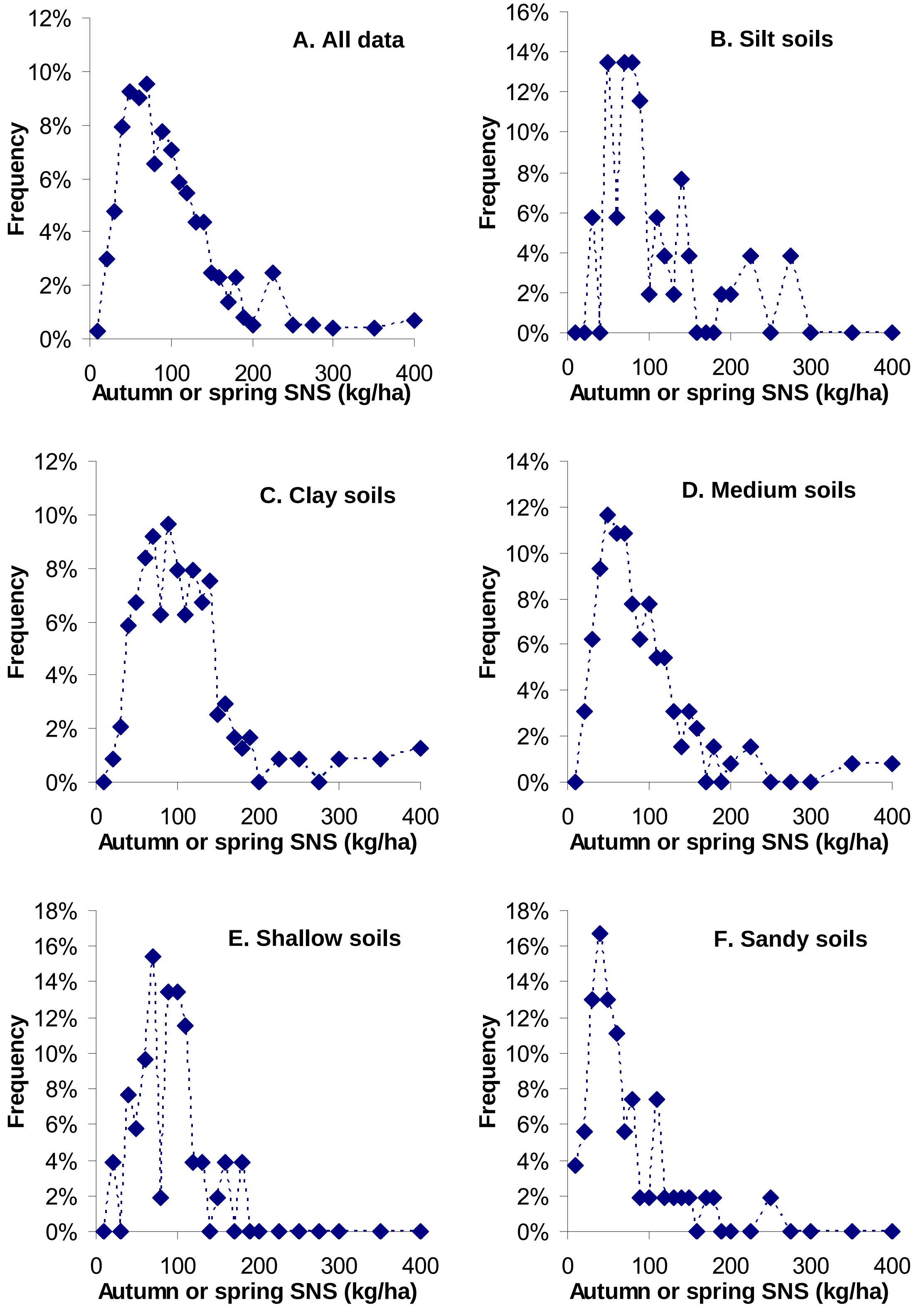


Figure 5. Frequency distribution of measured SNS for >550 experimental sites in UK since 1980, for all data (a) and divided into different soil types, (b-f).

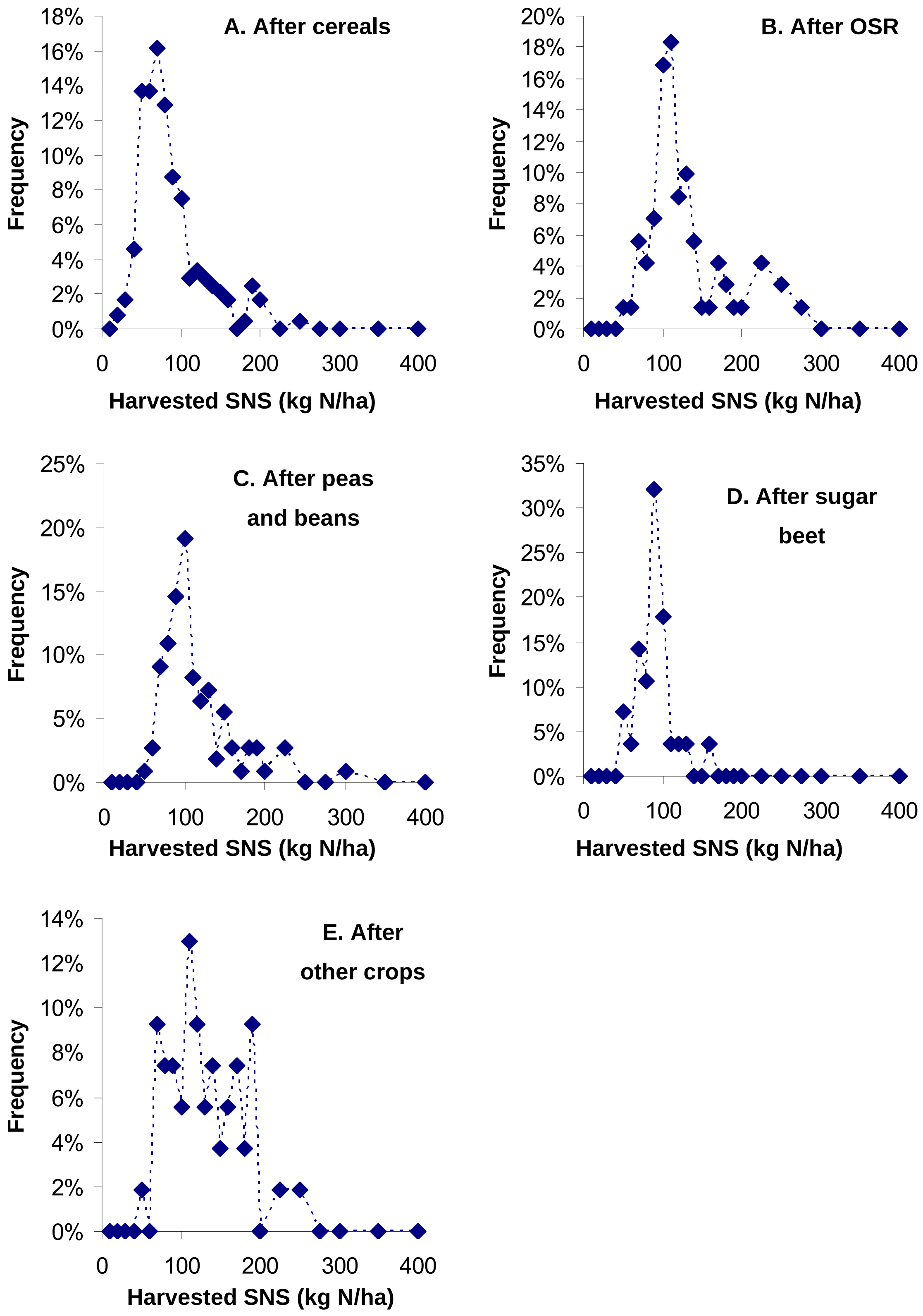


Figure 6. Frequency distribution of harvested SNS for >550 experimental sites in UK since 1980 divided into previous crop classes.

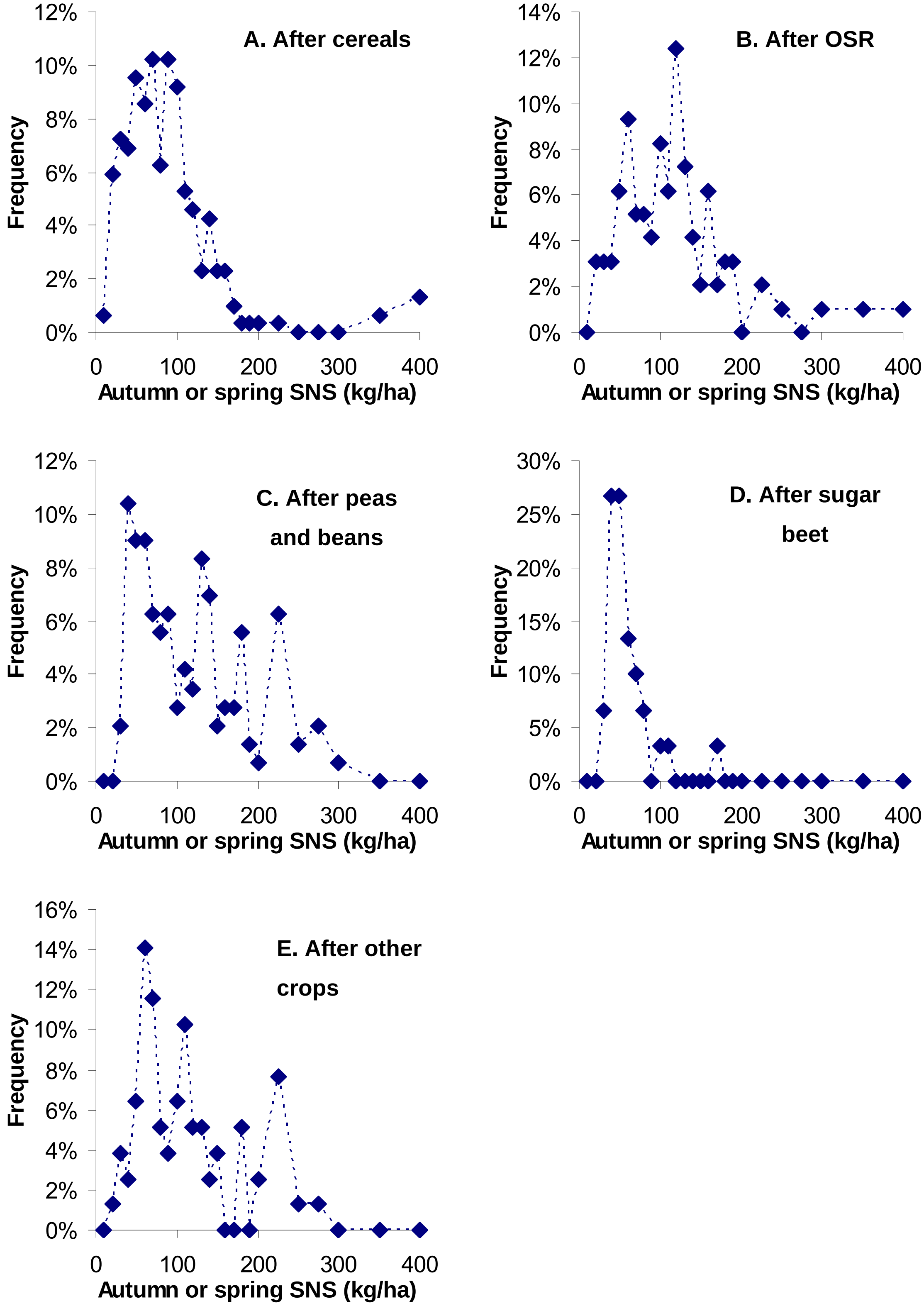


Figure 7. Frequency distribution of measured SNS for >550 experimental sites in UK since 1980 divided into previous crop classes.

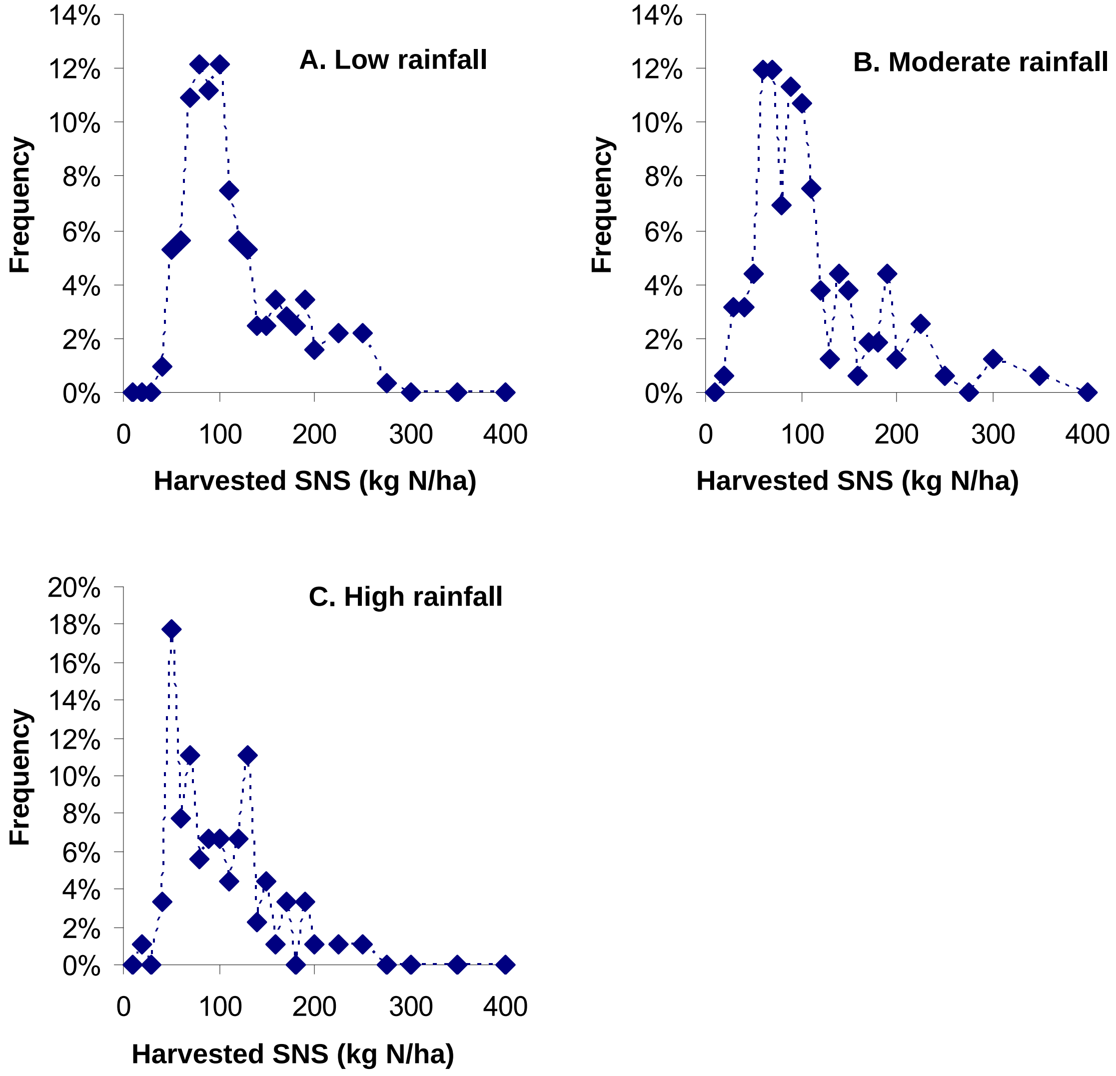


Figure 8. Frequency distribution of harvested SNS for >550 experimental sites in UK since 1980 divided into rainfall areas.

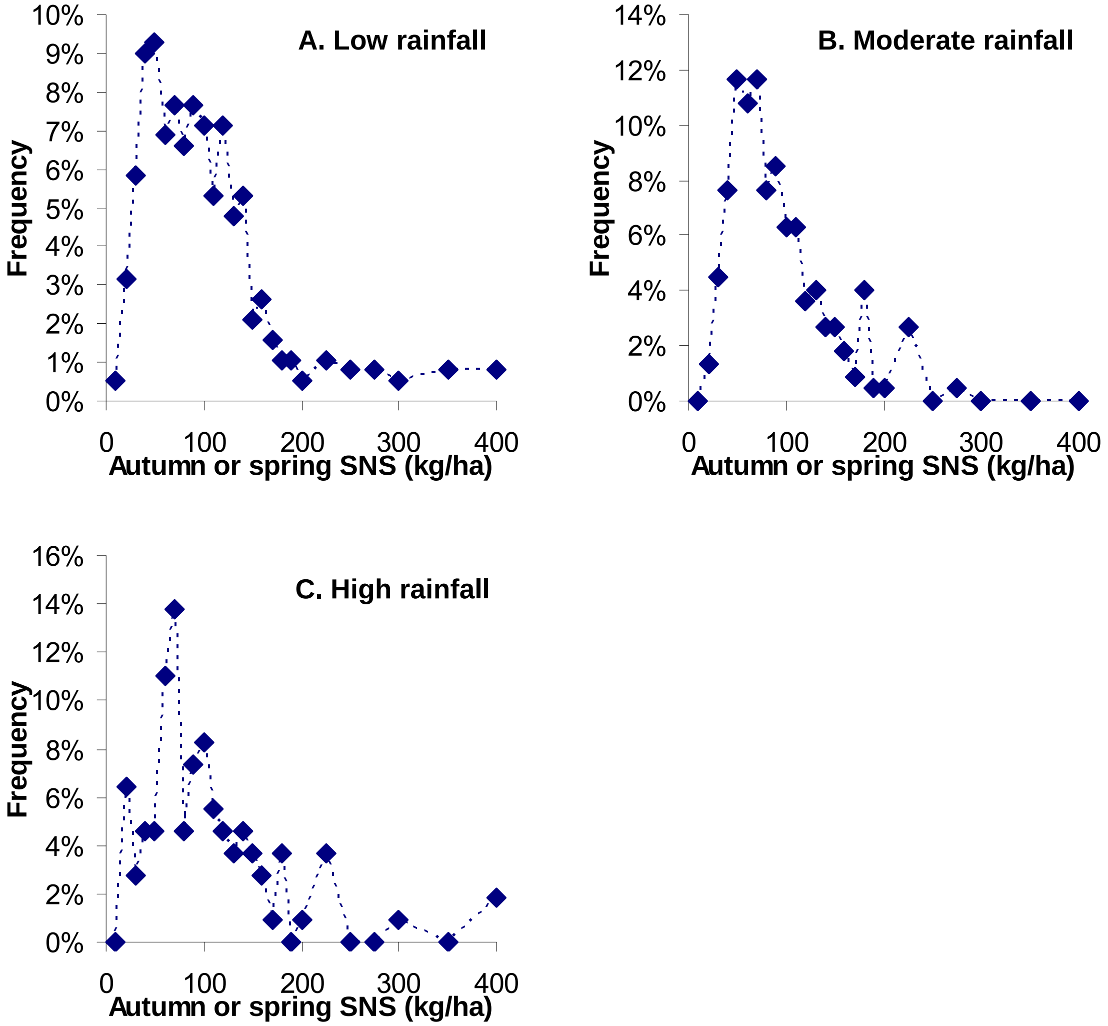


Figure 9. Frequency distribution of measured SNS for >550 experimental sites in UK since 1980 divided into rainfall areas.

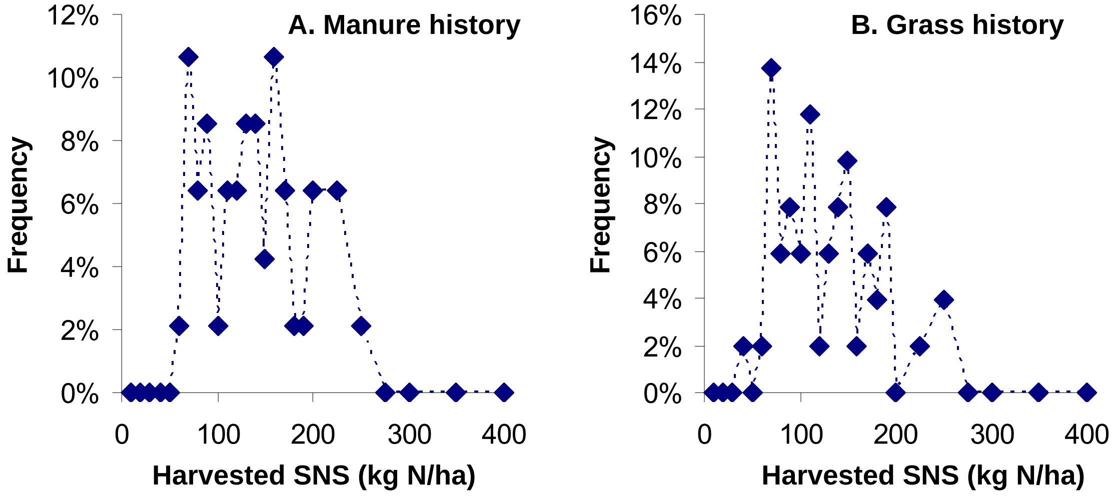


Figure 10. Frequency distribution of harvested SNS for >550 experimental sites in UK since 1980 where sites have history of manure or grass.

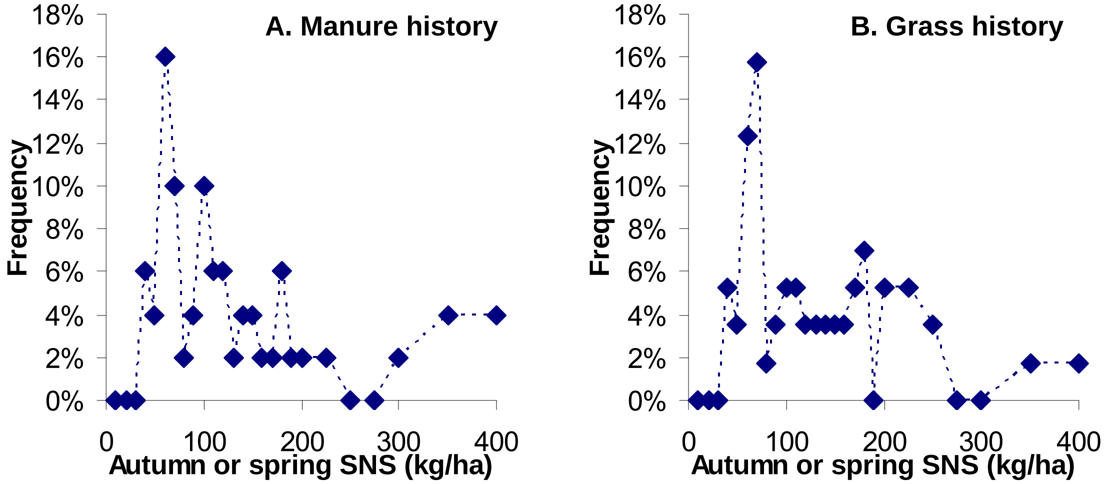


Figure 11. Frequency distribution of measured SNS for >550 experimental sites in UK since 1980 where sites have history of manure or grass

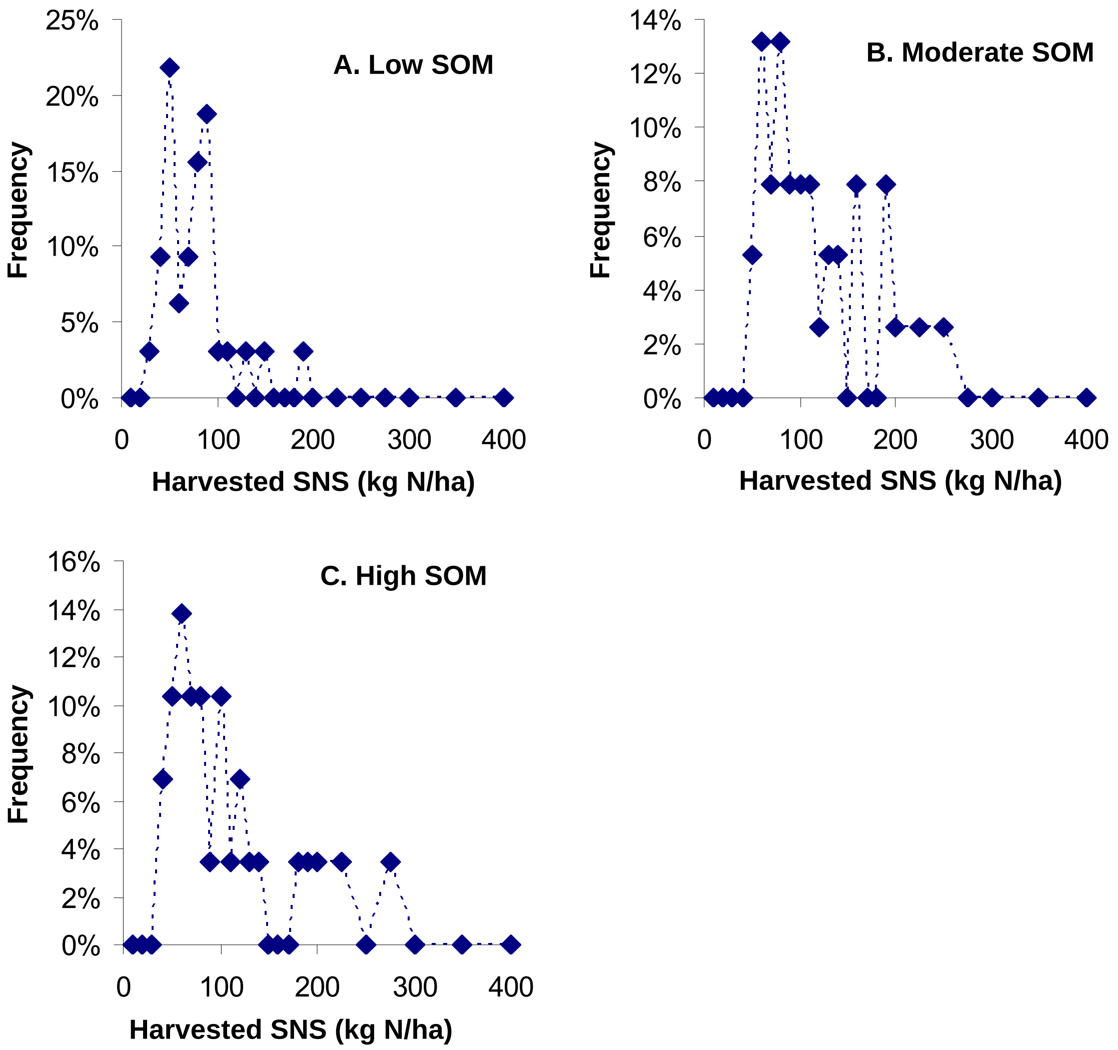


Figure 12. Frequency distribution of harvested SNS for >550 experimental sites in UK since 1980 divided into levels of soil organic matter (low <2% SOM or <0.18% N; medium <4% SOM or <0.3% N; high >4% SOM or >0.3%N).

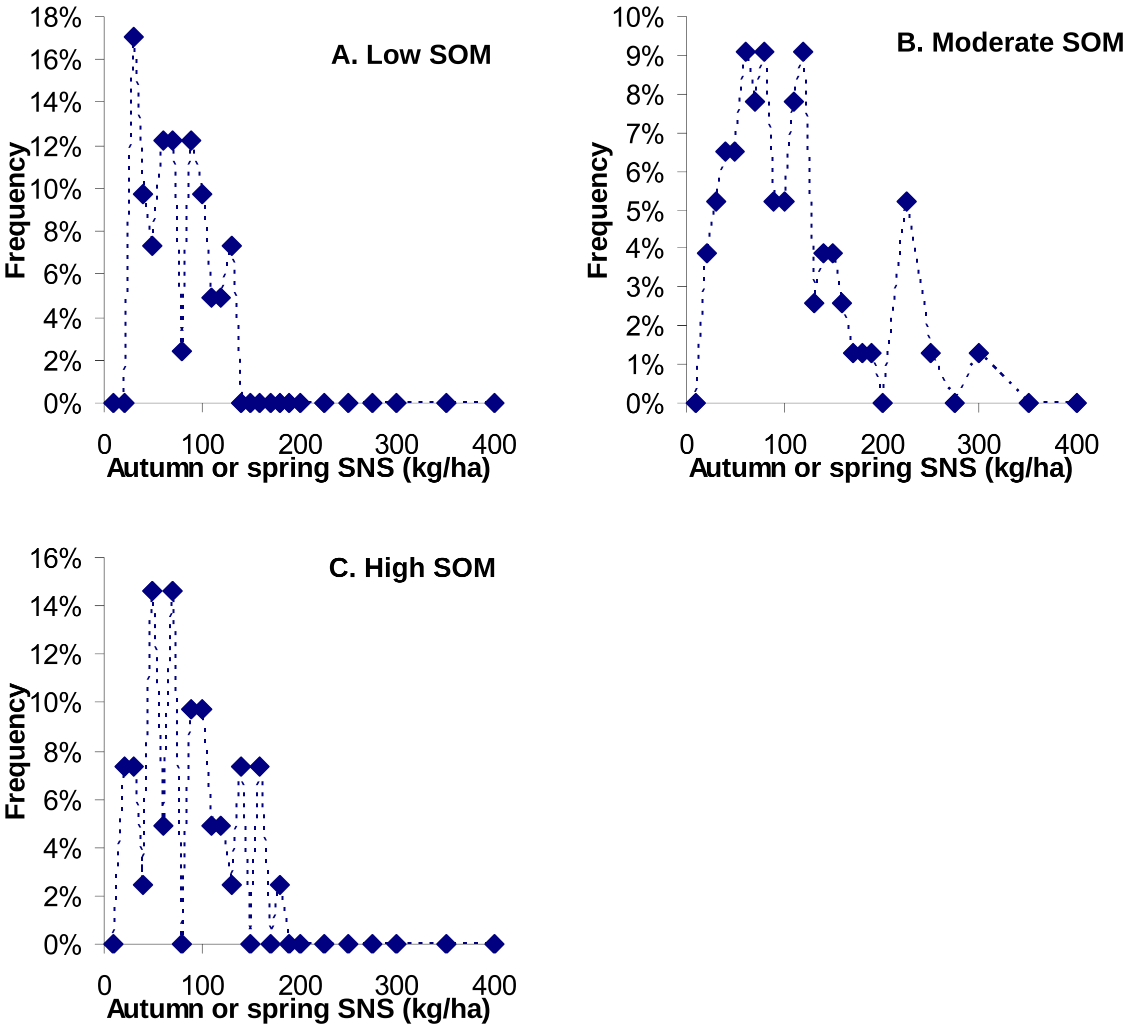


Figure 13. Frequency distribution of measured SNS for >550 experimental sites in UK since 1980 divided into levels of soil organic matter (low <2% SOM or <0.18% N; medium <4% SOM or <0.3% N; high >4% SOM or >0.3%N).

3.3.2. Spatial variability in SNS

Differences in N inputs, N off-takes, soil characters, drainage and SOM can lead to variability in SNS across fields at the smallest scale and at larger scales. Measurements of variability in SNS across a field have been made on a few occasions in the UK over the past 20 years and have recently been examined in an HGCA report by Marchant et al. (2012). The reader should refer to this report for further information. However, the most salient messages from Marchant et al. for this project (core number and pattern in a field) are reviewed in section 3.4.

3.3.3. Temporal variability in SNS

Being the result of many physical and biological processes SMN levels can vary hourly, daily, weekly and over the season. For example, as the crop grows it takes up N from the soil, so a greater proportion of SNS appears as crop N. Assessing temporal variation is always to an extent confounded by spatial variation, as it is impossible to sample and analyse exactly the same soil twice. Some of the variation seen in repeated measurements therefore inevitably displays this spatial variation.

Temporal variation is likely to be greatest when mineralisation and or immobilisation are very active – e.g. for several weeks after cultivation, for three months to a year after applying organic manure, or for a year or more after ploughing grass. Week to week variation in SMN on reasonably homogenous soils seems generally to be small, with consecutive samplings tending to be fairly consistent, especially where SNS levels are low (e.g. Figure 14). Leaching causes temporal variation, but this tends to occur over months, with SMN reducing in response to rainfall.

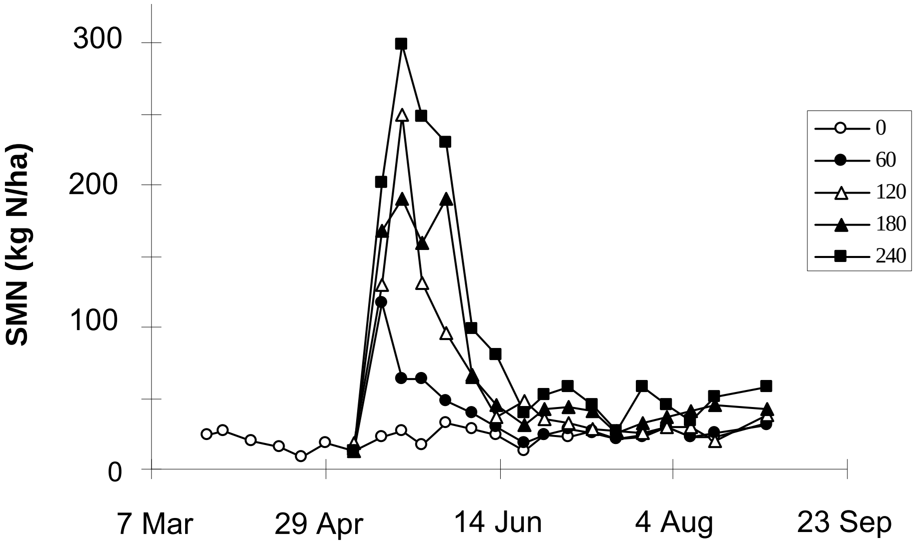


Figure 14. SMN on Samson's North, Boxworth after ploughing out of grassland with differing applications of N fertiliser in 1986 (R. Weightman unpublished).

UK datasets with regular sampling throughout winter and spring appear surprisingly r especially on unfertilised plots. Datasets of unfertilised plots from spring to harvest te show relatively little month to month variation. ADAS samplings at Surfleet (silt soil) show reasonable consistency for periodic sampling to depth, but much greater variation for more frequent samplings for 0-30 cm (Figure 15). Samplings on a deep silt soil at Sutton Bridge, Lincolnshire, show greater variability where previous N applications increases soil N (Figure 16).

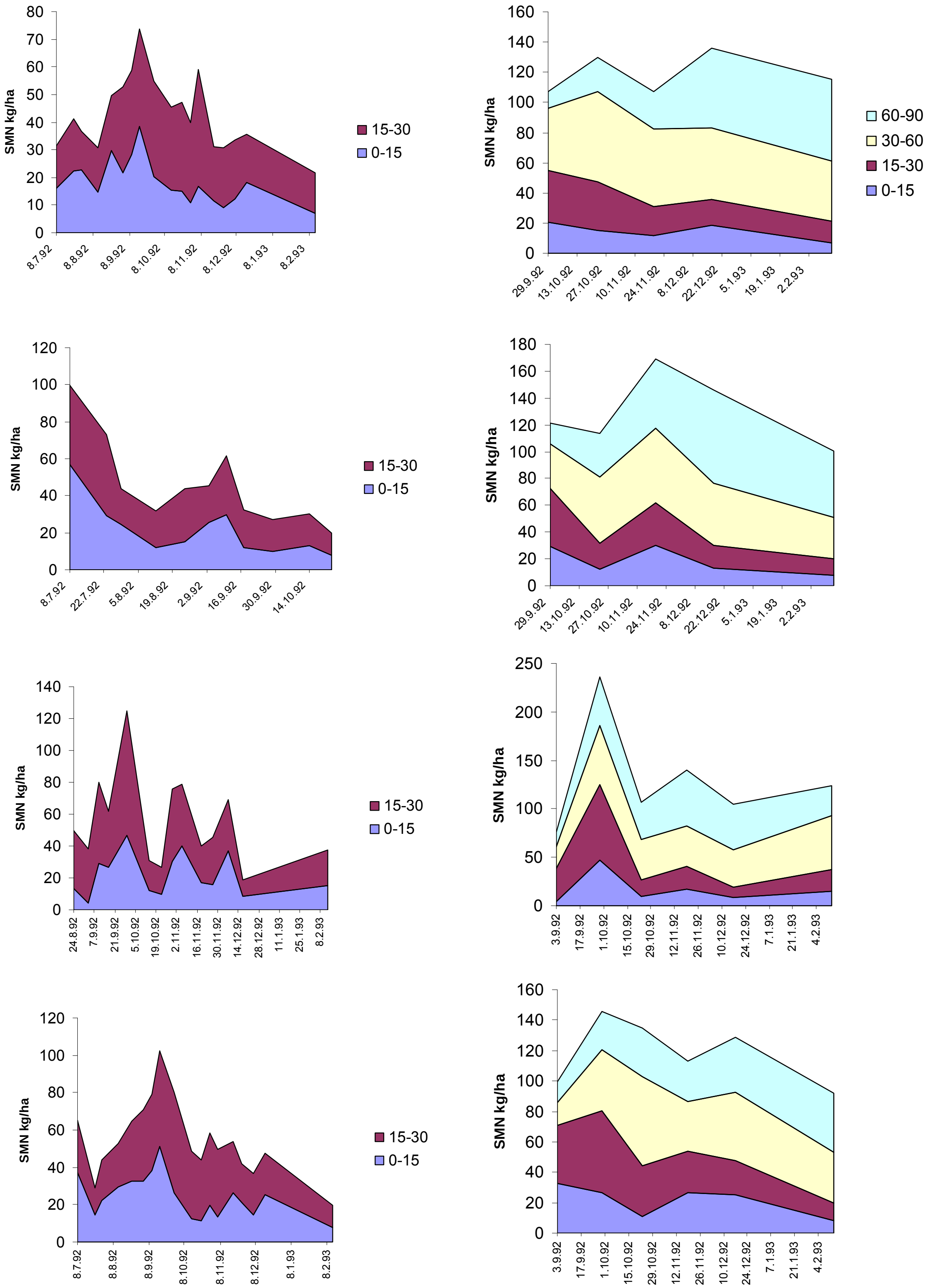


Figure 15. SMN (kg/ha) at Surfleet in cereals for four soil horizons of 4 fields to 90cm (right) and to 30 cm (left) (previously unpublished ADAS data).

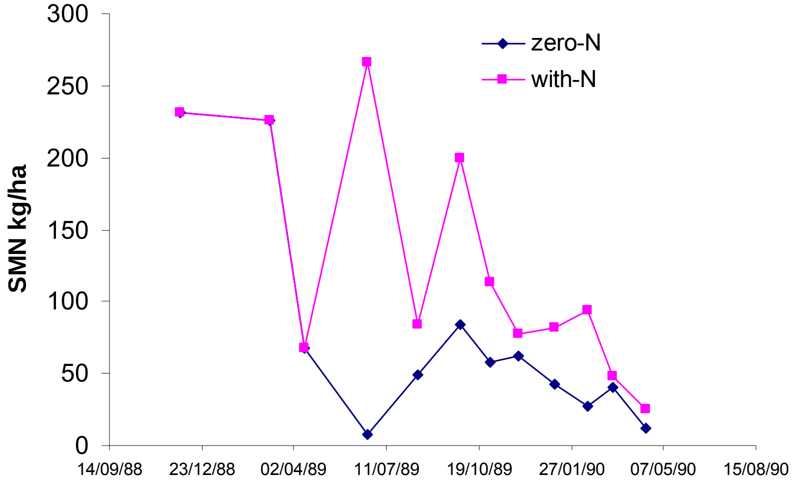


Figure 16. Changes in SMN to 90 cm over time in cereals with and without 200 kg N applied at Sutton Bridge (previously unpublished ADAS data).

Some datasets also show more variability than in the figures here, especially where N residues are high, such as after ploughing grass (Webb & Sylvester-Bradley, 1994; Mayhew 1988) or applying manure. Data from TAG (Figure 17) and NRM/Terra (Terra now GrowHow UK Ltd) (Figure 18) show some very large monthly variations in SMN at a significant minority of sites.

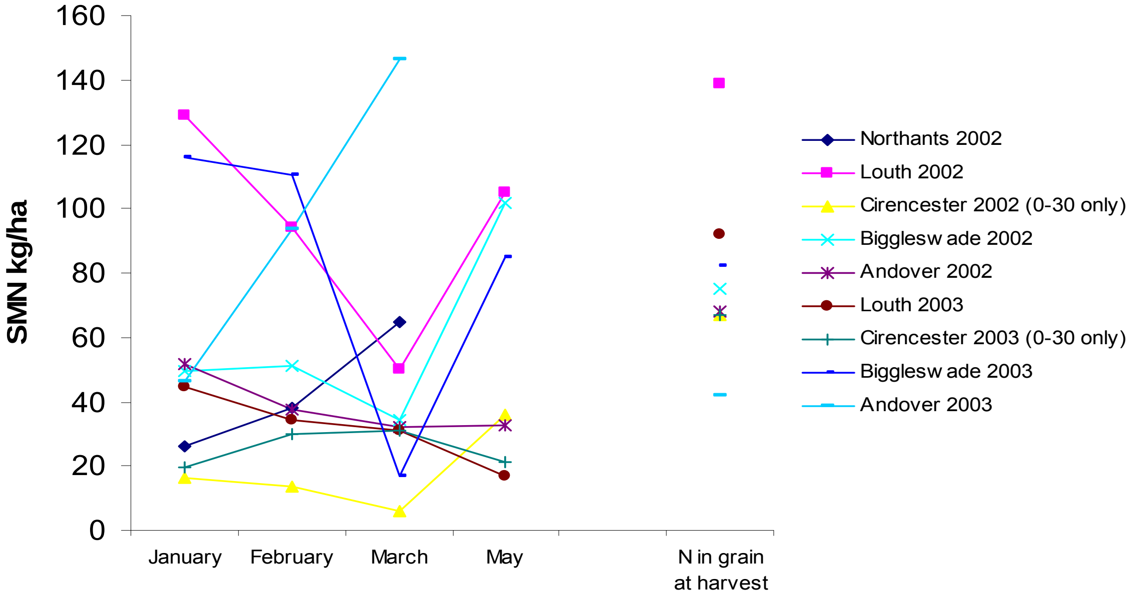


Figure 17. SMN over time for four fields sampled by TAG (after Knight 2006).

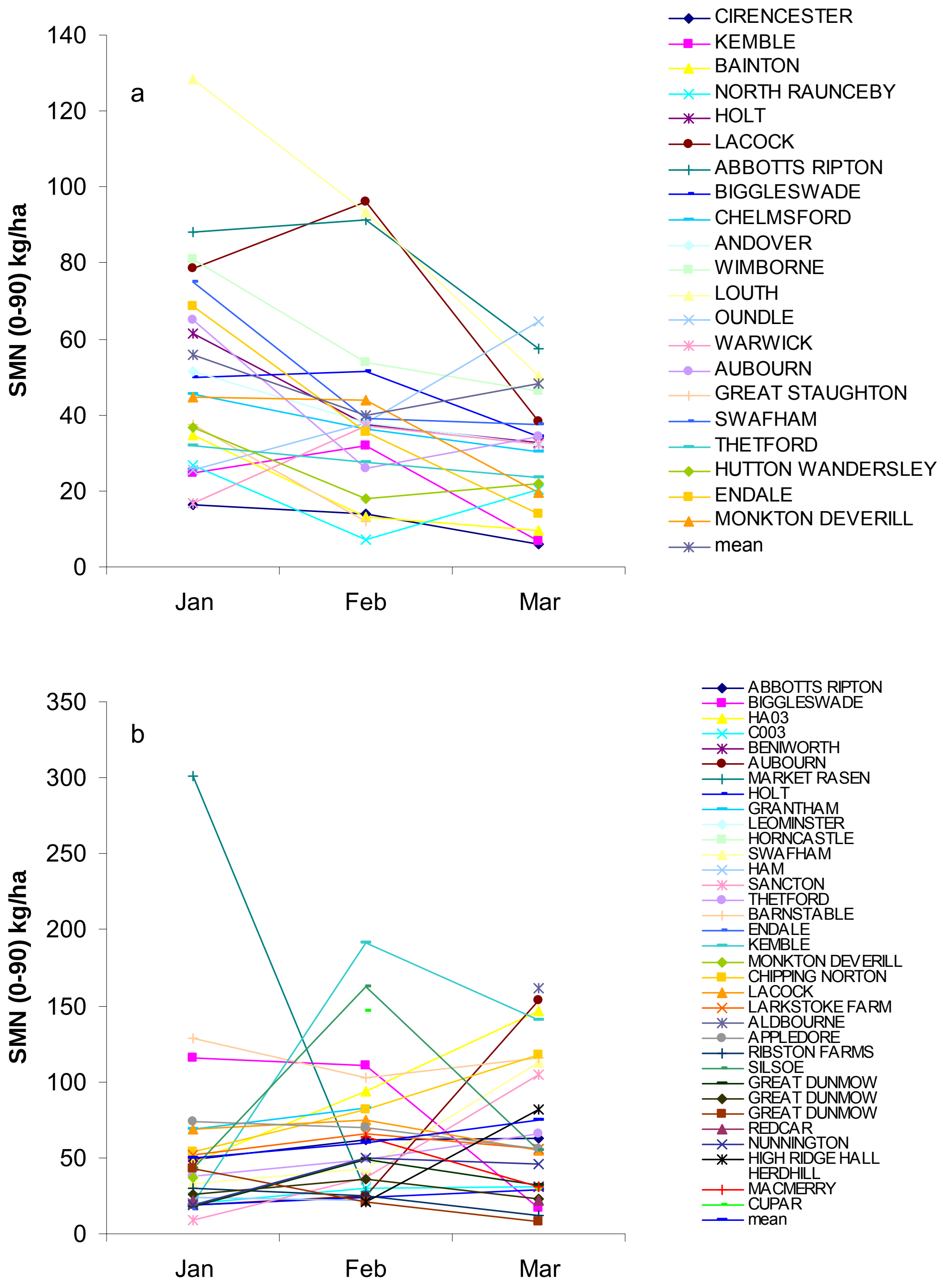


Figure 18. SMN over 3 spring months at 36 sites in a) 2002 and b) 2003. Data produced by Terra and NRM Min-N monitoring studies. Terra now GrowHow UK Ltd.

3.3.4. Measured SNS in relation to harvested SNS

There are clearly systematic differences in SNS caused by soil type, climate and farming system and their interactions as well as the above spatial and temporal variability that mean that unadjusted measurements of SNS from soil and crop in autumn or spring should never be expected to predict final harvested SNS with absolute accuracy and certainty. There are also many potential sources of error in the measurement of SNS, associated with sampling, analysis and interpretation. These issues are explored further in section 3.4. Both the systematic and the measurement variability contribute to the scatter in the relationship between measured SNS and harvested SNS shown in Figure 19. It should be noted that the relationship is also affected by errors in the assessment of harvested SNS from experimental data, i.e. due to errors in measurements of grain yield, harvest index, grain N% and straw N%.

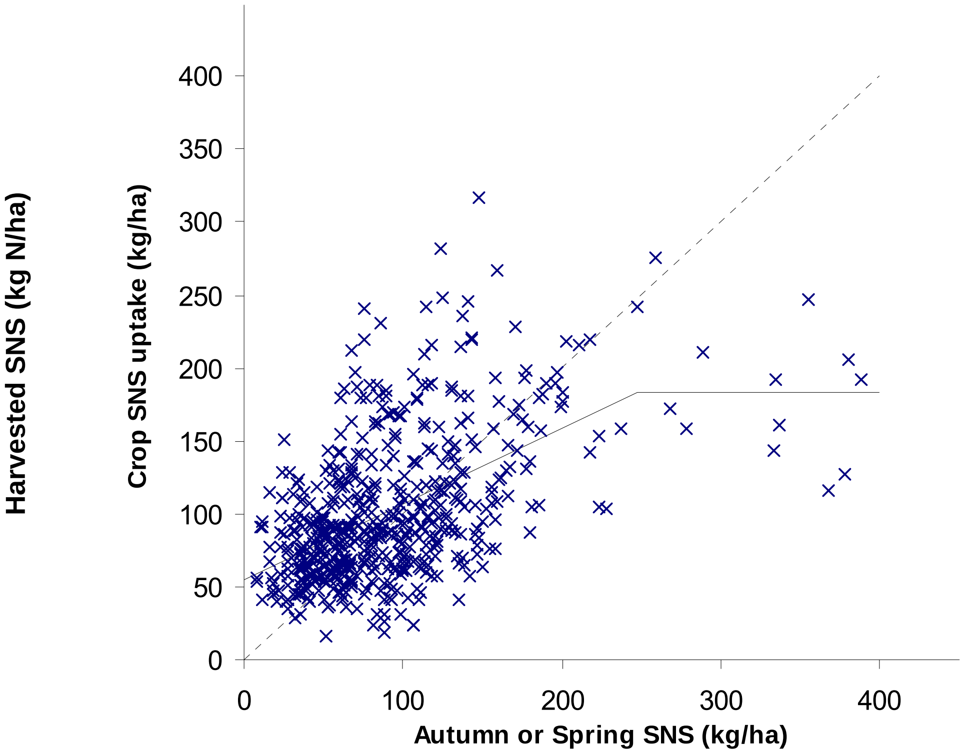


Figure 19. Relationship between measured SNS in autumn or spring and harvested SNS for >550 sites tested since 1980. Solid line shows fitted broken stick regression model, dashed line shows y=x. The regression explains 28% of the variation and the slope is 0.52.

Figure 19 shows the relationship between soil measured SNS in autumn or spring (whichever was available) and harvested SNS for all data available since 1980. A significant positive relationship exists, but the variation is large.

Visually, the relationship in Figure 19 seems to be reasonably described by the 1:1 line, but regression analysis shows the slope to be less than 1:1, and that it is justified to fit a breakpoint in the relationship. Various curves could also be fitted to this relationship, but given the variability any improvement in fit could scarcely be justified statistically. It is also likely that parameters from more sophisticated fitted curves would not have simple explanatory meaning and confidence in the relationship at the extremes or in extrapolation would be low. The simple split-line relationship with horizontal line after the breakpoint is favoured here because it gives three useful and meaningful parameters, as follows:

- **The intercept** is an estimate of expected harvested SNS when measured SNS is zero; it may be regarded as an estimate of how much N will be available to the crop on average from deposition and summer mineralisation. However, a slope differing from 1 implies that this varies with the amount of SNS measured. For this dataset the intercept was 55 kg/ha.
- **The slope** indicates the proportion of measured SNS that can be expected to appear in the crop at harvest. Recommendation systems have previously considered the intercept to be nil and the slope 1:1, implying a recovery or equivalence of 100% for SNS. It is probably best to avoid the notion of 'SNS recovery' since the SNS that is measured differs from that taken up by the crop. It is probably better to regard this as an average amount of N that will be taken up compared to that which is measured, acknowledging that processes of leaching, immobilisation, deposition and mineralisation will continue through the growing season. With an intercept and a breakpoint, the slope fitted for this dataset was 0.52 kg/kg, indicating that increments in measured SNS should not be expected to cause equivalent differences in harvested SNS.
- **The breakpoint** indicates the point at which measuring more SNS cannot be expected to give any increase in harvested SNS. This recognises that crops can only take up a finite amount of N. It appears here that unfertilised crops rarely take up more than ~250 kg/ha N however much N is measured in the soil. With an intercept and slope, the fit to this dataset gives a breakpoint at 247 kg/ha measured SNS, with an associated harvested SNS of 184 kg/ha. This implies that however much SNS we measure we should not expect, on average, for harvested SNS to exceed 184 kg/ha.

Given that there are different influences on soil N with different soil types, climates and farming systems we may expect the relationship between measured SNS and harvested SNS to differ. This is explored in Figures 20 and 21 and Table 1. Best relationships are seen for silt and clay soils (where 32% and 31% variation are accounted for respectively), with breakpoints above 250 kg/ha measured SNS. The relationship is less good for medium soils

(23% variation accounted for) and the breakpoint is less. For shallow and light soils the slope of the relationship is less (0.21 and 0.37 kg/kg respectively), the maximum expected SNS is less (92 and 113 kg/ha respectively) and the relationship explains less variation (0.1% and 19% respectively).

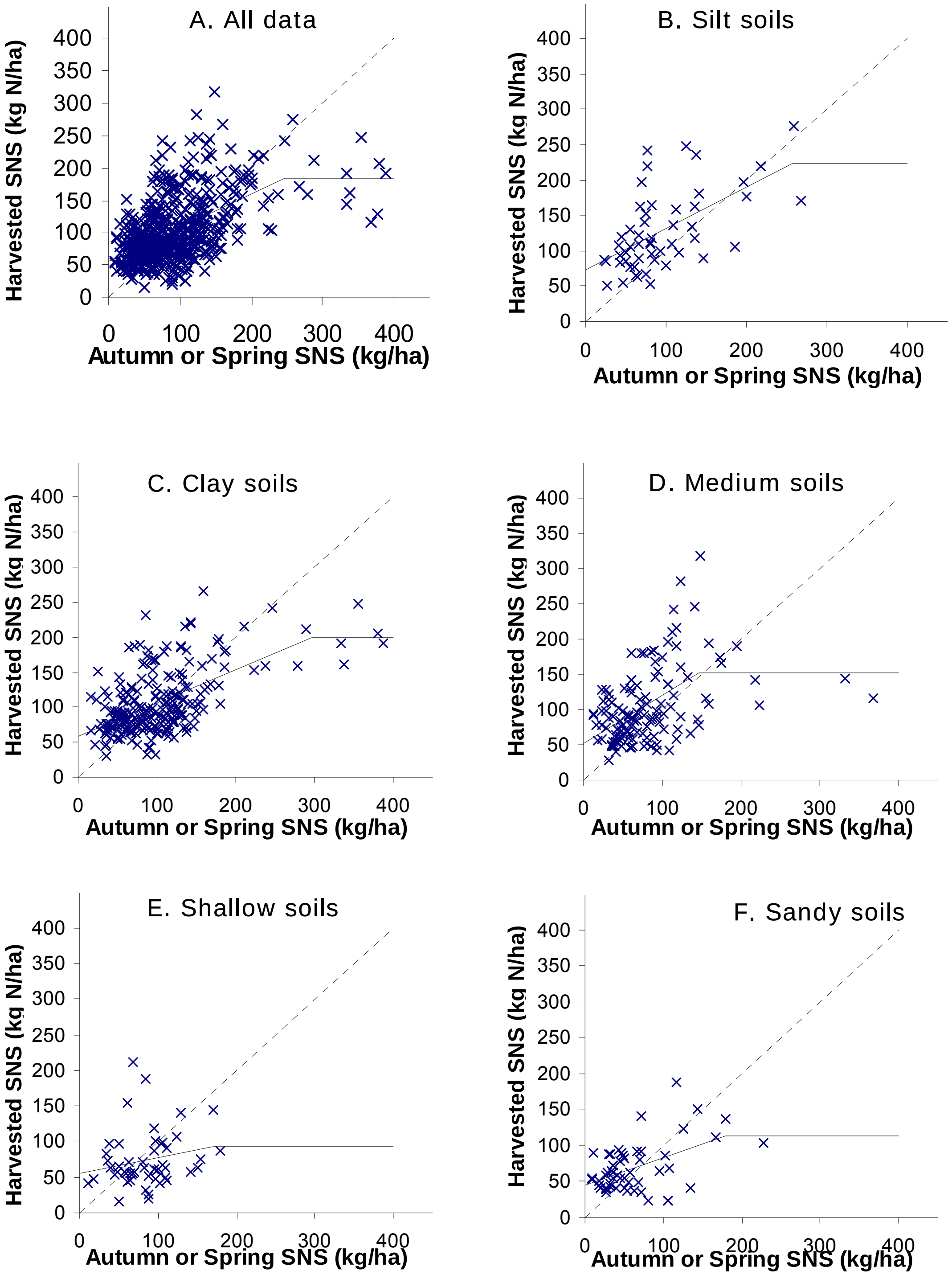


Figure 20. Relationship between measured SNS and harvested SNS for >550 experimental sites in UK since 1980, for all data (a) and divided into different soil types, (b-f).

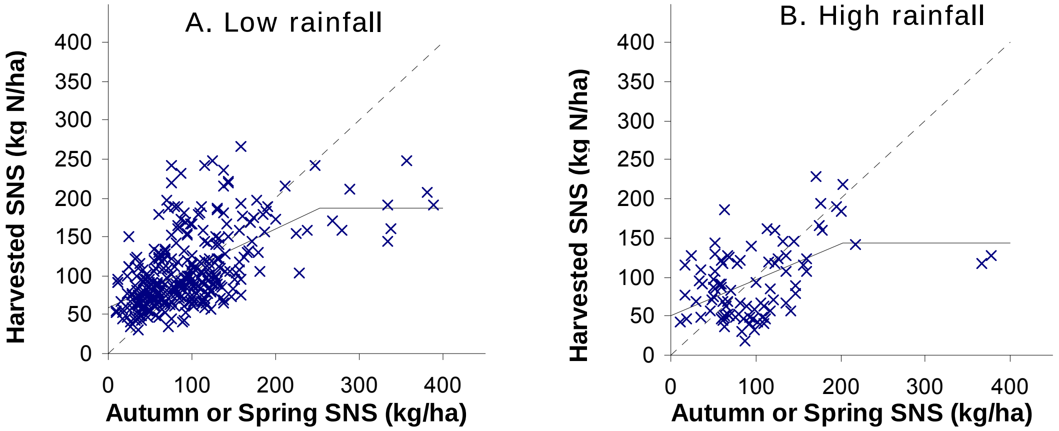


Figure 21. Relationship between soil measured SNS and harvested SNS for >550 experimental sites in UK since 1980 for different rainfall regions.

Table 1. Statistical results of broken stick regression analysis between measured SNS (autumn or spring) and harvested SNS for >550 experimental sites in UK since 1980 for different sub-groups of data.

Data group	% var. acc. for	Intercept	Slope	Breakpoint Harvested SNS	 Measured SNS
All	28	55	0.52	184	247
Silts	32	72	0.58	223	258
Clays	31	59	0.47	200	297
Medium soils	23	53	0.68	153	147
Shallow soils	0	56	0.212	92	171
Sandy soils	19	46	0.37	113	180
Low rainfall	32	59	0.51	187	252
High rainfall	23	50	0.46	143	203

The relationship is also stronger in low rainfall areas than high rainfall areas (32% vs 23% variation accounted for) with lower maximal expected harvested SNS for high rainfall areas (Figure 21).

Further conclusions are drawn from this review of past data later in the report, once the newly generated data have been described and reviewed in section 3.5. However, uncertainties in SMN sampling, analysis and interpretation are dealt with first, in section 3.4.

3.4. SMN sampling and analysis

3.4.1. Soil sampling in practice

The current cost of sampling a field to 90 cm with ~15 cores and having the soils (bulked into 3 horizons) analysed for SMN is approximately £100. If the average field size is approximately 10ha, SMN testing must have total benefits, both direct and indirect (e.g. reduced lodging) of at least £10/ha to be worthwhile.

RB209 (Appendix 2) recommends soil sampling where SMN analysis is required. Key elements of sampling, handling and analysis are described as follows:

- Samples must be taken to be representative of the area sampled;
- A minimum of 15-20 soil cores should be taken per field (based on a 10ha field) and bulked to form a representative sample;
- Thorough mixing of the bulked sample is vital prior to sub-sampling;
- Areas of land known to differ in some important respects (e.g. soil type, previous cropping, application of manures) should be sampled separately;
- In large fields (more than 10 ha), especially where the soil type is not uniform, more than one sample should be taken;
- It is important to avoid cross-contamination of samples from different depths;
- Use of a mechanised 1m long gouge auger (2.5 cm diameter) is a satisfactory method but care must be taken to avoid soil compaction and contamination;
- If each depth layer is to be sampled individually by hand, a series of screw or gouge augers of progressively narrower diameter should be used;
- After sampling, soils should not be frozen (this statement was only included in the most recent edition of RB209) but be kept refrigerated at less than 5°C and remain cooled while transported as quickly as possible to the laboratory;
- Samples should remain cooled until analysis which should be carried out as soon as possible after sampling;
- Samples should be analysed for nitrate-N and ammonium-N, with potassium chloride being a suitable extractant.

The new studies conducted within this project focused on sample handling (storage and sub-sampling) and sample analysis. These are reported in sections 3.4.3 and 3.4.4 respectively. Aspects of the initial sampling procedure in the field are reviewed in section 3.4.2.

3.4.2. Sampling in the field

Corer type and core volume

The preferred choice of corer for manual sampling of soils in 30 cm depth layers for SMN is a series of gouge augers of progressively narrower diameter. This minimises the likelihood of a core from one depth being cross-contaminated with soil from the depth above. Mechanised sampling typically relies on a 1m long gouge auger of constant diameter. This minimises cross-contamination as long as the core is taken in one bite.

There is little or no published research on the effects of soil core volume and sub-sampling procedure, to enable quantification of their likely effects on accuracy of the estimates of nitrate-N and ammonium-N.

Sampling intensity and pattern

Although not examined in this project, sampling intensity and pattern have been studied in a recently completed HGCA project. Full details can be found in the final report (Marchant *et al*, 2012), but the conclusions as they relate to SMN sampling are summarised here (See also Annex 6).

Optimal intensity of sampling for SMN increases with both field size and expected SNS (Table 2). More sampling is cost-effective on larger fields because of the potential for larger total yield and profit. More sampling is required when the expected SNS is large because this leads to large within-field variability of SMN. At one extreme, for a 60 ha field with an expected SNS of 275 kg/ha, the most profitable sampling strategy was found to be around 25 cores. This is greater than the 15-20 cores recommended in RB209 (although the latter advises splitting fields of more than 10 ha). However, a smaller number of soil cores was found to be optimal for fields of 20 ha or less and with an expected SNS of up to 125 kg/ha, compared to the 15-20 recommended in RB209 (Table 2).

Table 2. Optimal number of cores on 'W' when sampling SMN throughout the target area (from Marchant et al, 2012).

Target	Expected SNS (kg/ha)					
area	25	75	125	175	225	275
5 ha	3	4	4	5	6	6
10 ha	4	6	6	8	8	9
20 ha	5	8	8	10	10	13
30 ha	7	10	12	12	14	18
60 ha	10	14	15	18	23	23

In practice, fields of up to 5 ha or with an expected SNS of 25 kg/ha are unlikely to be sampled, so the optimal number of cores is likely to be between 8 and 12 for many situations, offering some potential for saving time compared to existing best practice advice.

Marchant *et al*. (2012) compared the suitability of various different types of sample designs to estimate the mean concentration of soil nutrients within a management zone. The designs considered were:

1. The 'W' design recommended in RB209 (see description below),
2. A spatially stratified design,
3. A design that had been optimized for prediction of the mean concentration by geostatistical methods, and
4. A design which stratified the sampling according a yield map from the previous season.

The ‘W’ design is commonly used by agronomists to determine the field mean nutrient content and is the design recommended in RB209. It requires the practitioner to walk in a ‘W’ pattern across the field and extract soil cores at regular distance. The ‘W’ should cover as much of the field as is possible. The design is favoured because of its simplicity. There is no need to use statistical algorithms or to exactly find sampling sites with a GPS. It does disperse points within the field. However there is potential for inefficiency at each apex of the ‘W’ since two cores might be extracted close together and as the number of cores increases there is a limit to how accurate the estimate of the field mean becomes. This is because sites not on the ‘W’ are never sampled.

The tests used realistic simulated data. One thousand simulations of the nutrients within the management zone were generated and then for each simulation the mean concentration was estimated using each design. The simulations were based upon models of the spatial variation of the nutrient which had been fitted to available datasets. The sample designs were assessed both in terms of the mean squared error of the estimates of the field mean and the practical implications of these errors. In the case of SMN the errors would lead to sub-optimal N fertiliser management decisions. The loss of profit because of these sub-optimal decisions were therefore modelled and recorded.

For all nutrients and field sizes the 'W' design had larger mean squared errors than the spatially stratified or optimized designs. This is in agreement with statistical theory (de Gruijter et al., 2006). However when the implications of these differences were considered they were found to be small (always less than £0.20 per ha lost profit for SMN). The optimized and stratified design are harder to implement than the 'W', both in terms of the statistical algorithms required and the ease with which sample locations can be found within the management zone. Therefore Marchant et al. (2012) concluded that, taking all factors into account, the 'W' design was the most efficient. They noted that, because RB209 fertiliser recommendations do not require very precise estimates of soil-nutrient concentrations, there are only small monetary implications of the additional errors from the 'W' design. If in the future more sensitive fertiliser recommendations are implemented, say if nutrient leaching had to be predicted accurately, then it might prove necessary to re-explore the implementation of optimized sample designs.

3.4.3. Sample handling, storage and transport

Steps to consider

Soil samples are typically combined from 10-15 core-sections in the field. However, sample management can have an influence on the measurement of mineral N by the laboratory. There are a number of steps to consider:

- Mixing of the sample of core-sections
- Sub-sampling
- Storage until dispatch to the lab (duration and temperature)
- Transport to the lab (duration and temperature)
- Storage at the lab prior to extraction (duration and temperature)

There have been relatively few published investigations into the effects of these steps on the final laboratory analysis result. However, where available the findings of relevant previous studies are reviewed below.

Previous studies

Sample storage

Nelson and Bremner (1972) investigated the effects of several pre-treatments and storage conditions on inorganic N contents of 10 Iowa soils. Storage at -5°C in an airtight container was found to be a satisfactory method of preserving field-moist soil samples for inorganic N analyses. There was no significant change in available ammonium-N or nitrate-N (the average change after 9 months storage was 0.1 ppm for ammonium and 0.8 ppm for nitrate). Air drying at 22°C increased mineral N contents of most of the soils studied, with the average increase being 4.2 ppm for ammonium and 1.7 ppm for nitrate. Oven drying at 55°C resulted in a slightly larger increase in ammonium (5.1 ppm) than did air drying. Storage of air-dried soils in paper bags for 9 months led to marked increases in mineral N contents, with an average increase of 10.2 ppm for ammonium. Only small increases were observed when stored in stoppered bottles.

Walworth (1992) conducted a laboratory study to determine the effects of time of extraction, and pre-extraction freezing and thawing, or drying, wetting and incubating, on centrifugally-collected soil solutions. Solutions were analysed for a number of factors, including ammonium-N and nitrate-N. Significant changes in soil solution composition were found as centrifugation time was varied, and as a result of pre-extraction drying-wetting or freezing-thawing. Neither method provided a good method of storing soil samples prior to soil solution extraction. Scherer (1992) also found an increase in nitrate-N in frozen and thawed soil samples compared to field fresh samples.

A study was undertaken by Silgram (1997) into the effects of freezing and thawing on SMN levels of grassland soil samples. Soils were sampled at 0-30 cm depth from four fields representing a range (0.3-0.65%) of total topsoil N, and ranging from a 4 year ley to long term grassland with different manure and fertiliser management regimes. Cores from each field were bulked and thoroughly mixed before sub-sampling into 5 replicates each of 7 storage treatments, including immediate (same day) extraction, refrigerated storage for 1 or 5 days at 4°C, and a number of different freezing-thawing treatments. Rapid (7 hour) or slow (16 hour) thaws were used to simulate daytime or overnight transit to laboratories respectively, with some treatments also having a second freeze-thaw cycle prior to final sample extraction.

Frozen soils consistently gave higher (7-53 kg/ha N) SMN values compared to samples extracted fresh, mostly due to increased nitrate levels although in one field it was due to increased ammonium. A single freeze and rapid thaw generally had a greater effect on SMN values than refrigerated storage for 1 day, but a lesser effect than refrigerated storage for 5 days. Rapid thawing of frozen soils in un-insulated conditions had a greater effect than 16 hour thaws in insulated cool boxes, when followed by a further freeze-thaw cycle. This suggested that overnight transport of samples in insulated containers was preferable to daytime transport without insulation. Method and timing of final thaw were also found to be critical. Thawing for 16 hours in a refrigerator at 4°C rather than at room temperature on a laboratory bench was found to lessen the effect on SMN.

The size of the effect also varied between fields, suggesting that soil properties (organic matter or total N% content) or manure and fertiliser management could have a strong influence. The results suggested that the pre-extraction storage method could account for differences of up to 38 kg/ha N between fresh grassland soils extracted immediately after sampling, and samples subjected to two freeze-thaw cycles.

Gelinskey and McGonigle (2002) and Ma *et al.* (2005) both studied sample handling effects on SMN results in the USA. They focused on air drying or freezing of soil before analysis. One study found that temperature on the day of sampling to be important. However, the soils they used were not arable and they did not examine refrigeration, so their results cannot be taken as particularly relevant to UK SMN services.

In conclusion, sample transport and storage time and temperature are important. The magnitude of storage time and temperature effects may depend on site / soil properties (organic matter content, total N, manure use), but is likely to be greater for grassland than arable soils.

Mixing and sub-sampling

Mixing of the total volume of soil cores obtained, and then sub-sampling before sending to the laboratory is a critical part of the SMN process, and a potential source of error. Good sub-sampling is particularly difficult for clay soils or where cores remain intact as solid ‘sausage’ shapes. Current advice has been that these should be sliced up into lengths of less than 1 cm prior to mixing. This is difficult to achieve where soil samples contain fibrous crop residues or other ‘lumpy’ organic matter. A specific procedure has been defined and used by soil scientists involving mixing, quartering, taking a small quantity from each quarter, then re-mixing, re-quartering and taking a further small quantity from each quarter; this process may be repeated as many times as is deemed necessary, but it can take in excess of 20 minutes to achieve a representative sub-sample from the total soil volume.

New sample handling studies – objectives

To evaluate the importance of sample handling and sub-sampling for UK conditions two studies were conducted during spring in 2009 and 2010 on soils with low and high organic matter. Each study sought to establish and quantify the impact on accuracy of nitrate-N and ammonium-N measurement of:

1. the time interval between SMN sampling and analysis, and failure to maintain a sample storage temperature of 2-4°C during that interval.
2. sub-sampling method.

New sample handling studies – methods

Site Selection

Four winter wheat field sites were selected in spring 2009 (Table 3) and spring 2010 (Table 4), two with a low N mineralisation potential (low organic matter, no previous manure or grass) and two with a high N mineralisation potential (high organic matter, previous manure or grass). Sites had to be located sufficiently close to ADAS Boxworth to allow delivery of all samples and extraction of some treatments within 24 hours.

Table 3. Sites selected for the spring 2009 sampling handling studies.

Site ID	Soil Type	Previous Crop	Grass History	Manure History	Spring 09 SMN (kg/ha) 0-30cm	Spring 09 SMN (kg/ha) 0-90cm
9A-059 Terrington	deep silt	OSR	N	Y	9	25
9A-072 Eastfield	deep clay	wheat	Y	N	50	92
9T-071 Morley	medium SCL	beans	N	N	17	30
9T-077 Beccles	organic ZL	beans	N	N	123	374

Table 4. Sites selected for the spring 2010 sampling handling studies.

Site ID	Soil Type	Previous Crop	Grass History	Manure History	Spring 10 SMN (kg/ha) 0-30cm	Spring 10 SMN (kg/ha) 0-90cm
10H-151 Lincs	deep silt	calabrese	N	N	32	173
10A-153 Boxworth	medium CL	OSR	N	N	16	61
10T-160 Morley	medium SCL	OSR	N	N	22	48
10T-162 Beccles	organic ZL	millet	N	N	41	333

Sample storage duration and temperature exercise

For each of the fields an area was selected measuring about 10 x 10m and with uniform soil type, management history and crop growth. Prior to the application of any N fertiliser, a sample of soil was obtained using a spade from a depth of 0-30 cm and weighing about 3.0-3.5 kg. The soil was placed in a bucket, ensuring that it was free from vegetation or other contaminants. From the bucket, eight (2010) or ten (2009) sub-samples of soil were obtained of about 300g each. These formed the first replicate of treatments 1-8 (2010) or 1-10 (2009).

In 2010 only, from the hole created and widening it if necessary, a further sample of soil was obtained using a spade from a depth of 30-60 cm and weighing about 1.0 kg. The soil was placed in a second bucket, again ensuring freedom from contaminants, including soil from the 0-30 cm layer. From the bucket, two sub-samples of soil were obtained of about 300g each. These formed the first replicate of treatments 9 and 10.

The process was repeated to obtain three more buckets of soil of about 3.0-3.5 kg each (and in 2010 three more buckets of soil of about 1.0 kg each), to form the second, third and fourth replicates of the treatments. The soil in each bucket was thoroughly mixed with a clean trowel or similar, using a knife to cut any lumps or fibrous material, and ensuring no pieces of more than 1 cm diameter or length remained.

2009 Treatments

Ten 300g sub-samples were taken at random (making each one up from six random quantities of 50g of soil) from the first bucket, and placed in separate bags. The exact procedure was to add one 50g quantity of the mixed soil to each of the ten sub-sample bags, then stir the soil again to re-mix, add a second 50g quantity to each bag, stir again and so on. These were labelled as replicate 1, treatments 1-10. The process was repeated for the other three buckets of soil to obtain the sub-samples for replicates 2, 3 and 4. A temperature logger was inserted inside the bag of soil of replicate 2 of each of treatments 4, 8, 9 and 10. The sub-samples for treatments 1, 2, 3, 4 and 10 were placed immediately in insulated chilled packs at 2-4°C. Those for treatments 5, 6, 7, 8 and 9 were placed in an ordinary box at ambient temperature. Where samples were to be transported immediately, they were maintained at these temperatures throughout the journey. Where they were to be stored overnight prior to transport early the next morning, treatments 1, 2, 3, 4 and 10 were placed in a refrigerator at 2-4°C and treatments 5, 6, 7, 8 and 9 were stored at room temperature. The soil sub-samples were then stored and extracted as described in Table 5.

Table 5. 2009 Sample storage duration and temperature treatments.

Treatment	Mixing before sub-sampling	Storage / transport temperature (first 24 hours)	Storage temperature (after 24 hours)	Time of extraction (interval after sampling)
1	Thorough	2-4°C	2-4°C	within 36 hours
2	Thorough	2-4°C	2-4°C	3 days
3	Thorough	2-4°C	2-4°C	7 days
4	Thorough	2-4°C	2-4°C	14 days
5	Thorough	ambient (room)	room temp	within 36 hours
6	Thorough	ambient (room)	room temp	3 days
7	Thorough	ambient (room)	room temp	7 days
8	Thorough	ambient (room)	room temp	14 days
9	Thorough	ambient (room)	2-4°C	3 days
10	Thorough	Freeze within 24 hours. Store at 2-4°C until freezing. Thaw at 2-4°C overnight (16 hours) in a refrigerator. Extract 14 days after sampling, within 24 hours of starting to thaw.		

2010 Treatments

Eight 300g sub-samples were taken at random from the first 0-30 cm depth bucket and placed in separate bags, following the exact same procedure as in 2009. These were labelled as replicate 1, treatments 1-8. Two 300g sub-samples were taken from the 30-60 cm depth bucket, and placed in separate bags, again following the exact same procedure. These were labelled as replicate 1, treatments 9 and 10. The process was repeated to obtain the sub-samples for replicates 2, 3 and 4. A temperature logger was placed inside the bag of soil of replicate 2 of treatments 4, 8 and 10. The sub-samples for treatments 1, 2, 3, 4, 9 and 10 were placed immediately in insulated chilled packs at 2-4°C. Those for treatments 5, 6, 7 and 8 were placed in an ordinary box at ambient temperature. Where samples were to be transported immediately, they were maintained at these temperatures throughout the journey. Where they were to be stored overnight, treatments 1, 2, 3, 4, 9 and 10 were stored in a refrigerator at 2-4°C and treatments 5, 6, 7 and 8 were stored at room temperature. The soil sub-samples were then stored and extracted as described in Table 6.

Table 6. 2010 Sample storage duration and temperature treatments.

Treatment	Sample Depth cm	Mixing before sub-sampling	Storage/transport temperature	Time of extraction (interval after sampling)
1	0-30	Thorough	2-4°C	6-24 hours
2	0-30	Thorough	2-4°C	2 days
3	0-30	Thorough	2-4°C	4 days
4	0-30	Thorough	2-4°C	7 days
5	0-30	Thorough	ambient / room	6-24 hours
6	0-30	Thorough	ambient / room	2 days
7	0-30	Thorough	ambient / room	4 days
8	0-30	Thorough	ambient / room	7 days
9	30-60	Thorough	2-4°C	2 days
10	30-60	Thorough	2-4°C	7 days

Mixing and sub-sampling exercise

2009 Treatments

For each of the four fields used for the sample handling exercise, and in the same 10m x 10m area, prior to the application of any N fertiliser approximately 25 randomly located (but at least 1m apart in any direction) soil cores were taken to 0-30 cm depth to give at least 5 kg of soil in a bucket. A further 25 cores were taken from a wider 100m x 100m area, including the 10m x 10m area, to give at least 5 kg of soil in a second bucket, ensuring that in both cases the soil was free from any contaminants. The soil from the 10m x 10m area was used to generate twelve sub-samples forming three replicates of treatments 11a, 12a, 13a and 14a. The soil from the 100m x 100m area was used to produce a further twelve sub-samples forming three replicates of treatments 11b, 12b, 13b and 14b. For both the ‘a’ and ‘b’ treatments, the sub-samples were generated as follows.

Without mixing, six 400g sub-samples were taken at random (obtaining each sub-sample with a single quantity of soil) from each of the two buckets of soil. These formed the three replicates of treatments 11a/12a and 11b/12b. The remaining soil in each bucket was thoroughly mixed for up to 20 minutes, using a knife to cut any lumps or fibrous material, and ensuring no pieces of more than 1 cm diameter or length remained. From each of the two buckets a further six 400g sub-samples were taken at random, making each sub-sample up from eight random quantities of 50g each of soil. The exact procedure was to add one 50g quantity of the mixed soil to each of six sub-sample bags, then stir the soil again to re-mix, add a second 50g quantity to each sub-sample bag, stir again and so on. These formed the three replicates of treatments 13a/14a and 13b/14b.

The sub-samples for treatments 11a/11b and 13a/13b were placed in insulated chilled packs. The sub-samples for treatments 12a/12b and 14a/14b were placed in an ordinary box at ambient temperature. Where samples were to be transported immediately, they were maintained at these temperatures throughout the journey. Where samples were to be stored overnight prior to transport, treatments 11a/11b and 13a/13b were placed in a refrigerator at 2-4°C and treatments 12a/12b and 14a/14b were stored at room temperature. The sub-samples were then stored and extracted as described in Table 7.

2010 Treatments

For each of the four fields used for the sample handling exercise, and in the same 10m x 10m area, prior to the application of any N fertiliser approximately 16 randomly located (but at least 1m apart in any direction) soil cores were taken to 0-30 cm depth to give at least 3.5kg of soil in a bucket. A further 16 cores were taken from a wider 200m x 200m area, including the 10m x 10m area, to give at least 3.5kg of soil in a second bucket, ensuring that in both cases the soil was free from any contaminants. The soil from the 10m x 10m area was used to generate ten sub-samples forming five replicates of treatments 11a and 12a. The soil from the 200m x 200m area was used to produce a further ten sub-samples forming five replicates of treatments 11b and 12b. For both the ‘a’ and ‘b’ treatments, the sub-samples were generated as follows.

Table 5.6. 2009 Mixing and sub-sampling treatments.

Treatment	Sample area (m)	Mixing before sub-sampling	Storage / transport temperature	Time of extraction (interval after sampling)
11a	10 x 10	No mixing	2-4°C	within 36 hours
11b	100 x 100	No mixing	2-4°C	within 36 hours
12a	10 x 10	No mixing	ambient / room	7 days
12b	100 x 100	No mixing	ambient / room	7 days
13a	10 x 10	Thorough	2-4°C	within 36 hours
13b	100 x 100	Thorough	2-4°C	within 36 hours
14a	10 x 10	Thorough	ambient / room	7 days
14b	100 x 100	Thorough	ambient / room	7 days

Without mixing, five 300g sub-samples were taken at random (obtaining each sub-sample with a single quantity of soil) from each of the two buckets of soil. These formed the five replicates of treatments 11a and 11b. The remaining soil in each bucket was thoroughly mixed for up to 20 minutes, using a knife to cut any lumps or fibrous material, and ensuring no pieces of more than 1cm diameter or length remained. From each of the two buckets a further five 300g sub-samples were taken at random, making each sub-sample up from eight random quantities of 50g each of soil, following the exact same procedure as used in 2009. These formed the five replicates of treatments 12a and 12b.

The sub-samples for all treatments were placed in insulated chilled packs at 2-4°C. Where samples were to be stored overnight prior to transport the next morning, they were placed in a refrigerator at 2-4°C. The sub-samples were then stored and extracted as described in Table 8.

Table 8. 2010 Mixing and sub-sampling treatments.

Treatment	Sample area (m)	Mixing before sub-sampling	Storage/transport Temperature	Time of extraction (interval after sampling)
11a	10 x 10	No mixing	2-4°C	within 36 hours
11b	200 x 200	No mixing	2-4°C	within 36 hours
12a	10 x 10	Thorough	2-4°C	within 36 hours
12b	200 x 200	Thorough	2-4°C	within 36 hours

Sample extraction and analysis

For the sampling methodology studies the sample extraction procedure was as follows:

The moist soil sample was broken down as much as possible, removing any stones, and 40g of the sample was weighed into an extraction vessel. 100g was also weighed out for dry matter determination. To the 40g of moist soil, 200ml of 2M KCl solution was added in each extraction vessel and it was then shaken for two hours. The extract was filtered straight away using Whatman GFA filters and the extracts frozen. A blank was included with every batch extracted. As soon as possible after each exercise had been completed, the frozen extracts were transported in insulated containers at 2-4°C to a single laboratory for immediate nitrate-N and ammonium-N analysis by standard SMN testing procedure. Results were analysed by factorial analysis of variance using GenStat.

New sample handling studies – results

Sample storage duration and temperature

Figure 22 shows the change in SMN level (mg/kg) over time for soil samples taken in spring 2009 from four fields and stored either at ambient (room) or cold (refrigerated at 2-4°C) temperature. With one exception SMN increased with time regardless of the storage temperature, and the increase started within 3 days of sampling. The rate of increase was, however, slower for samples that were stored at the cold temperature. Eastfield, which had previously had grass in the rotation, was atypical in that SMN decreased with time when stored at room temperature.

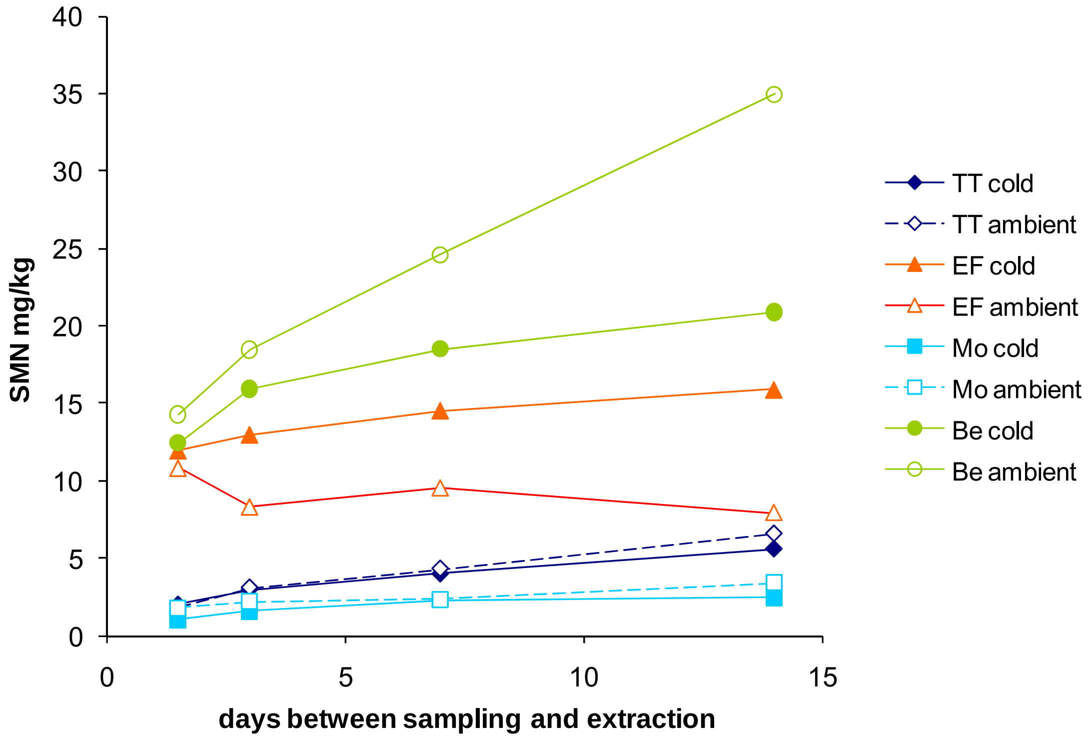


Figure 22. Effect of interval between sampling and extraction on measured SMN for soil samples taken in spring 2009 from four fields and stored at two temperatures. Abbreviations are site codes; TT= Terrington; EF= East field, Lincs Mo = Morley; Be = Beccles.

When averaged over all four fields, there was a highly significant linear increase in SMN with time (Table 9). The mean rate was 0.54 mg/kg/day increase in SMN for 7 days duration. Overall there was no significant effect of storage temperature, but there was a highly significant site x temperature interaction (F Prob. <0.001) as a result of three fields showing a more rapid increase in SMN at room temperature, and one field showing a decrease.

Table 9. Effect of storage temperature and duration on SMN values (mg/kg). Four site mean spring 2009.

Storage Temperature	Storage Duration (Days) 1.5	3	7	14	Mean	Temp. Mean
Cold (2-4^{O}C)	6.86	8.36	9.83	11.21	9.07	d.f. 96 s.e.d. 0.590 F Prob. NS
Ambient (room)	7.18	7.99	10.18	13.20	9.64	
Mean	7.02	8.18	10.01	12.21		
Duration Mean	d.f. 96 s.e.d. 0.835 F. Prob. <0.001 (Linear)					

The cause of the increase in SMN was an increase in nitrate-N, with ammonium-N decreasing with storage duration (Table 10):

Table 10. Effect of storage duration on ammonium-N and nitrate-N values (mg/kg). Four site mean spring 2009.

	Storage Duration (Days)				Duration
Extractant	1.5	3	7	14	(Linear)
Ammonium-N	0.70	0.59	0.39	0.28	d.f. 96 s.e.d. 0.147 F Prob. 0.003
Nitrate-N	6.32	7.59	9.62	11.93	d.f. 96 s.e.d. 0.871 F Prob. <0.001

Table 11 shows the effect of storage temperature on SMN values 3 days after sampling. Eastfield showed a decreasing trend with storage temperature in the amount of SMN measured. Beccles showed an increasing trend with storage temperature in the amount of SMN measured. However, the temperature effect was not significant.

Table 11. Effect of storage temperature on SMN values (mg/kg) 3 days after sampling.

Storage			Site			Site x
Temperature	Terrington	Eastfield	Morley	Beccles	Mean	Temp.
Cold (2-4^{O}C)	2.97	12.98	1.58	15.91	8.36	d.f. 36 s.e.d. 2.247 F Prob. NS
Ambient for 1 day then cold	3.13	10.88	1.58	17.02	8.15	
Ambient (room)	3.07	8.27	2.17	18.46	7.99	

Table 12 shows the effect of storage temperature on measured SMN values 14 days after sampling. Three fields had a lower SMN when stored at 2-4°C than when stored at room temperature, but Eastfield had a higher SMN when stored at 2-4°C. Frozen storage resulted in the highest SMN values for Terrington and Eastfield, but the lowest for Beccles. The site x temperature interaction was highly significant. Frozen storage resulted in a lower amount of nitrate-N but a higher amount of ammonium-N, thus total SMN was unaffected (Table 13).

Table 12. Effect of storage temperature on SMN (mg/kg) 14 days after sampling.

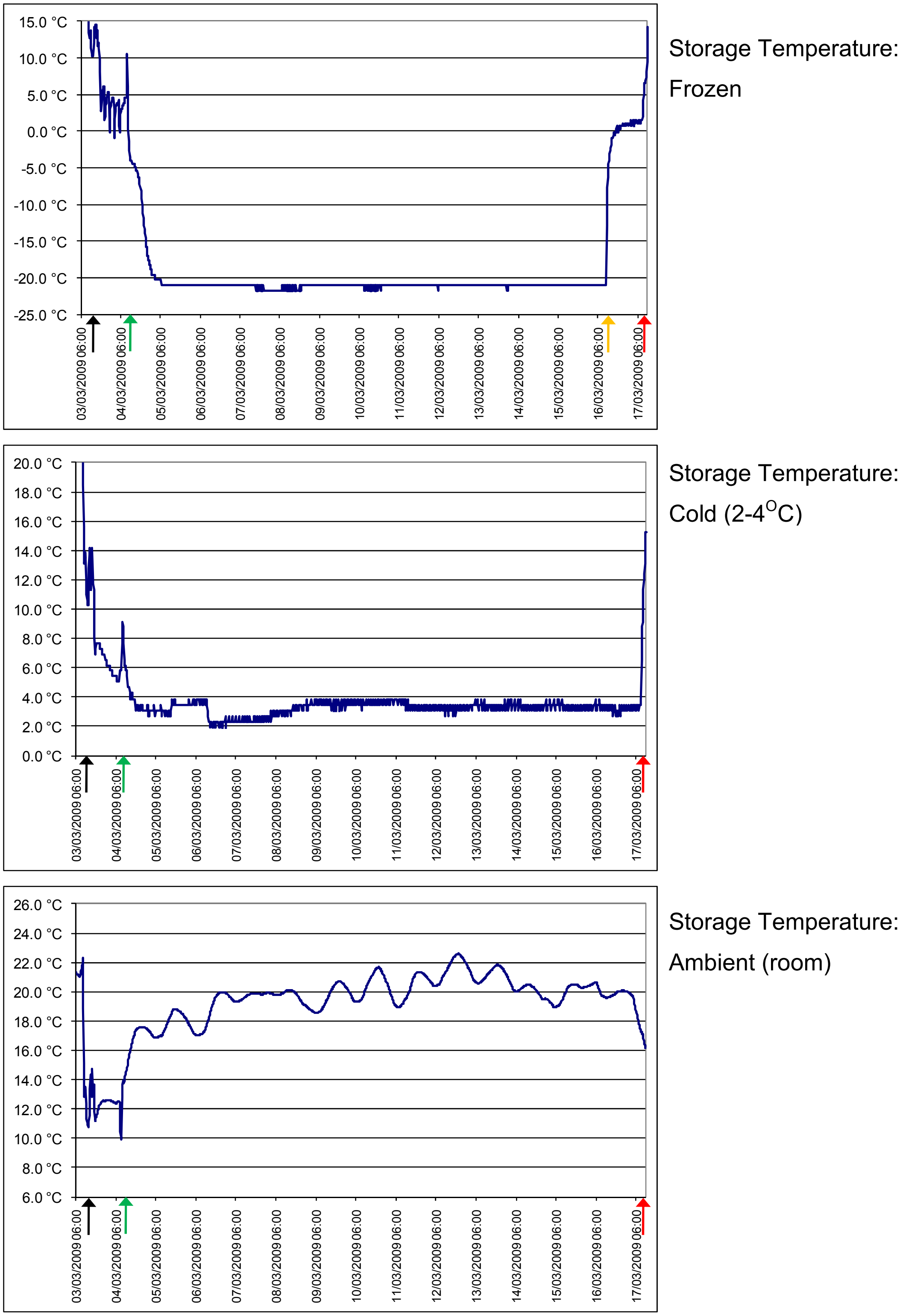
Storage			Site			
Temperature	Terrington	Eastfield	Morley	Beccles	Mean	Site x Temp.
Frozen	6.95	18.50	3.13	16.51	11.27	d.f. 36 s.e.d. 2.410 F Prob. <0.001
Cold (2-4^{O}C)	5.58	15.89	2.48	20.90	11.21	
Ambient (room)	6.55	7.92	3.41	34.93	13.20	

Table 13. Effect of storage temperature on SMN values (mg/kg) 14 days after sampling.

Storage	SMN (mg/kg)		
Temperature	Ammonium-N	Nitrate-N	Total
Frozen	4.01	7.27	11.27
Cold (2-4^{O}C)	0.25	10.97	11.21
Ambient (room)	0.30	12.90	13.20
Temp. d.f.	36	36	36
s.e.d.	0.325	1.302	1.205
F Prob.	<0.001	<0.001	NS

Figure 23 shows an example comparison for the Beccles site of the temperature profile over the fourteen day period from sampling to extraction for the sub-samples that made up replicate 2 of treatments 10 (stored frozen), 4 (stored cold at 2-4°C) and 8 (stored at room temperature). The first arrow on the date/time axis marks when the loggers were placed in the soil samples, the second when they were placed in their storage location (freezer, refrigerator or room), the third (treatment 10, frozen, only) when the sample was removed from the storage location and the fourth when the loggers were removed and the samples were extracted. These show that for most of the time the temperature of the frozen samples remained below -20°C, the refrigerated samples were maintained between 2 and 4°C and the temperature of samples stored in a room increased from 12°C to a maximum of 22°C.

Figure 24 shows the change in SMN level (mg/kg) over time for soil samples taken in spring 2010 from four fields and stored either at ambient (room) or cold (refrigerated at 2-4°C) temperature. An increase in SMN was recorded for all four fields between 4 and 7 days after sampling, and this was greatest where samples were stored at room temperature. For two fields, SMN also increased between 1 and 4 days after sampling. Of the other two fields, one showed little change in SMN during this interval and the other (with very low levels of SMN) appeared to show a small decrease.



Storage Temperature:

Frozen

Storage Temperature:

Cold (2-4^{O}C)

Storage Temperature:

Ambient (room)

Figure 23. Three temperature traces from the sample storage duration and temperature study in spring 2009 (Beccles site).

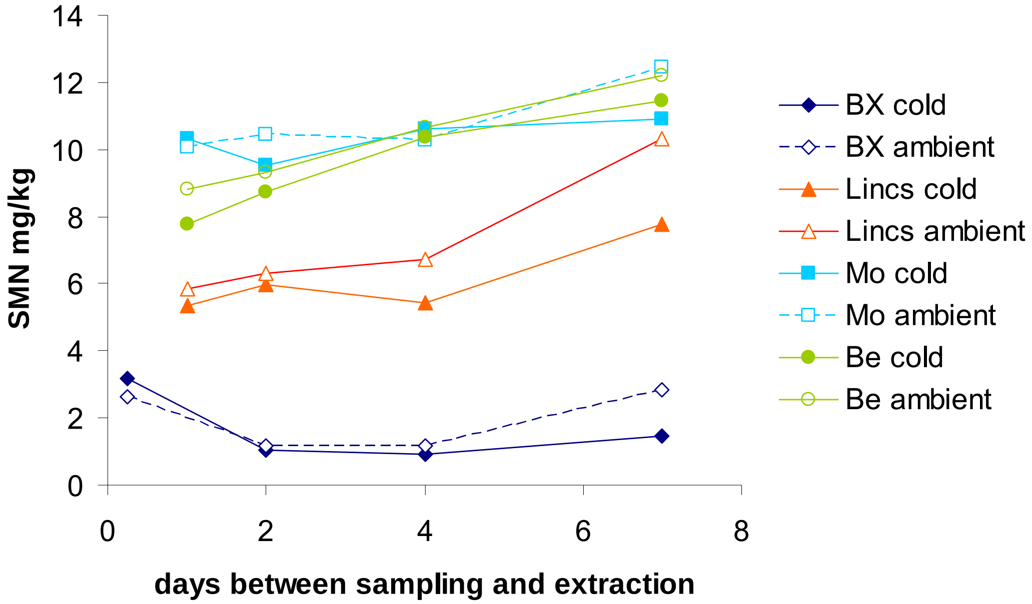


Figure 24. Effect of interval between sampling and extraction on measured SMN values for soil samples taken in spring 2010 from four sites and stored at two temperatures. Abbreviations are site codes; Lincs = Lincolnshire site, Mo = Morley; Be = Beccles; BX = Boxworth.

When averaged over all fields, there was a highly significant linear increase in measured SMN levels with time (Table 14). The mean rate was 0.22 mg/kg/day increase in SMN when stored at the cold temperature. There was a significant effect of storage temperature, the rate increasing to 0.42 mg/kg/day (duration x temperature F Prob. = 0.018).

Table 14. Effect of storage temperature and duration on SMN values (mg/kg). Four site mean, spring 2010.

Storage	Storage Duration (Days)					
Temp.	<=1	2	4	7	Mean	Temp. Mean
Cold (2-4^{O}C)	6.65	6.33	6.90	7.91	6.95	d.f. 96 s.e.d. 0.192 F Prob. <0.001
Ambient (room)	6.85	6.82	7.35	9.50	7.63	
Mean	6.75	6.57	7.12	8.70		
Duration mean	d.f. 96 s.e.d. 0.272 F Prob. <0.001 (Linear)					

The impact of sampling depth on the effect of storage duration on SMN values is shown in Table 15. At all sites there was an increase in SMN for samples taken from 30-60cm when stored for 7 days, as there was for samples taken from 0-30cm depth. However the average increase for samples from 30-60cm depth was only 4%, compared to 25% for samples from 0-30cm depth.

Table 15. Effect of storage duration on SMN values (mg/kg) for 30-60cm compared to 0-30cm depth soil samples. Four site mean spring 2010 (stored cold at 2-4°C).

Sample Depth (cm)	Site	Storage Duration (Days) 2	7
0-30	Beccles	8.72	11.46
	Boxworth	1.06	1.47
	Lincs	6.02	7.77
	Morley	9.51	10.92
	Mean	6.33	7.91
30-60	Beccles	42.70	44.42
	Boxworth	2.43	2.80
	Lincs	21.05	21.49
	Morley	7.79	8.08
	Mean	18.49	19.20
Treatment (site mean)		d.f. 184 s.e.d. 1.236 F Prob. <0.001	

Mixing and sub sampling

Table 16 shows the effect of thorough mixing of the soil prior to sub-sampling on the average SMN level for the four fields sampled in each year. In spring 2009, thorough mixing of the soil sample resulted in a significantly higher amount of nitrate-N (and therefore SMN) being measured. In 2010 however there was no effect of mixing on the amount of SMN measured. This was probably related to the temperatures when soils mixed, it being warmer in 2009.

Table 16. Effect of sample mixing on SMN values in spring 2009 and 2010: mean of four sites (and two storage durations/temperatures in 2009).

Treatment Regime	Average SMN mg/kg Ammonium	Nitrate	2009 Total	2010 Total
Thorough	1.14	6.70	7.84	7.29
No Mixing	1.18	5.30	6.48	7.54
Mixing d.f.	64	64	64	64
s.e.d.	0.380	0.387	0.673	0.548
F Prob.	NS	<0.001	0.048	NS

Table 17 shows the effect of the size of the sampling area on the average SMN level for the four fields sampled in each year. In both years, the average SMN measured was higher for the narrow (10 x 10m) than the wide (100 x 100m or 200 x 200m) sampled area, but this difference was only significant in 2010.

Table 17. Effect of sampling area on SMN values in spring 2009 and 2010: mean of 4 sites (and two storage durations/temperatures in 2009).

Treatment			Average SMN mg/kg			
Regime	Narrow	2009	Wide	Narrow	2010	Wide
Thorough	8.17		7.51	8.74		5.84
No Mixing	6.95		6.01	8.85		6.23
Treatment Mean	7.56		6.76	8.79		6.04
Area d.f.		64			64	
s.e.d		0.673			0.548	
F Prob.		NS			<0.001	

Coefficients of variation (CV) for the replicate sub-samples comprising the thoroughly mixed treatments are compared to those for the no mixing treatment for each field in Table 18. Replicate sub-samples from the thoroughly mixed treatments tended to have a slightly lower CV than those from the no mixing treatments. The difference in CV between the thorough and no mixing treatments was not dependent on the average level of SMN in the samples.

Table 18. Effect of sample mixing on mean sub sample SMN values and coefficient of variation.

		Average SMN (mg/kg)		CV (%)	
		No Mixing	Thorough	No Mixing	Thorough
2009	Terrington	2.95	2.83	29	30
2009	Lincs	4.89	8.08	35	30
2009	Morley	1.33	1.73	39	33
2009	Beccles	16.76	18.71	58	52
2010	Boxworth	4.96	4.47	24	23
2010	Lincs	6.68	7.95	40	29
2010	Beccles	8.66	9.55	35	26
2010	Morley	8.45	7.20	27	15
Average		*6.84*	*7.57*	*36*	*30*

New sample handling studies – discussion

Sample storage duration and temperature

The rates of increase in SMN in samples stored cold at 2-4°C were greater than expected, especially in spring 2009. The increase in SMN that occurred when analysis was delayed by only 36 hours (from 1.5 days to 3 days after sampling) could for example in practice result from samples being sent to a laboratory at the end of a week and having to be kept in a refrigerator until the start of the next week before analysis. It is very evident that cold storage of samples helps, but this does not obviate the need to strive for rapid analysis. The different behaviour of the samples from Eastfield when stored at room temperature is notable. The slight decrease in SMN level with time is evidence of net immobilisation (rather than net mineralisation) due to the field having previously had grass in the rotation.

Freezing of soil samples has sometimes been used where there is a need for long term storage. In spring 2009, after 14 days the average increase in nitrate-N (over and above the 6.01 mg/kg measured at 1.5 days in the cold stored sample) was reduced from 4.96 mg/kg for the cold stored sample to 1.26 mg/kg for the frozen sample (Table 12). However, freezing increased ammonium-N (over and above the 0.85 mg/kg measured at 1.5 days in the cold stored sample) by 3.16 mg/kg, whereas cold storage reduced ammonium-N by 0.6 mg/kg. Therefore freezing was reducing nitrification but not slowing the release of ammonium, probably due to mineralisation.

The increases in SMN that were seen due to sample storage in spring 2010 were somewhat smaller than in 2009, although the longest storage duration in 2010 was only 7 days. This was despite a similar range of SMN levels in the samples from each year to begin with. The cold stored samples in particular showed a much slower rate of increase. The reason for this is not certain, but as the sampling in spring 2010 followed a colder winter than the sampling in spring 2009, it is possible that mineralisation was slower getting going in 2010, or that soil temperatures were lower at the time of sampling. It was anticipated that SMN in the deeper 30-60cm soil layer would alter more slowly due to the soil having less organic matter and the results from spring 2010 appear to confirm this.

Mixing and sub-sampling aeration of the soil during the prolonged mixing process is the most likely reason for this. It is uncertain why no increase was seen in spring 2010, but (as with the smaller impact of storage duration) one possible explanation is a slower start to mineralisation due to the colder winter. Alternatively it may be that different soil temperatures at the time of sampling and mixing caused the different results. The consistently increased SMN for the narrow (10m x 10m) compared to the wide (200m x 200m) sampled areas in spring 2010 is also surprising and is difficult to explain.

The main purpose of this particular study was to assess the degree of uncertainty that could be introduced to SMN measurements as a result of failure to obtain a representative sub-sample from the bulk of soil that is collected from within a field. It was observed that, especially for soils with potentially high SMN values due to high levels of organic matter or crop residues, this could explain some of the variation in SMN among replicate sub-samples seen within the standardisation exercises (see section 3.4.4). Although there was evidence of a reduction in variability where soil samples were thoroughly mixed before sub-sampling, in many cases the reduction was quite small.

The narrow and wide sample areas were included in order to examine whether or not variability (and therefore the importance of mixing prior to obtaining a sub-sample) might be greater where soil samples are collected over a larger area. However, there was little evidence of this being the case.

In practice, the chosen duration of mixing should be sufficient to obtain a homogeneous soil sample prior to obtaining a sub-sample for sending to the laboratory, but it should not be excessive to minimise the risk of increased mineralisation.

3.4.4. Laboratory analysis

Standard laboratory procedures

The standard procedure for the analysis of SMN is described in MAFF Reference Book 427, The Analysis of Agricultural Materials (Anon., 1986). The standard operating procedures employed by three laboratories involved in analysis for SMN were compared here (data from a fourth lab are included).

Potential sources of difference in measurement highlighted by this comparison are the period of storage of soil samples prior to extraction, the procedure for sub-sampling the soil received by the lab prior to extraction, the molarity of the KCl extractant, the duration of the extraction process, the method of extractant separation and the assumed bulk density used during subsequent calculations of SMN kg/ha.

Giebel *at al*. (2006) reported an exercise in two successive springs, conducted as part of a study on spatial variability. At a number of sample points in five fields, six cores were taken within a 1m radius. These were mixed, divided into two samples and then analysed separately for SMN. Uncertainty due to analytical / sub-sampling errors was found to be of the order of 5-10 kg/ha N for the 0-60 cm layer, and was calculated to contribute less than 40% to the local variance.

Past exercises in the UK have reported poor agreement between labs (Knight, 2006), though it is not clear from these whether this may have been caused by inherent sub-sample variability or differences in sample transport and storage, rather than being due to laboratory techniques themselves.

Standardisation studies – Objectives

Studies were carried out to gauge any systematic variation in test results between laboratories and to test confidence in the measured values. Two exercises were conducted, one in spring and one in autumn 2008. Duplicate sub-samples all from the same initial soil sample were sent to each of three laboratories and analysed for SMN. Other soil N tests were also done, but only in spring 2008. The results were supplemented with data from three similar exercises conducted by the laboratories themselves (including a fourth laboratory) between 2007 and 2009.

Standardisation studies – Methods

Up to ten fields were selected from those that were being sampled for Task 3 in spring 2008 (Table 19) and autumn 2008 (Table 20). The fields were chosen to represent the range of SMN levels that were expected to be obtained in Task 3, with the aim of half of the fields chosen having medium SMN levels (>100 kg/ha within 0-90 cm depth).

Table 19. Fields selected for the spring 2008 standardisation exercise.

Site ID	Soil Type	Previous Crop	Grass History	Manure History	Spring 2008 SMN kg/ha 0-30cm	0-90cm
8A-011(A)	light sand	peas	No	Yes	60	129
8A-012(B)	light sand	linseed	No	Yes	34	75
8A-003(C)	deep silt	OSR	No	No	17	61
8A-004(D)	deep silt	wheat	No	No	33	69
8T-036(E)	medium SCL	wheat	Yes	No	30	112
8T-044(F)	shallow chalk	OSR	No	Yes	50	80
8T-032(G)	medium SCL	beans	No	No	10	32
8T-033(H)	medium SCL	OSR	No	Yes	25	67
8S-044(I)	deep clay	OSR	No	No	9	37
8S-045(J)	deep clay	beans	No	No	24	63

SCL = Sandy Clay Loam.

Table 20. Fields selected for the autumn 2008 standardisation exercise.

Site ID	Soil Type	Previous Crop	Grass History	Manure History	Autumn 2008 SMN kg/ha 0-30cm	0-90cm
9A-056(A)	deep clay	OSR	N	Y	67	135
9A-059(B)	deep silt	OSR	N	N	25	71
9A-064(C)	deep clay	maize	N	Y	16	31
9S-093(D)	medium CL	wheat	N	N	28	47
9S-097(E)	medium CL	wheat	N	N	29	58
9T-071(F)	medium SCL	beans	N	N	10	34
9T-076(G)	organic ZL	lettuce	Y	Y	188	425
9T-081(H)	deep clay	OSR	Y	N	39	121
9T-084(I)	organic ZCL	potatoes	N	N	73	695

SCL = Sandy Clay Loam; CL= Clay Loam; ZL= Silty Loam, ZCL= Silty Clay Loam

Two 0-30 cm depth soil sample cores were taken at each of nine sampling points within a 10m x 10m area, following the same procedures as used in the main Task 3. The 18 cores were expected to be sufficient to give a total fresh soil weight of at least 3 kg. The soil was then thoroughly mixed at each site to ensure that sub-samples were as identical as possible, and to enable fair comparisons of differences between individual analyses by different laboratories. Particular care was taken with clay soils or where cores remained as solid ‘sausage’ shapes (in which case each core was cut into 1 cm lengths before mixing), or where the soil sample contained fibrous crop residues or other organic material.

Six sub-samples of about 500g each were obtained by taking eight to ten small portions of soil of 50-70g. These were labelled to identify the site and sub-sample number. Back-up samples were retained from any soil remaining. Two of the six sub-samples, chosen at random, were sent to each of the three laboratories, packed in insulated chilled packs and for next day delivery. Where overnight storage was unavoidable, samples were stored in a refrigerator at 2-4°C (*not* frozen).

In both spring and autumn 2008 both of the sub-samples sent to each laboratory were analysed for dry matter %, nitrate-N (mg/kg) and ammonium-N (mg/kg). In spring 2008 only, one of the two sub-samples sent to each laboratory was analysed for mineralisable N by anaerobic incubation and hot KCl extraction, total N% (by Dumas or Kjeldahl) and soil organic matter % (by Walkley Black Method).

For the autumn 2008 exercise only, a pre-programmed ‘Tiny-Talk’ temperature recorder was included inside one of the sub-samples in the middle of each insulated pack. Once initiated, the loggers were capable of recording temperature every 15 minutes for up to eighteen days. The time when each logger was placed in the soil was recorded. The aim was for all sub-samples to be extracted and analysed by the laboratory within 24-72 hours of sampling. If not extracted immediately upon receipt, the sub-samples were stored in a refrigerator at 2-4°C. The dates that the sub-samples were received, analysed and the temperature loggers removed were all recorded.

Standardisation studies – results

Results from the spring 2008 standardisation exercise are shown in Tables 21 and 22 (mean of ten sites). The final range of SMN values for the sites chosen was narrower than expected, with some much lower than anticipated from the autumn 2007 values. Only two sites had more than 40 kg/ha N at 0-30 cm depth. Nevertheless there were significant differences between laboratories for both nitrate-N and ammonium-N (Tables 21 and 22). The differences in ammonium-N were of little practical consequence as the mean values were low. The differences in nitrate-N were more substantial, with laboratory 3 typically recording higher values, although this was not the case at every site. The differences were such that the mean calculated 0-30cm SMN for laboratory 3 was nearly twice that for laboratory 1, although this only translated to a difference of 20 kg/ha. Significant differences in dry matter % were also recorded, but again of little practical consequence.

Table 21. Spring 2008 HGCA standardisation exercise (DM, ammonium, nitrate and SMN).

	DM %	Ammonium mg/kg	Nitrate mg/kg	SMN 0-30cm kg/ha
Lab 1	81.1	0.14	5.17	21.2
Lab 2	81.9	1.76	5.09	27.4
Lab 3	80.9	1.15	9.23	41.5
d.f.	30	30	30	30
Lab s.e.d	0.1689	0.582	0.501	3.86
F Prob.	<0.001	0.029	<0.001	<0.001

Similar comparisons for the anaerobic incubation, hot KCl extraction and total N% tests likewise showed significant differences (Table 22). However, it should be noted that the anaerobic incubation and hot KCl tests were not routine procedures for all of the laboratories. There were significant site x laboratory interactions, and with only the data from this one exercise no specific conclusions can be drawn.

Table 22. Spring 2008 HGCA standardisation exercise (incubation, KCl, SOM and Total N).

	Incubation mg/kg	Hot KCl mg/kg	Soil Organic Matter %	Total N %
Lab 1	33.1	15.30	3.131	0.1985
Lab 2	49.4	20.98	3.315	0.2055
Lab 3	55.1	14.98	3.096	0.2250
d.f.	17	16	17	17
Lab s.e.d	3.36	1.766	0.215 (NS)	0.00825
F Prob.	<0.001	0.006	0.128	0.014

Results from the autumn 2008 exercise are shown in Tables 23 and 24 (mean of nine sites). The range of SMN values for the sites chosen (9 - 170 kg/ha at 0-30 cm depth) was wider than in spring 2008. There were once again significant differences for both nitrate-N and ammonium-N, but the trends between laboratories were not the same as in spring 2008. They were not consistent between sites either. The differences in ammonium-N were relatively minor. The differences in nitrate-N were smaller than in spring 2008, with this time laboratory 3 tending to record lower values. This translated to a difference of only about 10 kg/ha in the 0-30 cm SMN between the laboratories with the highest and lowest mean values. Laboratory 2 recorded significantly higher % dry matter than the other two laboratories, as in spring 2008.

Table 23. Results of autumn 2008 HGCA standardisation exercise (DM, NH_4, NO_3 and SMN).

	DM %	NH_4 mg/kg	NO_3 mg/kg	SMN 0-30 cm kg/ha
lab 1	74.6	0.972	12.98	55.7
lab 2	77.0	0.952	11.28	48.8
lab 3	75.0	1.647	9.64	45.1
d.f.	26	26	26	26
Lab s.e.d	0.2399	0.085	0.848	3.40
F Prob.	<0.001	<0.001	0.002	0.014

Combined results from the spring and autumn exercises are shown in Table 24. Overall there were significant differences between laboratories for ammonium-N, nitrate-N and dry matter %. However, other than for dry matter, the laboratories that produced the highest or lowest values were not the same each year.

Table 24. Results of combined 2008 HGCA Standardisation Exercise (DM, ammonium, nitrate and SMN).

	DM %	Ammonium N mg/kg	Nitrate-N mg/kg	SMN 0-30 cm kg/ha
Lab 1	78.0	0.53	8.87	37.5
Lab 2	79.6	1.38	8.02	37.6
Lab 3	78.1	1.39	9.43	43.2
d.f.	57	57	57	57
Lab s.e.d	0.1433	0.309	0.482	2.59
F Prob.	<0.001	0.01	0.018	0.05

Figure 25 brings together the SMN results from the two project exercises with data from three similar studies conducted by the laboratories in the autumns of 2007, 2008 and 2009. For each site, the results produced for individual sub-samples by each laboratory (y axis) are compared against the mean for all of the sub-samples from that site (x axis). In many cases, the range in SMN values for sub-samples from the same site measured by the different laboratories was relatively narrow, with overlapping values where two sub-samples were tested by each laboratory. There were a few exceptions, notably one site where the average was 172 kg/ha SMN and the range was 74 to 251 kg/ha, with clear segregation in the values between laboratories (Lab 1: 217 and 251, Lab 2: 179 and 188, Lab 3: 74 and 122). This site was noted as an organic soil. In addition to the previously-mentioned higher SMN levels recorded by laboratory 3 in spring 2008 (Lab 3 07-08 on Figure 25), there was a tendency for laboratory 4 (included in an inter-lab exercise outside this project) to record higher SMN levels in autumn 2009 (Lab 4 09-10 on Figure 25).

Figure 26 shows a comparison of the temperatures of the sub-samples sent from one site to each of the three laboratories in autumn 2008. The first arrow on the date/time axis marks the time when the loggers were placed in the soil samples, the second when they were collected for transport by the courier, the third when they were received by the laboratory and the fourth when the samples were analysed (and the loggers removed). The traces show considerable differences in the temperatures of the samples being sent to each laboratory, both before and during transport. In this example the samples being sent to two of the laboratories cooled from around 8-10°C to nearer 4°C over the twelve hour period between 12pm on 2 December and 12am on 3 December, but the opposite was true for the sample being sent to the third laboratory.

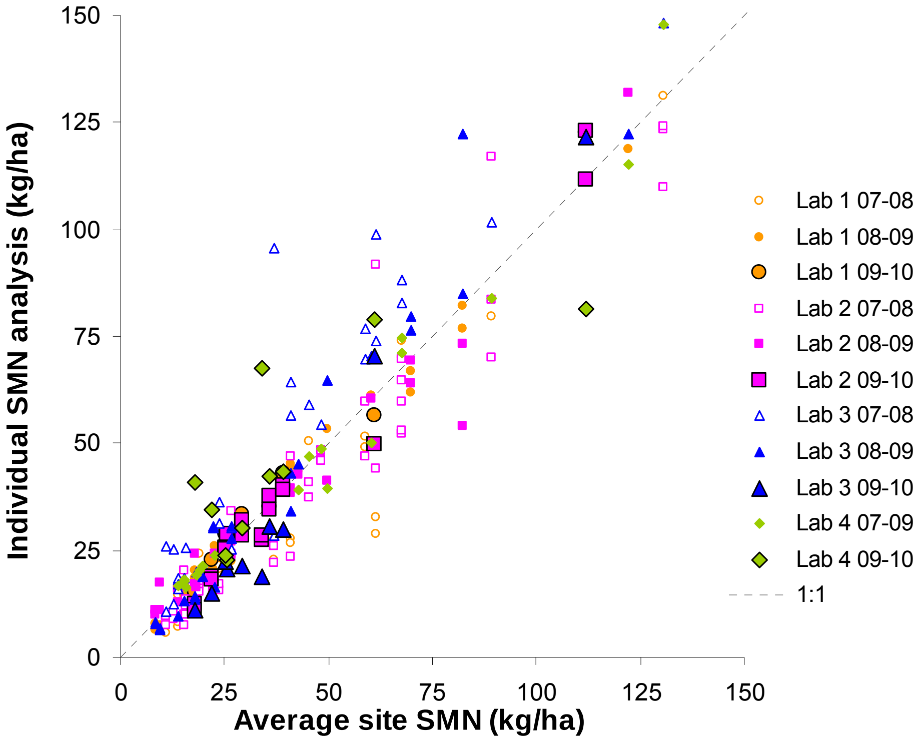


Figure 25. SMN (kg/ha) recorded by different laboratories for individual soil sub-samples from the same field sample, compared to the mean value for those sub-samples. Dotted line shows y=x.

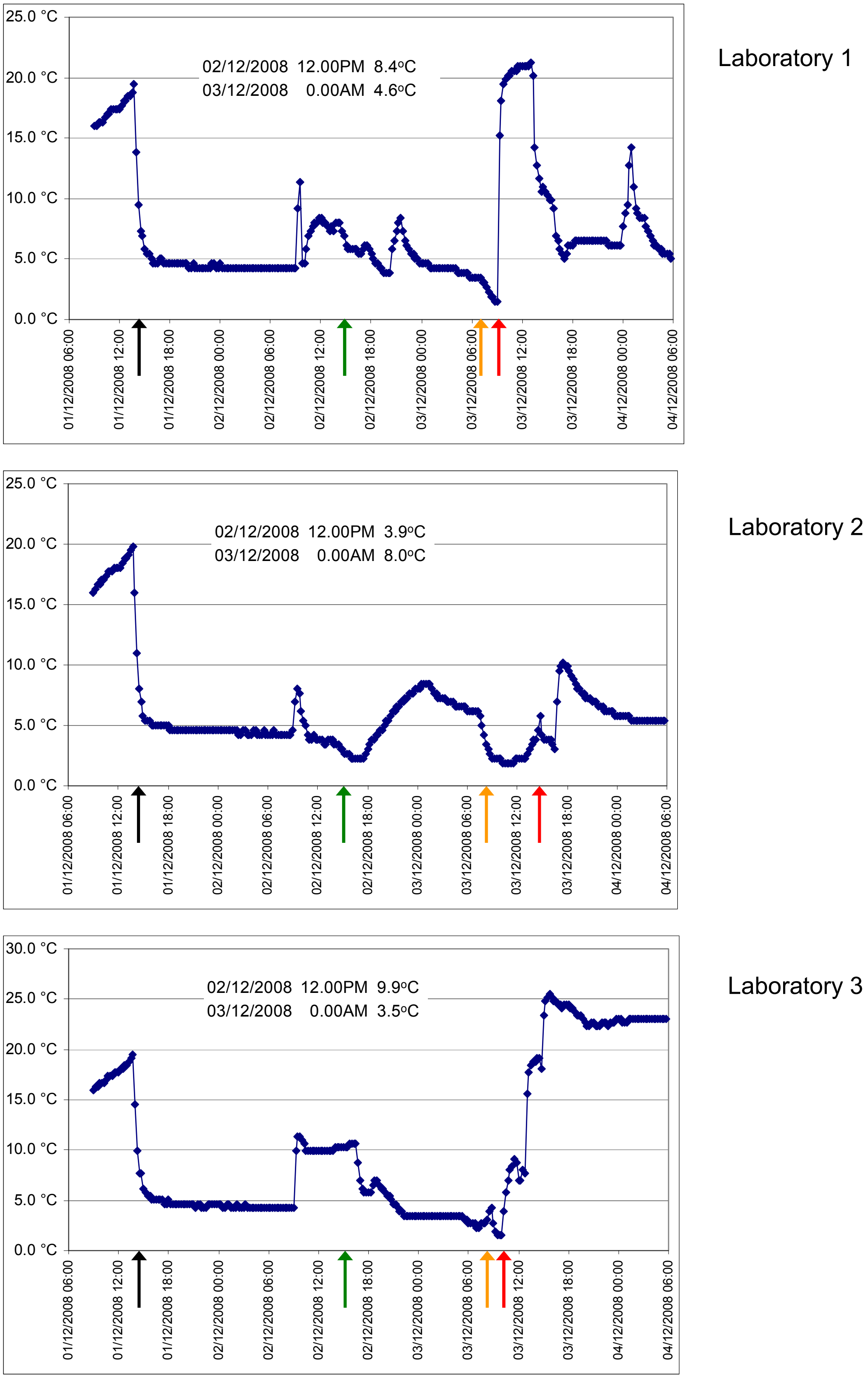


Figure 26. Temperature traces for standardisation soil sub-samples sent for standardisation tests to three different laboratories in autumn 2008.

Standardisation studies – discussion

The results from the two exercises that were conducted as part of the project and the three ring tests conducted by the laboratories themselves show that there is the potential for systematic differences in measured SMN values. However, these are not necessarily consistent from year to year. In many cases they equate to relatively small differences in the amount of SMN reported to be present, and are of little practical consequence; in some cases the differences in SMN recorded between duplicate samples sent to the same laboratory were similar in magnitude to the differences between laboratories.

It is also important to recognise that any apparent difference in measured SMN between laboratories is not necessarily the result of the analyses themselves. A comparison of Standard Operating Procedures for determining available nitrate and ammonium in soil for the three laboratories involved in the project revealed no notable differences in procedure other than the molarity of the extractant reagent used (2M KCl used by two of the laboratories, 1M KCl by the other) and the method of separation during extraction (centrifuge for one laboratory, filtration but using different filters for the other two). Neither is likely to have had a significant impact on the results reported here.

A more important difference is likely to have been the duration of sample storage prior to extraction. Examination of potential reasons for the higher levels of nitrate-N recorded by one laboratory during the spring 2008 exercise revealed that samples had been stored (refrigerated) for longer (up to 7 days) prior to extraction than by the other two laboratories (which also had shorter time limits for extraction specified in their SOPs). The sample storage study conducted in spring 2009 revealed that testing at 7 days could lead to an increase of up to 0.7 mg/kg/day in SMN levels. In addition, temperature traces obtained in autumn 2008 highlighted the variation that samples can be exposed to even when similarly and appropriately packaged, and transported by overnight courier.

A combination of warming up of the soil and delayed transport or extended storage prior to analysis is likely to account for many instances where higher than expected levels of SMN are recorded. The increase in nitrate-N with time and temperature is likely to have resulted from mineralisation (and nitrification), and this could explain why the sample that gave the most obvious differences between laboratories was from an organic soil.

3.4.5. Conclusions – sample handling and analysis

- There are several stages in the sampling and analysis process that have the potential to introduce uncertainties (errors or variation) into SMN measurement. SMN testing should therefore be looked upon as offering an approximation, and not an exact value.
- When sub-sampling from a bulk of soil collected within a field, it is important that the sub-sample obtained is representative. However, superfluous mixing should be avoided as this may stimulate mineralisation and lead to over-estimation of the available nitrate-N. The best method for sub-sampling is to take many small portions of soil from throughout the bulk of the sample to ensure a representative sub-sample but avoiding unnecessary mixing.
- It is vital to keep the interval between sampling and analysis for SMN as short as possible. Samples should routinely be analysed within 3 days of sampling. On average SMN in a 90 cm profile increases by ~5 kg/ha per day of delay, even when samples are kept refrigerated (2-4°C).
- It is important that samples are kept cool before analysis. The average increase in topsoil SMN was 0.37 mg/kg per day of storage at 2-4°C, compared to 0.49 mg/kg per day of storage at ambient temperatures.
- It is important to keep the interval between sampling and analysis for SMN as short as possible. On average SMN in a 90 cm profile increases by ~5 kg/ha per day of delay, even when samples are kept refrigerated (2-4°C).
- It is important that the delay from sampling to analysis is standardised for any sets of samples that are to be compared. It is suggested that standard delays of ~24, ~48 or ~72 hours could be adopted. Long term (one week or more) storage of soil samples is not appropriate for SMN testing.
- Freezing is not suitable for commercial SMN testing. Freezing may be necessary for large batches of samples (such as from field experiments) but experimenters should recognise that the amount of SMN present can change (as shown in the literature) and nitrification can be encouraged (as shown here). Where storage for longer than three days is required, consider extracting samples immediately so that the extracts can be frozen.
- Differences in the results obtained by different laboratories for sub-samples from the same sample of soil are likely to be small as long as there are no differences in the delay from sampling to extraction.
- Ongoing ring-tests are crucial in order to monitor for any potential systematic differences in SMN test results between labs.

3.5. SNS prediction – gathering evidence

This chapter examines some key questions regarding the estimation of SNS, namely:

- When is it best to sample SMN; autumn or spring?
- What depth is it necessary to sample to?
- How should crop N be estimated?
- How should mineralisation be estimated, or measured?
- What bulk density estimate should be used in converting from mg/kg N to kg/ha N?
- How should results be adjusted for stone content?

We first look back at relevant past datasets, then describe the generation and analysis of a new dataset that forms the major contribution of this project.

3.5.1. Lessons from past data and experience

Autumn vs spring sampling

Figure 27 shows a good relationship between SMN measured in autumn and the following spring at four sites reported by MacDonald et al. (1992), across a range of soil types.

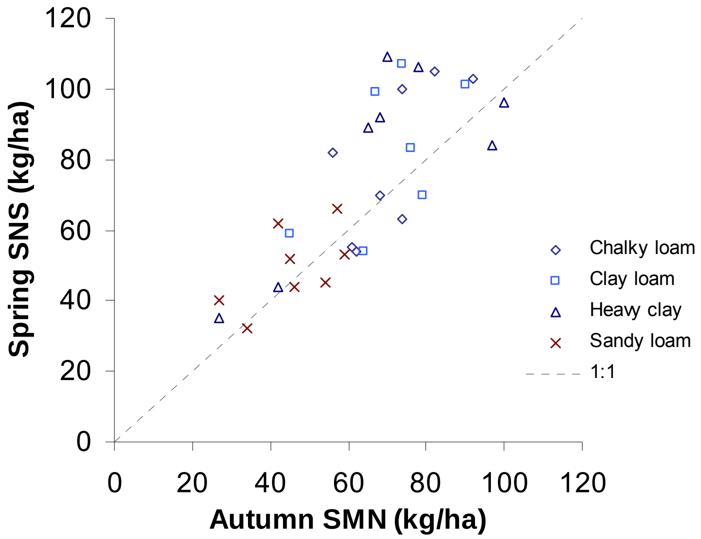


Figure 27. Relationship between SMN 0-90 cm in autumn and SNS in spring for sites with 4 soil types over 3 years (1986-1989) under winter wheat or oilseed rape, taken from MacDonald et al. (1992).

A wider range of data where SNS measures are available in both autumn and spring (Figure 28) shows the importance of soil type in this relationship. On the retentive clay and silt soils measured SNS in autumn can be expected to be similar to measured SNS in spring. However, on the less retentive soils a large proportion of SMN measured in autumn appears to be lost over winter, especially where SMN measures are high. This is most pronounced on sandy soils, where big differences in SNS in autumn translate to small differences by spring. This suggests that autumn sampling is not appropriate for sandy and shallow soils, and perhaps also not for some of the lighter medium soils.

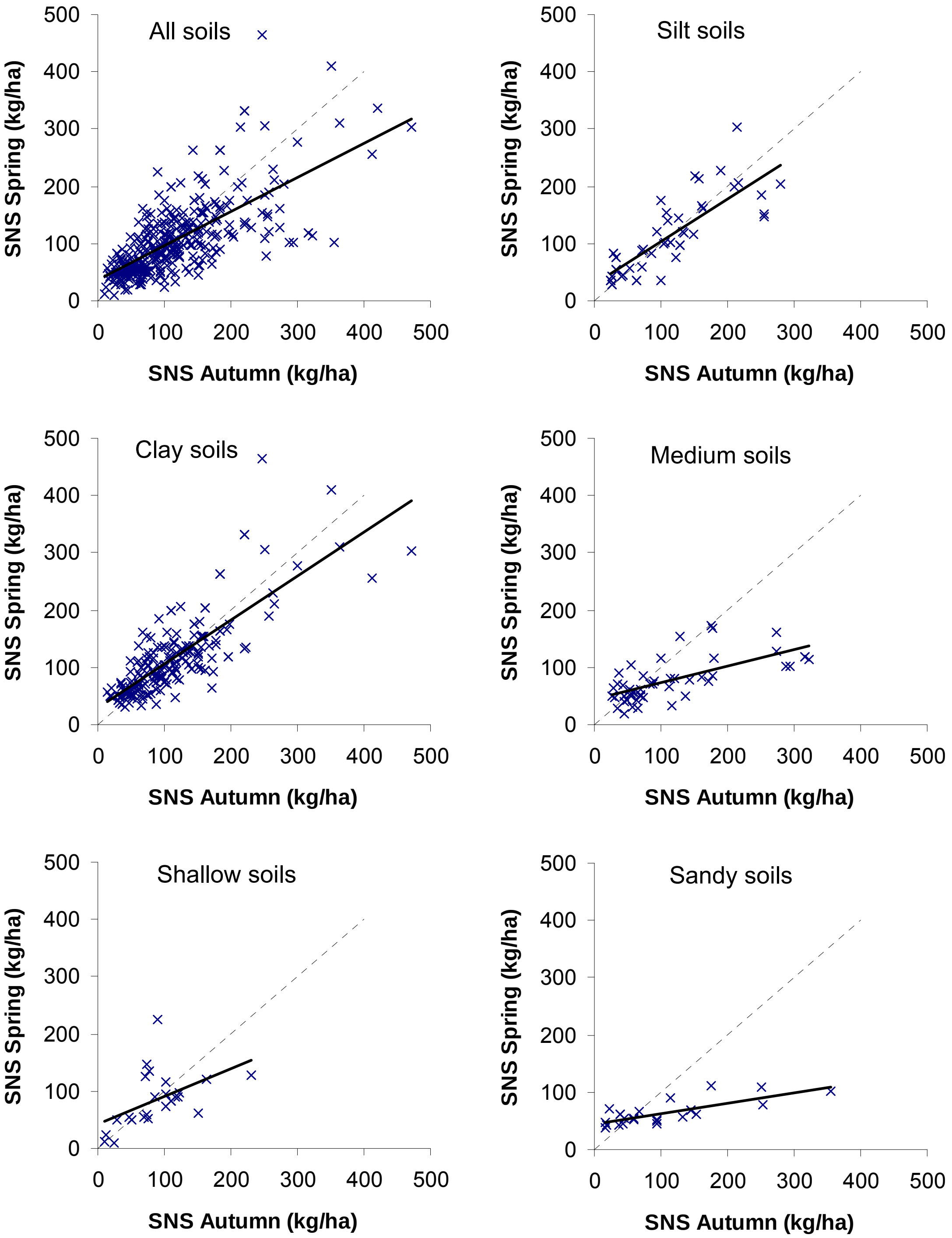


Figure 28. Relationship between autumn and spring SNS from over 40 projects between 1980 and 2010, grouped by RB209 soil group. Dashed line shows y=x.

Does autumn or spring sampling best relate to harvested SNS?

Figure 29 shows that, overall, the relationship of harvested SNS with SNS measured in autumn or in spring is broadly similar, for a dataset comprising sites since 1980 where soil measures have been made both in autumn and spring. Split-line regression analysis shows that the intercept, slope and breakpoint are similar overall (Table 25), though there are some differences between soil types. Autumn SNS appears as good or better than spring SNS in explaining harvested SNS for silt, clay and medium soils, spring SNS gives a better relationship for sandy soils and both spring and autumn SNS have poor relationships with shallow soils.

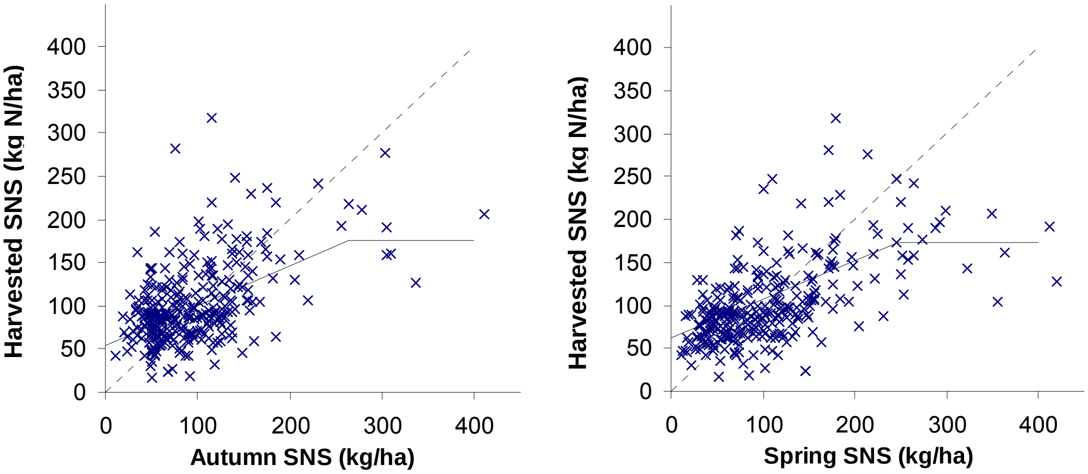


Figure 29. Relationships of (a) autumn SNS and (b) spring SNS with harvested SNS from past data where measures were made in both spring and autumn.

Table 25. Results of split-line regression of autumn SNS and spring SNS 0-90 cm against harvested SNS for sites (in past projects) in which both autumn and spring SNS were measured for different soil groups.

	ALL SOILS	SILTS	CLAYS	MEDIUM	SHALLOW	SANDS
Number of sites	303	19	161	45	22	25
AUTUMN SNS						
Intercept	54	70	52	38	42	67
Slope	0.46	0.76	0.46	0.81	0.17	0.15
Breakpoint X	264	214	299	179	260	253
Breakpoint Y	176	232	189	183	85	105
% variation explained	37.7	42.1	50.7	52.0	3.6	4.2
Spring SNS						
Intercept	55	62	57	35	35	33
Slope	0.48	0.86	0.40	1.10	0.44	0.77
Breakpoint X	291	172	>400	127	53	371
Breakpoint Y	195	210	240	174	59	317
% variation explained	33.2	48.5	40.6	27.9	0.0	16.4

Sampling Depth

It has normally been recommended that SMN sampling be done to 90 cm depth (where soils are at least that deep) taking samples in three 30 cm horizons (or to depths which best match transitions from top soil to subsoil). However, sampling to 90 cm deep is not a trivial exercise, especially if sampling is manual. If sampling to 30 or 60 cm could give equivalent results this would give considerable advantages. Figure 30 shows that the relationship between measured SNS and harvested SNS improves with increasing sampling depth; for autumn SNS, variance accounted for increases from 28%, to 34% to 41% from 0-30 cm to 0-60 cm to 0-90 cm respectively; for spring sampling, variance accounted for increases from 7% to 23% to 31% respectively. This suggests that depth of sampling may be more important in spring than in autumn, which may give credence to some recommendations that sampling 0-60cm in autumn can be acceptable.

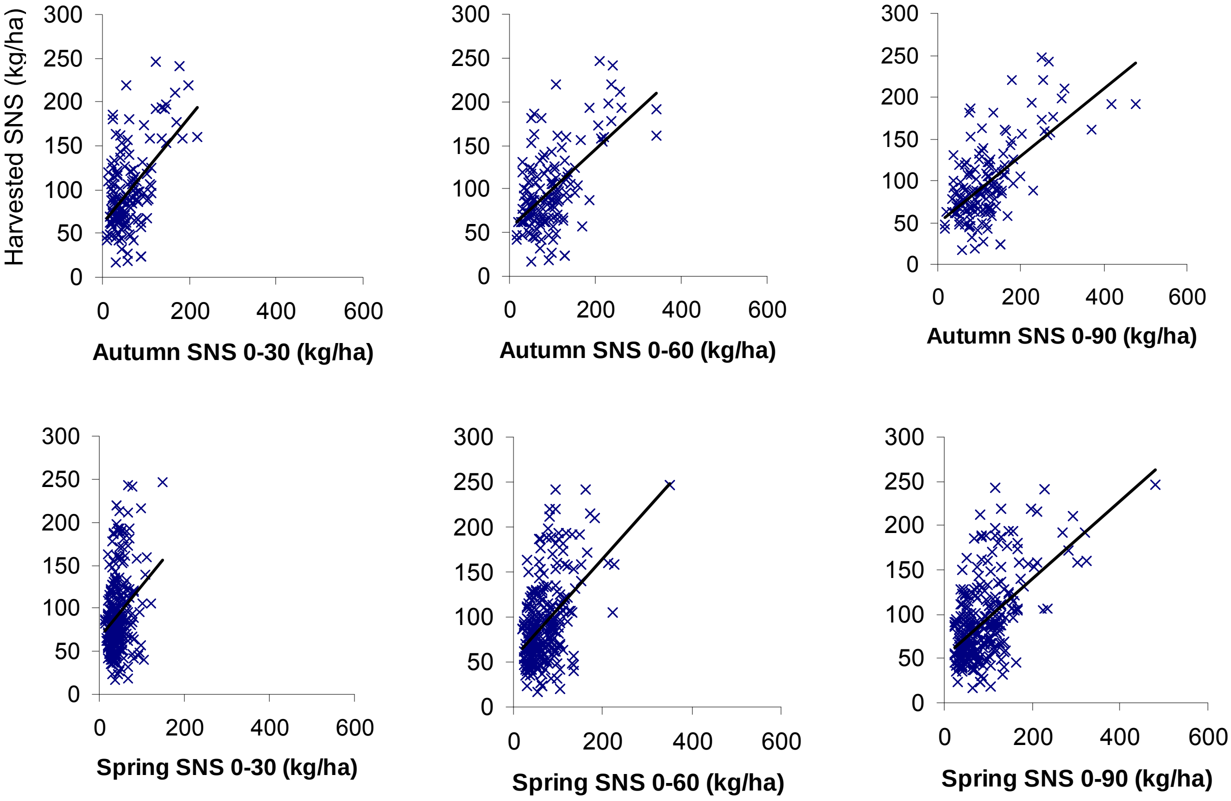


Figure 30. Relationship between measured SNS with harvested SNS for different depths in autumn and spring. NB autumn and spring datasets were not identical so are not comparable.

Crop N

The effect of accounting for crop N is demonstrated simply by comparing relationships between measured SMN and harvested SNS with relationships between measured SNS (SMN + crop N) and harvested SNS. Inclusion of crop N improves the r^2 of the linear relationship by 3% in autumn, but, in this dataset, it worsens the spring relationship by around 3%. Within this dataset a range of methods has been used to estimate crop N, and some spring measures have large crop N. If the dataset is restricted only to measures since 2000, then the relationship is *improved* by around 5% by including crop N content.

Mineralisation measures

Various studies have investigated measurements to try to predict the mineralisable component of SNS through a range of techniques such as anaerobic incubation and Hot KCl extraction (McTaggart & Smith, 1992; 1993; Smith & Li, 1993; Stockdale & Rees, 1994; Fisher et al., 1996; Chambers 1997; Bhogal et al., 1999 (MAFF NT1511); Shepherd et al., 2000; Defra 2002 (OF0164); Wang et al., 2003; Murphy et al., 2007; Sharifi et al., 2007, 2008; Bushong et al., 2007; Ros et al., 2011). Whilst some studies show that mineralisation measures relate better to harvested SNS than measurements of SMN this usually only applied within one site; use of mineralisation measures to estimate SNS in a commercial context is more challenging, as only a fraction of the potentially mineralisable N (PMN) may become available. A system has been commercialised by GrowHow UK that determines AAN from PMN using a calibration derived from a wide range of soil types, geographic location and farming systems (Annex 4). This has not previously been validated by independent research.

Figure 31 shows the relationship with harvested SNS of various direct and indirect measures of mineralisation where such measures are available from past studies. The sites were not the same for each measure so fair comparisons between methods cannot be made. There are weak positive associations between the measures and harvested SNS. The best use for mineralisation measures was in conjunction with SMN measurements, explaining more of the variation in harvested SNS. Unfortunately, datasets which include SMN, mineralisation potential and unfertilised harvested SNS are too limited for a meaningful analysis here.

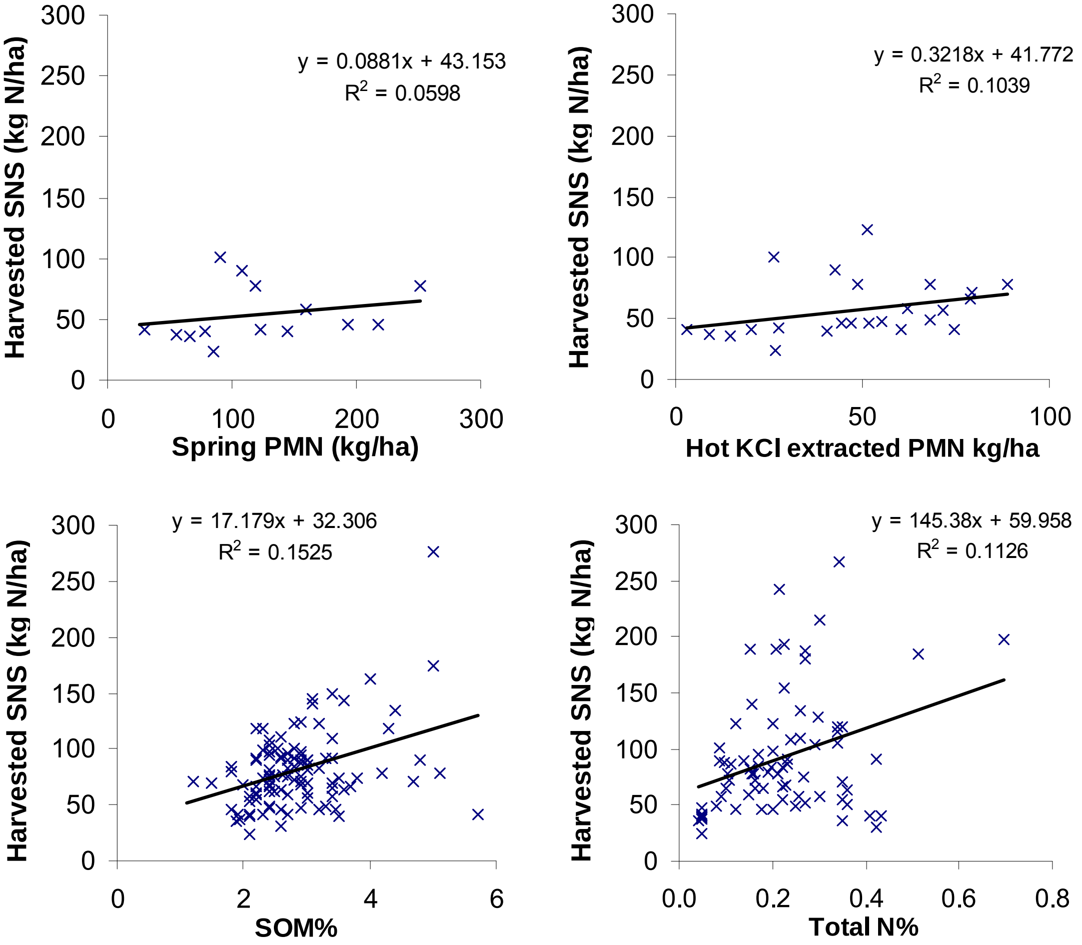


Figure 31. Relationship between various measures of mineralisation potential and harvested SNS from data generated since 1980. Sites present in each dataset are not consistent, so comparisons between measures are not meaningful.

Bulk Density and stoniness

SMN analyses are made on the basis of N concentration; mg N per kg of soil. To convert to an area basis (kg/ha) requires an assumption about the density of the soil. For simplicity, a typical bulk density of 1.33 kg/l is often used. When applied to 30 cm (0.3 m) of soil the conversion from mg/kg to kg/ha then simplifies to 4 from the following:

$$SMN_{kg/ha} = SMN_{mg/kg} / 1000 * 1.33 * 0.3 * 10000.$$

However, soils can vary substantially in their bulk density due to a range of factors including soil texture, soil depth, organic matter, compaction, consolidation and cropping.

Measurement of bulk density by the standard method (MAFF, 1982) is laborious, and not appropriate for routine use with SMN sampling. Using different bulk density assumptions for different soil textures may be more appropriate than using 1.33 kg/l across the board. Hill

Court Farm Research (HCFR) use bulk density estimates for different soil textures and depths as in Table 26.

Table 26. Estimated Bulk densities by soil texture and depth as used by HCFR

	Soil depth (cm)		
Soil Texture	**0-30**	**30-60**	**60-90**
C	0.80	1.52	1.52
ZC	0.90	1.56	1.56
SC	1.00	1.60	1.60
ZCL	1.10	1.65	1.65
CL	1.20	1.68	1.68
SCL	1.30	1.73	1.73
ZL	1.40	1.78	1.78
L	1.45	1.55	1.55
SL	1.50	1.60	1.60
LS	1.60	1.65	1.65

It is not easy to test past datasets for whether adjusting bulk densities improves SNS predictions, and to our knowledge, this has not been attempted.

Stone content

Stone contents also affect the calculation of SMN per ha from an N concentration in soil. All but the smallest stones would normally be removed from the soil sample before extraction. Thus the SMN concentration analysed by the lab applies to the non-stone soil. No adjustment is normally made for the volume of soil taken up by stones. For example, if a soil is 20% stone by volume and stones are removed before SMN analysis, the measured concentration of SMN only applies to 80% of the soil volume, so appropriate SMN values per ha may be 20% less than stated. An added complexity is that porous stones (e.g. soft chalk) may hold some mineral N, whereas impervious stones (e.g. flint) will not. The issue of dealing with stone content in SMN analysis and calculations does not seem to have been thoroughly investigated previously.

3.5.2. New data for determining best SMN practice

In order to provide more evidence to answer the unresolved questions in SMN sampling, a large new dataset was created from measures on commercial fields across arable areas of England and Scotland from 2007 to 2010. The main questions to be resolved were; appropriate timing and depth for SMN measurement, appropriate accounting for bulk density and stoniness, appropriate estimation of crop N, the value of mineralisation measures, and whether adjustments should be made for leaching after sampling. Collation of field and cropping information at each site would allow calculation of SNS by FAM for comparison, and identify situations where SMN testing is most and least useful. In order to allow the best chance of testing meaningful relationships, sites were chosen to give a wide range in expected SNS, targeting sites with a history of manure or grass to include high SNS levels. An unfertilised area at each site allowed harvested SNS to be measured, hence providing the final comparator against which other measures can be assessed.

3.5.3. New SNS dataset methods

Site selection

Around 45 winter cereal sites per year (~18 managed by ADAS, ~18 by TAG and 9 by SAC) were sought to give a good coverage of soil type, geographic location, previous cropping, farming system, past manure use, grass history and expected SNS level. Sites that had received manure in the current season were avoided, as were sites immediately following grass. The aim was for about half of the sites to give SNS levels greater than 100 kg/ha. Additional sites were provided by GrowHow for harvests 2009 and 2010, giving greater geographic spread. Additional sites following field vegetable crops were also included in 2009 and 2010 (5 sites per year), funded by HDC. A further 20 sites following peas and beans were provided by PGRO in the final year.

Information was gathered from the farmer on soil series, previous cropping, cultivations used, fate of crop residues, previous N fertiliser applications, previous manure applications in the past 5 years, and when the field had last been in grass; variety and N fertiliser use on the current commercial crop were also recorded.

The vast majority of sites (97%) were growing winter wheat, though 3 barley crops, 1 oat and 1 rye crop were also used. Table 27 shows the spread of previous cropping, soil type and manure and grass history, and Figure 32 shows the geographic range of sites used.

Table 27. Summary of previous cropping, soil types and grass/manure history for the sites used in the SNS study.

		Year			
	2008	2009	2010	total	proportion
Previous crop					
cereal	12	16	19	47	25%
OSR	20	28	14	62	33%
beans	3	6	14	23	12%
peas	2	2	12	16	9%
field vegetable	1	6	5	12	6%
potato	0	4	2	6	3%
sugar beet	2	1	1	4	2%
grass	0	2	3	5	3%
maize	0	3	1	4	2%
outdoor pigs	0	1	1	2	1%
other	2	0	1	3	2%
Soil type					
silt	6	11	18	35	19%
clay	12	12	12	36	19%
medium	15	35	34	84	45%
shallow	4	3	3	10	5%
light	5	5	4	14	7%
organic	0	3	2	5	3%
Field history					
Manure history	14	24	19	57	30%
grass history	4	11	8	23	12%
Total	42	70	76	188	

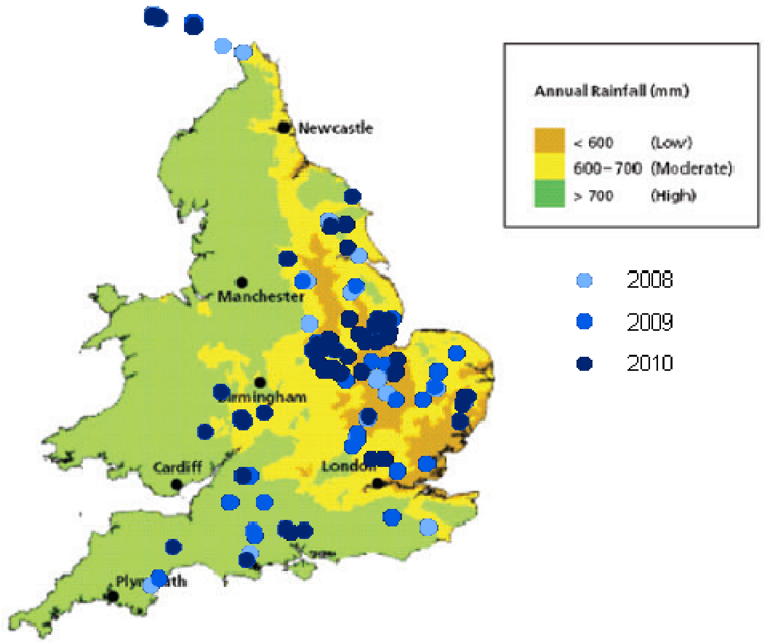


Figure 32. Geographic location of the sites used in this SNS study. Colour of dots shows year used, background map shows rainfall region from RB209.

Measurements

Field plot

At each site a representative area of the field was found where a 10m by 10m area was marked out, and from within which all measurements were taken from 9 sampling points within the area. This defined area was left unfertilised with N by the farmer. Spatial variability within such a small defined area was expected to be less than in a normal field situation, so soil sampling errors are likely to be less than in a commercial situation.

Signs were erected on the tramlines either side of the plot area saying “No N fertilisers” to mark the points where the fertiliser operator should turn off the spreader. A generous area was left around the field plot to ensure that no fertiliser got onto the plot area from adjacent tramlines, especially where spinning disc spreaders were used. In some instances a large tarpaulin was used to cover the plot area when fertiliser applications were made.

In addition to the main field plot where all soil measures were made, three additional areas surrounding the field plot were identified where additional crop samples were made at harvest of the commercially fertilised crop.

Soil sampling

Soil samples were taken in autumn (November or early December) and spring (late February or early March). Soil cores were taken from the 30 cm soil horizons to 90 cm depth from the 9 sampling points in the plot, each horizon being bulked from the 9 cores to give one sample from each horizon for analysis. Where possible samples were taken using Eijkelkamp “Stepwise” 30 mm soil corers for the top 30 cm and EJH Danish 22 mm and 19 mm corers for 30-60 cm and 60-90 cm depths respectively. Care was taken not to cross contaminate soil from one horizon to another, and to avoid any contamination from vegetation, removing the top 1 cm of soil if necessary. In 2007/8 only top soil samples were taken on a 0-15 cm and 15-30 cm basis, 0-30cm samples were taken in 2008/9 and 2009/10.

Samples were dispatched to the labs in cool boxes with ice blocks as soon as possible after sampling. Sampling was timed to avoid sending samples on a Thursday or Friday so that samples were not in storage or transit over the weekend.

Assessments were taken of topsoil texture using flow chart from RB209 (Annex 2) for each horizon. In 2007/8 attempts were made to get an indicative measure of bulk density by weighing soil cores. With knowledge of corer volume an estimate of bulk density could be calculated. However, results were deemed too variable and untrustworthy to continue this in future years. Stone content of the topsoil was assessed by digging one spit with a spade and visually assessing stone size and abundance using reference charts from the Soil Survey Handbook (Annex 1). An estimate of stone content of the deeper soil layers was made, using the table below:

Table 28. Assessment of stone content in subsoil

Description	Stones %	Identification
Stoneless	0	No stones
Slightly stony	1-15	Occasional stones appearing in soil core
Moderately Stony	16-35	Stones felt when turning corer, stones or voids in sample common
Very Stony	36+	Corer penetration difficult, impossible in places.

Visual assessments were also made of the crop at the time of sampling including average plant density, average stage of tillering (i.e. Zadoks Growth stage or number of tillers per plant) and visual estimates of ground cover and green area index. Estimates of crop N were then made using the table below.

Table 29. Assessment of crop N kg/ha

	Plant density (per m^2)			
Stage of tillering	*<80*	*80-140*	*150-250*	*>260*
seedling	*Consult*	0	0	0
up to 3 leaves	*study*	5	5	5
1-2 tillers	*director*	5	5	15
3-5 tillers	*about*	15	15	30
over 5 tillers	*aborting site.*	30	30	50

Shoots m^{-2}	*GAI*	*Crop N (Kg/ha)*
500	0.5	15
1000	1	30
1500	1.5	45

If crop N was deemed to be more than 25 kg/ha then 3 quadrats (0.25 m^2) were taken from the plot area and samples weighed, dried to 100% DM, reweighed, bulked and dispatched to the lab for N analysis by Dumas.

Soil sample analysis

In 2007/08 analysis of soil samples was shared between 3 laboratories (Eurofins, NRM and HCFR). From 2008/09 onwards all soil samples were analysed by HCFR. All SMN samples were analysed for % dry matter, ammonium-N and nitrate-N concentration (mg/kg). In addition topsoil samples in spring were also analysed for mineralisable N by anaerobic incubation, mineralisable N by Hot KCl extraction (2007/08 only), total N% by Dumas or Kjeldahl and SOM% by the RB247 Walkley Black Method.

Harvest crop samples

Crop samples were taken from each site by hand before the crop was combined. Nine samples were taken from the 9 sampling points in the unfertilised area using a 0.25 m^2 quadrat. All shoots in each quadrat were cut at ground level and kept separate. Three samples were also taken from each of the three areas identified in the surrounding commercial crop. The fresh weight of each quadrat sample was measured and the number of shoots counted. A representative sub-sample of ten shoots was taken from each quadrat, the sample was weighed and then sent to ADAS Boxworth for processing, where samples were weighed again, sub-samples bulked into 3 samples, ears and straw were separated, oven dried and weighed, ears were threshed and grain dried and weighed to allow calculation of harvest index (grain dry weight/total dry weight). After threshing chaff was recombined with straw for N analysis. In 2010 the 3 grain and 3 straw samples from each unfertilised and fertilised site were analysed separately to assess N uptake variability and measurement error. For later years it was deemed that variability in straw and grain N% between reps was sufficiently small for single determinations to be made on bulked samples in future years; variability was most influenced by grain yield. Grain and straw N% was determined by Dumas method by NRM laboratories.

Grain yield, grain N yield, straw yield, straw N yield and total N yield were calculated for the fertilised and unfertilised plots. Standard errors were also calculated from the variability in dry matter yield between the three subsamples. It should be noted that standard errors presented for N uptake do not include variability in N% measures as bulked samples were used in 2009 and 2010.

Estimating rainfall, drainage and N retention

The program IRRIGUIDE (Bailey & Spackman, 1996) was used to model leaching and N retention for each site. Over-winter rainfall for each site was calculated from Met Office weather data. IRRIGUIDE uses soil texture information in 30 cm horizons to estimate when soils reach field capacity, hence the date when drainage begins, the amount of drainage and when drainage ends. Using rainfall data, the drainage between October and April, after autumn sampling and after spring sampling was calculated.

A simpler method for estimating N retention was also used at each site, using the approach adopted in HGCA nitrogen for winter wheat management guidelines (Sylvester-Bradley 2009) reproduced in Table 30. For each site, two estimates of N retention following autumn sampling were made; one using generic rainfall from the generic rainfall map in RB209; the other using an in-year estimate of rainfall; in each case over winter rainfall was classed as below 180 mm (dry), 180 to 230 mm (moderate) or above 230 mm (wet). An attempt was also made to estimate retention following spring sampling, using estimates in Table 31.

Table 30. N retention (%) over winter for RB209 soil groups and over-winter rainfall classes (Sylvester-Bradley 2009).

Rainfall class	Deep silt	Deep clay	Medium	Shallow	Light sands
Dry	100%	95%	90%	70%	40%
Moderate	100%	90%	80%	50%	20%
Wet	80%	70%	60%	30%	10%

Table 31. N retention (%) after spring sampling for RB209 soil groups and rainfall classes.

Rainfall class	Deep silt	Deep clay	Medium	Shallow	Light sands
Dry	100%	100%	100%	80%	70%
Moderate	100%	95%	90%	70%	50%
Wet	95%	90%	85%	50%	40%

Sites excluded from analysis

In total 24 sites were excluded from further analyses for a variety of reasons. For 10 sites no N uptake data were collated, usually because the site had been compromised by an over-application of fertiliser. Seven more sites were confirmed as having had over-applications of N fertiliser after N uptake results had been analysed. Two sites gave anomalously low yields, even where N was applied, indicating that N supply was not the limiting factor, hence crop N uptake was not a fair assay for SNS. Samples from four Scottish sites in spring 2009 were delayed in transit, and subsequent SMN analyses were anomalously high. One site had no results from autumn sampling. Excluding these 24 sites left 164 sites in the final dataset.

3.5.4. New SNS dataset – results

Harvested SNS of unfertilised crops for the 164 sites ranged from 20 to 303 kg/ha, with an average of 106 kg/ha and median of 94 kg/ha. 56% of sites had final harvested SNS lower than 100 kg/ha. This is similar to harvested SNSs explored in the wider dataset from 1980-2010 described in section 3.3, despite the fact that a proportion of expected high SNS sites were explicitly targeted in this most recent dataset. Full results of all measurements plus RB209 SNS predictions are displayed in Figure 33a, and they are represented in Figure 33b *et seq* as frequency distributions. NB. For RB209 SNS estimates, very high or low estimates are not possible; mean FAM SNS was 96kg/ha, median was 90kg/ha and 59% of sites had SNS less than 100 kg/ha. Measured SNS showed a much more skewed distribution, with some very low values and a few sites giving very high SNS, ranging from 16 to 776 kg/ha in autumn (mean 116 kg/ha; median 87 kg/ha) and from 15 to 555 kg/ha in spring (mean 81 kg/ha; median 59 kg/ha). There was a noticeable difference in the distribution between measured SNS in autumn and spring, with a much higher proportion of sites having low SNS in spring; 79% of sites had spring SNS less than 100 kg/ha and 52% had SNS less than 60kg/ha, whereas in autumn 62% of sites gave SNS less than 100 kg/ha and only 20% of sites were less than 60 kg/ha.

Note that data in the third year are augmented by 20 sites after legumes (Figure 33a). This subset includes an increased proportion of sites where harvested SNS exceeded measured SNS by a significant margin. These sites were subject to particular scrutiny; two sites that had some evidence of overspreading with fertiliser N were excluded from subsequent data analysis but the remainder were retained in the analysis on the grounds that, without definite evidence, overspreading here was no more likely to have occurred than at other sites.

Figures 33b-41 show the frequency distributions of harvested SNS and measured SNS for different soil types and rainfall areas. These show that high levels of harvested SNS (>~160kg/ha) are seen most commonly on clay and silt soils in low or moderate rainfall areas; within this dataset no very high levels of harvested SNS were seen on light or shallow soils, or in high rainfall areas. The patterns in the frequency distributions of harvested SNS are generally matched by the estimates of SNS from RB209 or from SMN sampling.

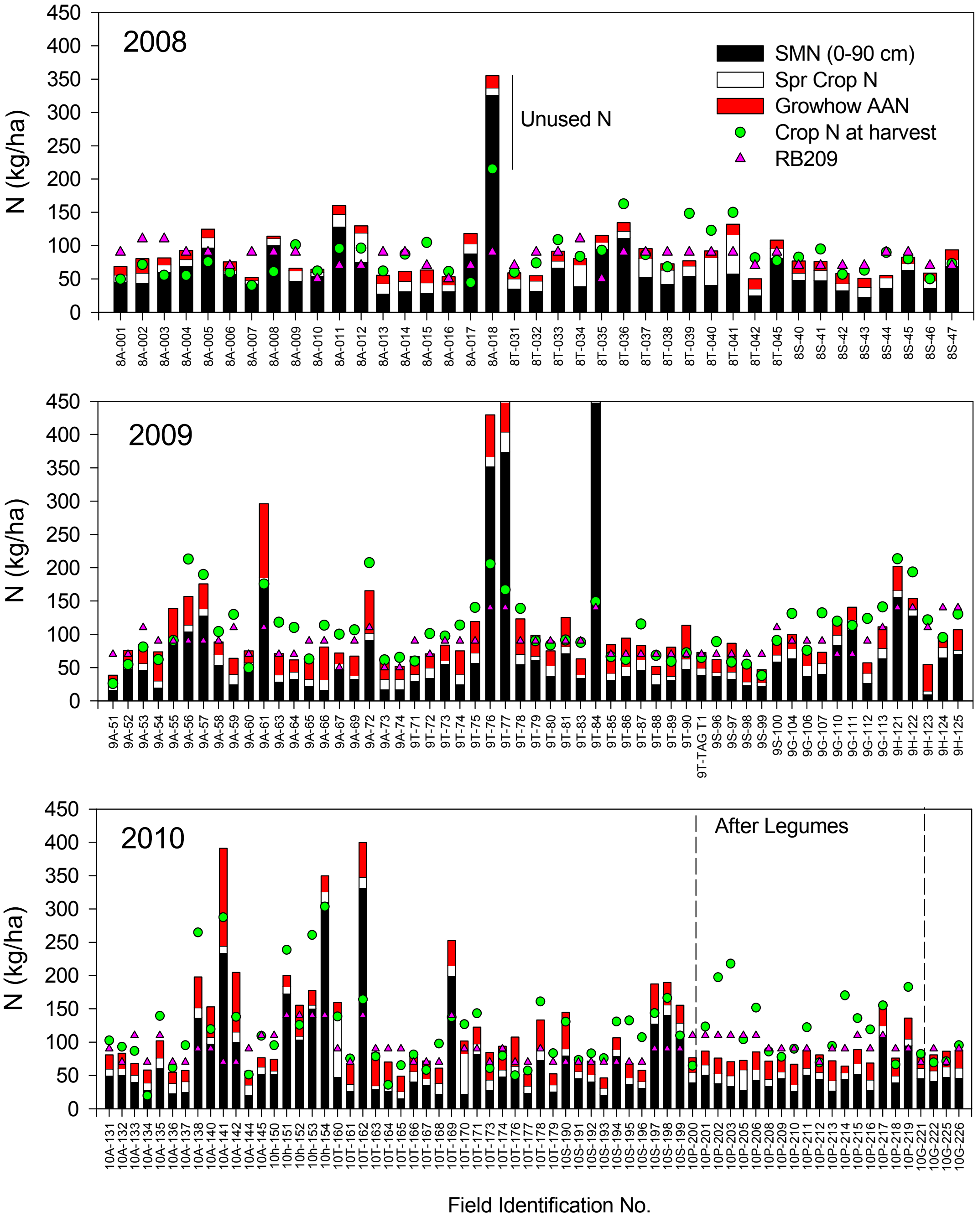


Figure 33a. Harvested SNS, spring SNS, GrowHow AAN and RB209 SNS for all sites included in the dataset from 2008, 2009 and 2010.

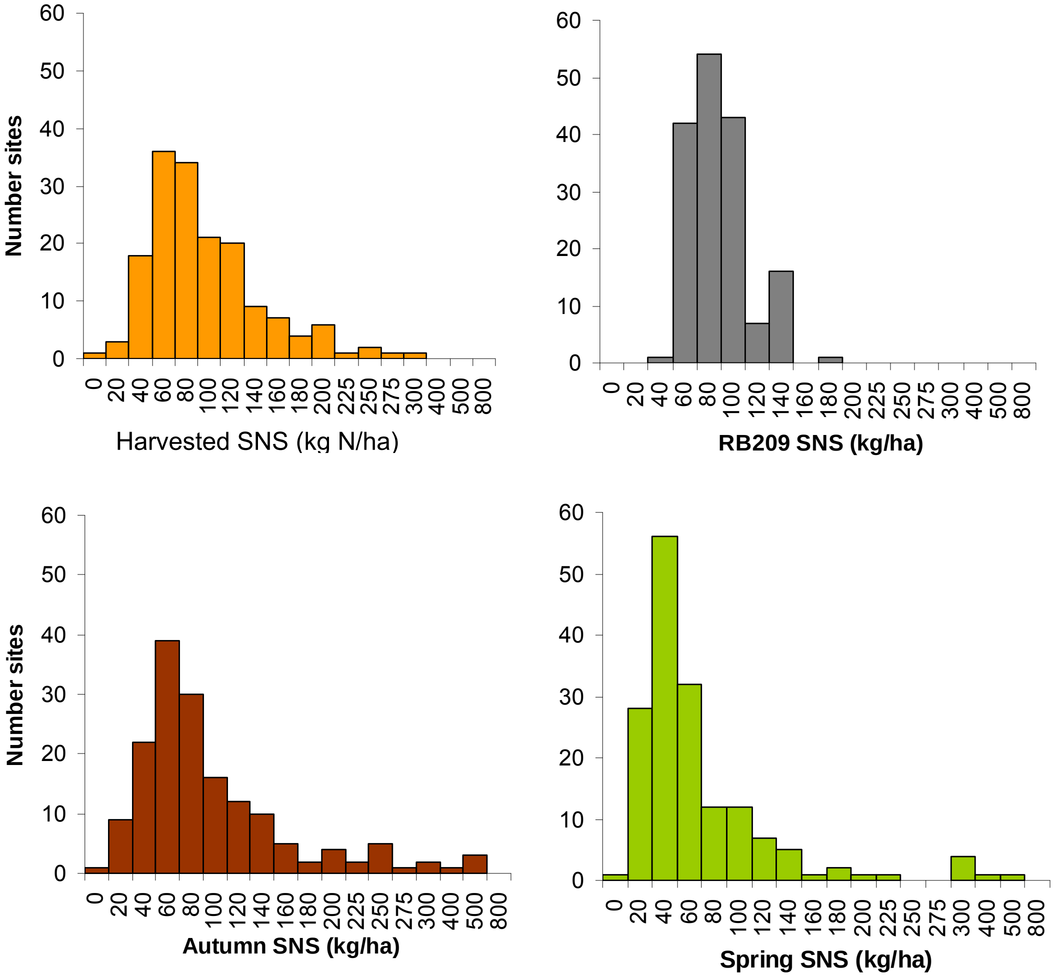


Figure 33b. Frequency distributions from 164 sites measured from 2008 to 2010. A) final harvested SNS by unfertilised crop at harvest; B) FAM estimate of SNS using RB209, including allowance for manures; C) SNS (SMN + Crop N) measured in autumn; D) SNS (SMN + Crop N) measured in spring

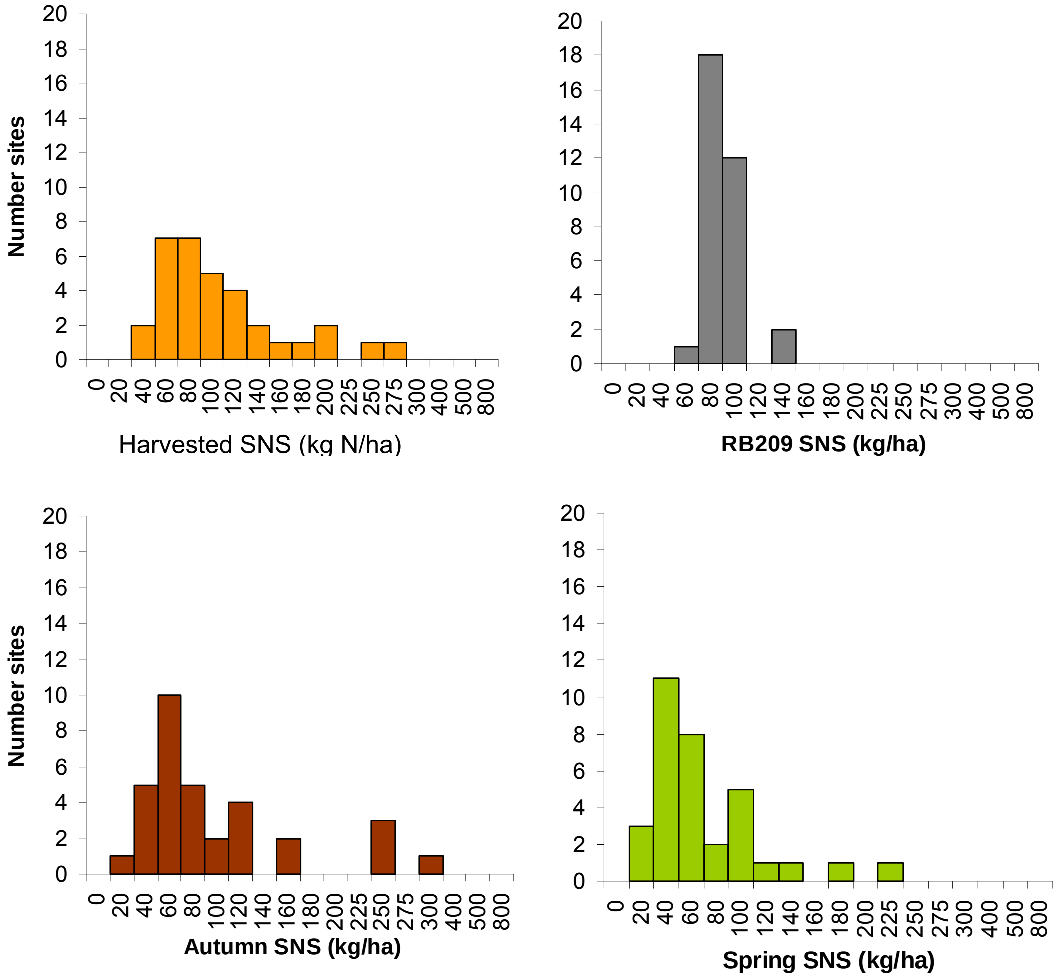


Figure 34. Frequency distributions of SNS on CLAY SOILS from a subset of 33 sites measured in 2008-2010. A) final harvested SNS by unfertilised crop at harvest; B) FAM estimate of SNS using RB209, including allowance for manures; C) SNS (SMN + Crop N) measured in autumn; D) SNS (SMN + Crop N) measured in spring

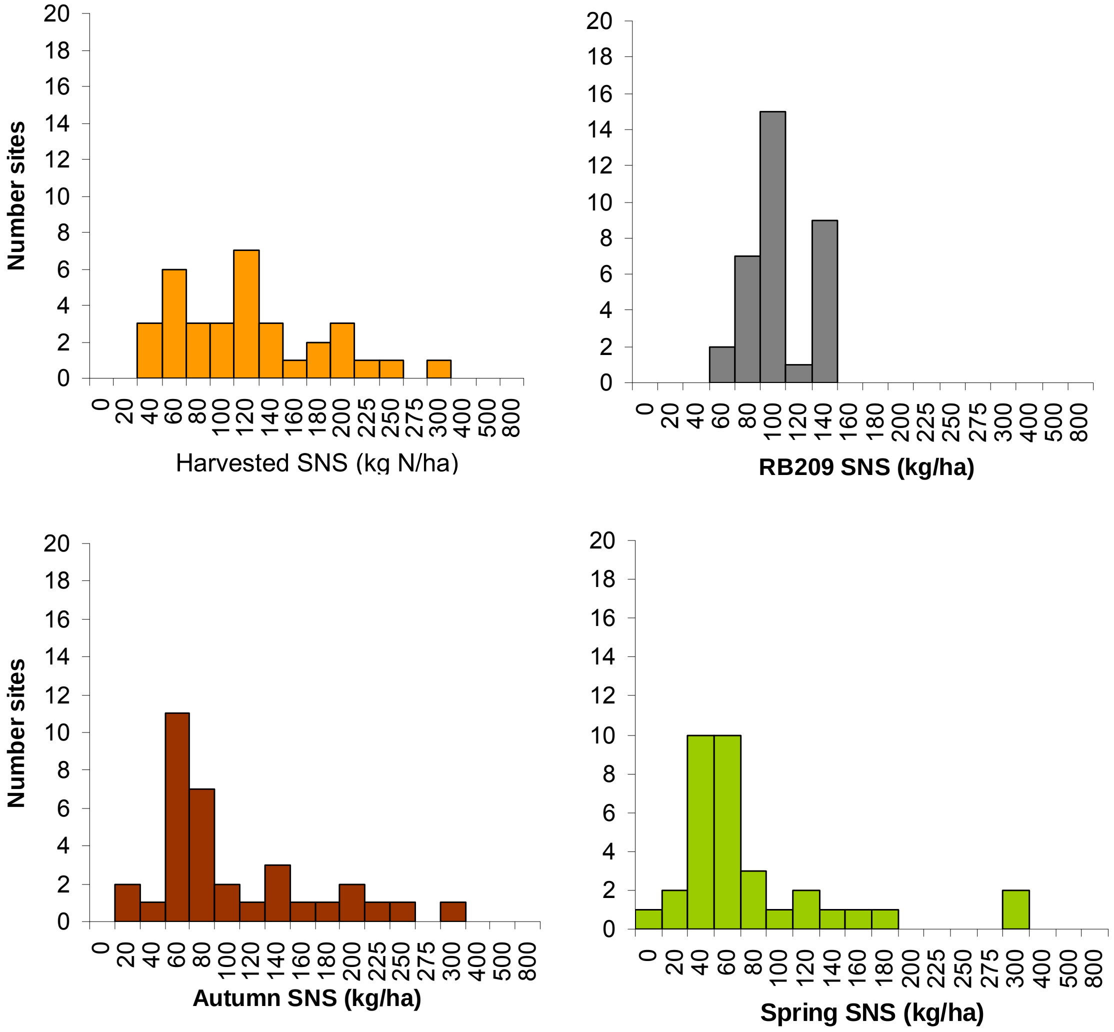


Figure 35. Frequency distributions of SNS on DEEP SILTY SOILS from a subset of 34 sites measured in 2008-2010. A) final harvested SNS by unfertilised crop at harvest; B) FAM estimate of SNS using RB209, including allowance for manures; C) SNS (SMN + Crop N) measured in autumn; D) SNS (SMN + Crop N) measured in spring

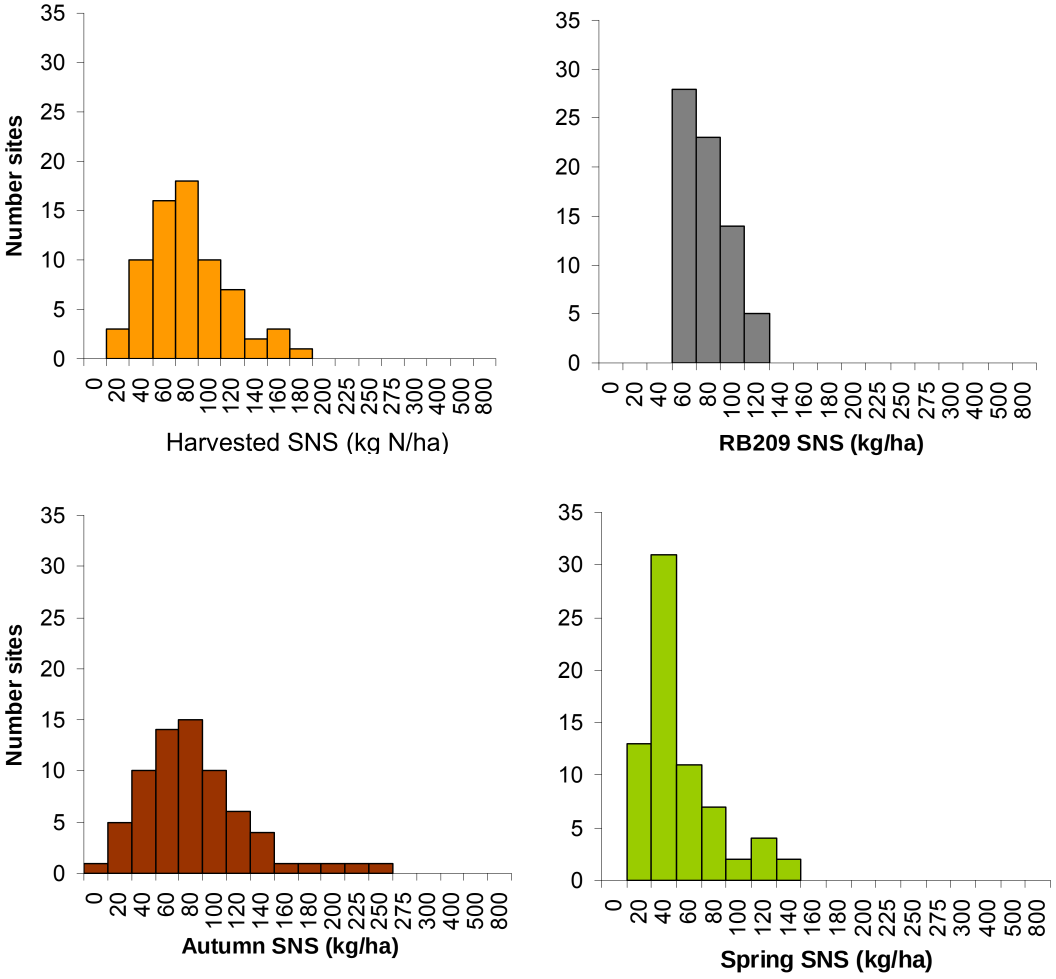


Figure 36. Frequency distributions of SNS on MEDIUM SOILS from a subset of 70 sites measured in 2008-2010. A) final harvested SNS by unfertilised crop at harvest; B) FAM estimate of SNS using RB209, including allowance for manures; C) SNS (SMN + Crop N) measured in autumn; D) SNS (SMN + Crop N) measured in spring

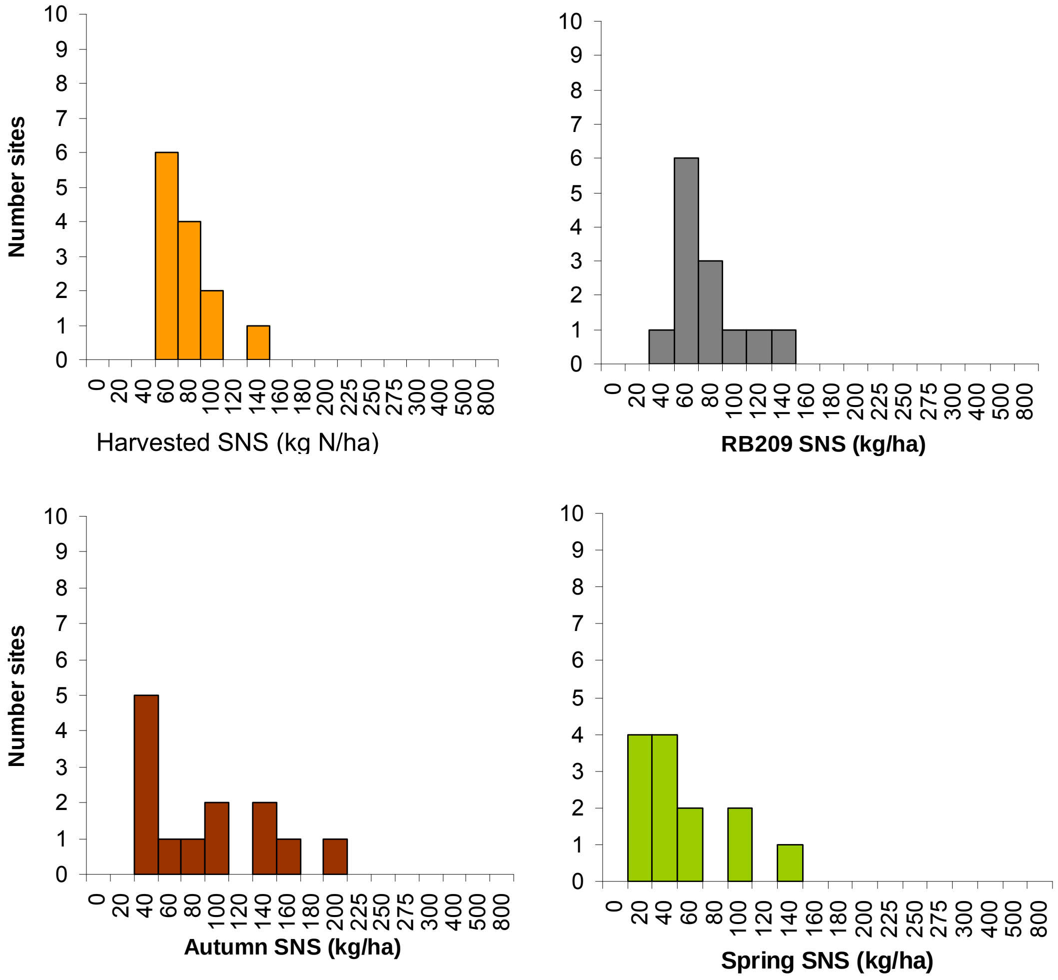


Figure 37. Frequency distributions of SNS on LIGHT SANDS from a subset of 13 sites measured in 2008-2010. A) Final harvested SNS by unfertilised crop at harvest; B) FAM estimate of SNS using RB209, including allowance for manures; C) SNS (SMN + Crop N) measured in autumn; D) SNS (SMN + Crop N) measured in spring

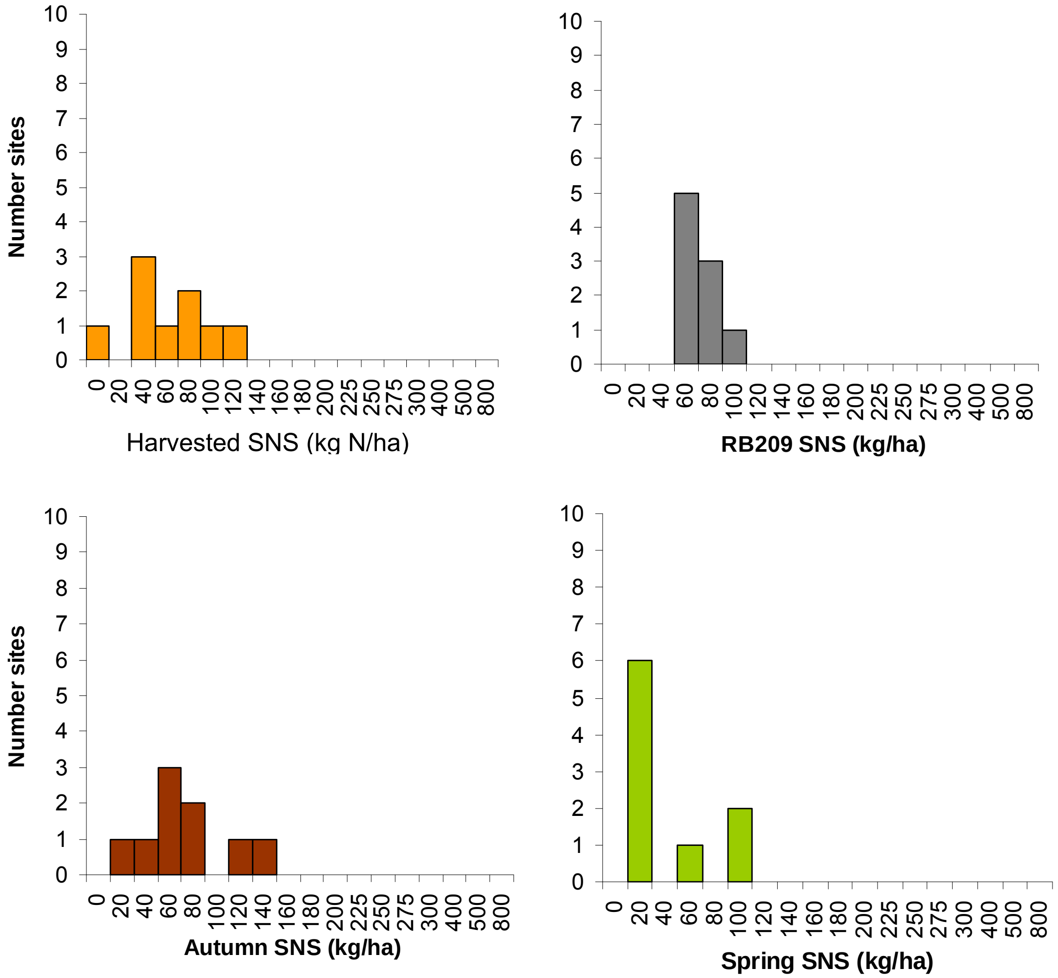


Figure 38. Frequency distributions of SNS on SHALLOW SOILS from a subset of 9 sites measured in 2008-2010. A) final harvested SNS by unfertilised crop at harvest; B) FAM estimate of SNS using RB209, including allowance for manures; C) SNS (SMN + Crop N) measured in autumn; D) SNS (SMN + Crop N) measured in spring

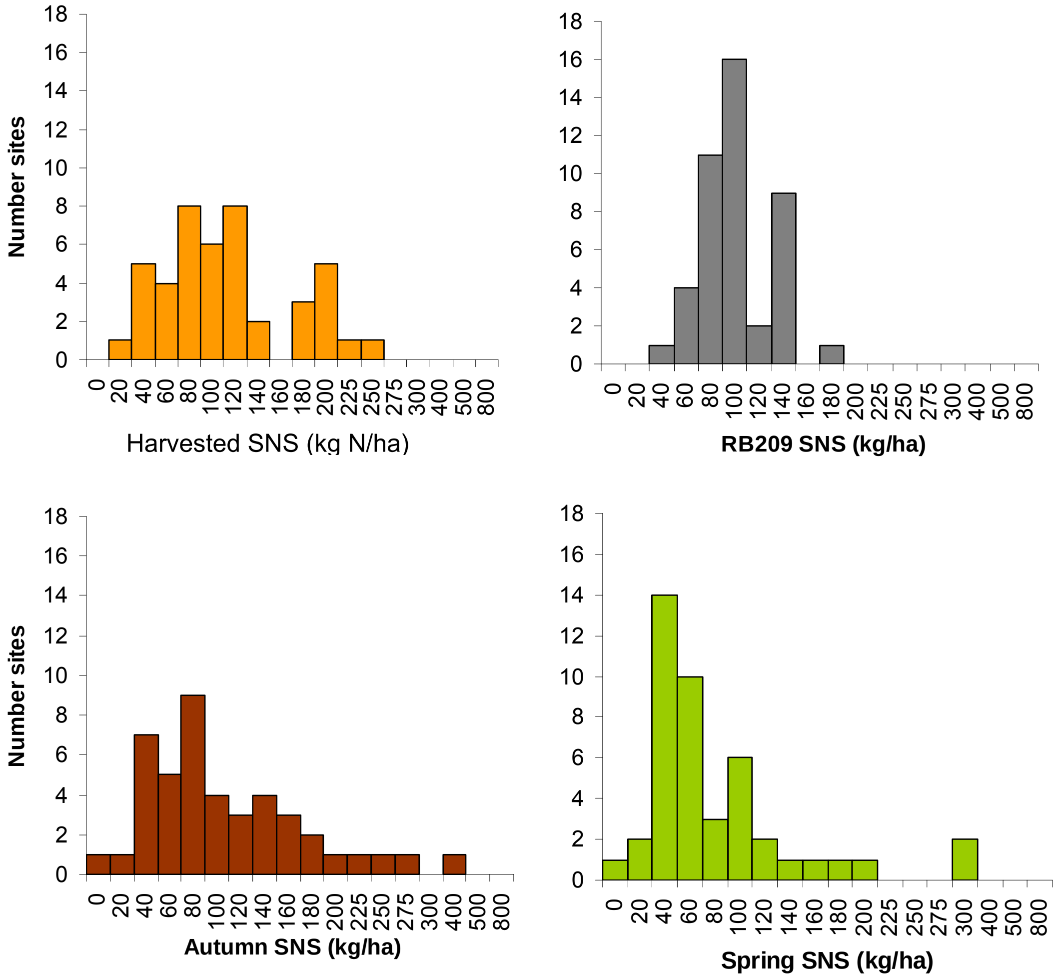


Figure 39. Frequency distributions of SNS on LOW RAINFALL AREAS from a subset of 44 sites measured in 2008-2010. A) final harvested SNS by unfertilised crop at harvest; B) FAM estimate of SNS using RB209, including allowance for manures; C) SNS (SMN + Crop N) measured in autumn; D) SNS (SMN + Crop N) measured in spring

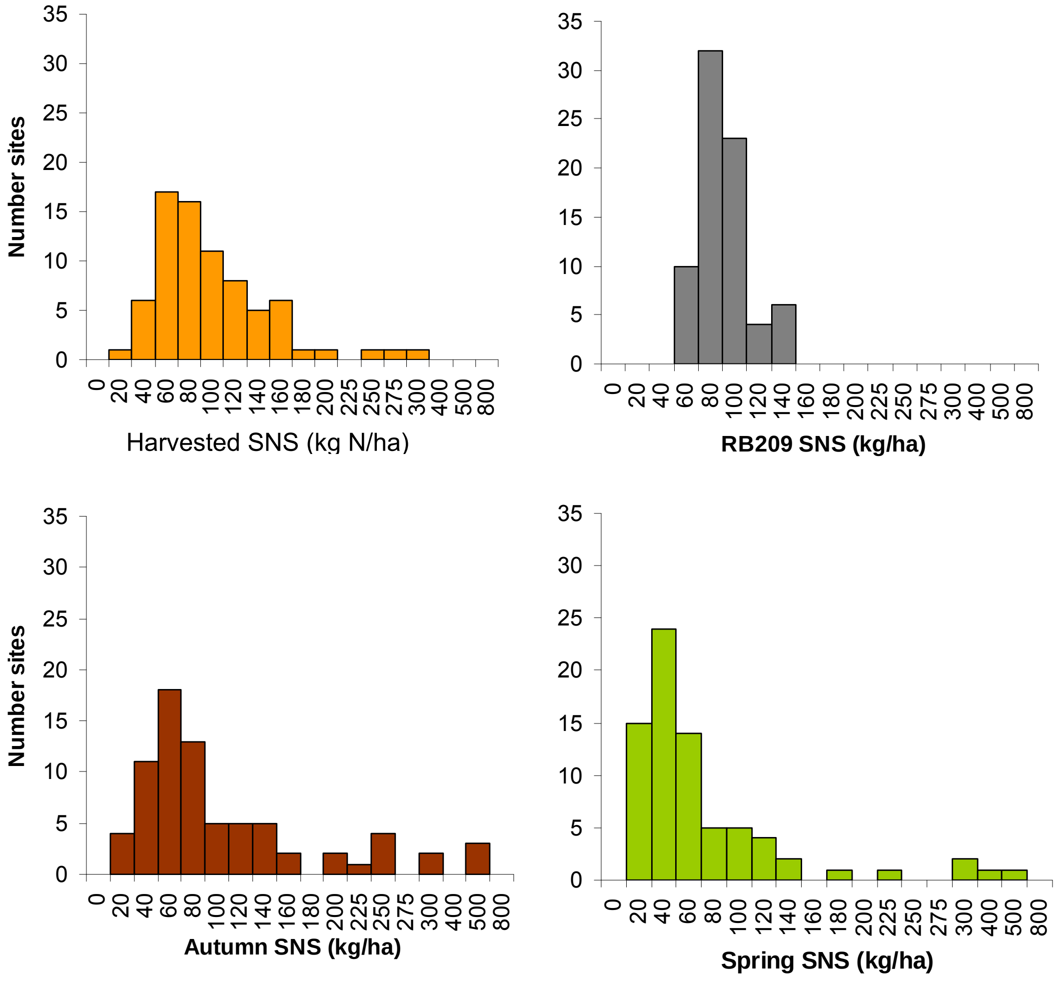


Figure 40. Frequency distributions of SNS on MEDIUM RAINFALL AREAS from a subset of 75 sites measured in 2008-2010. A) final harvested SNS by unfertilised crop at harvest; B) FAM estimate of SNS using RB209, including allowance for manures; C) SNS (SMN + Crop N) measured in autumn; D) SNS (SMN + Crop N) measured in spring

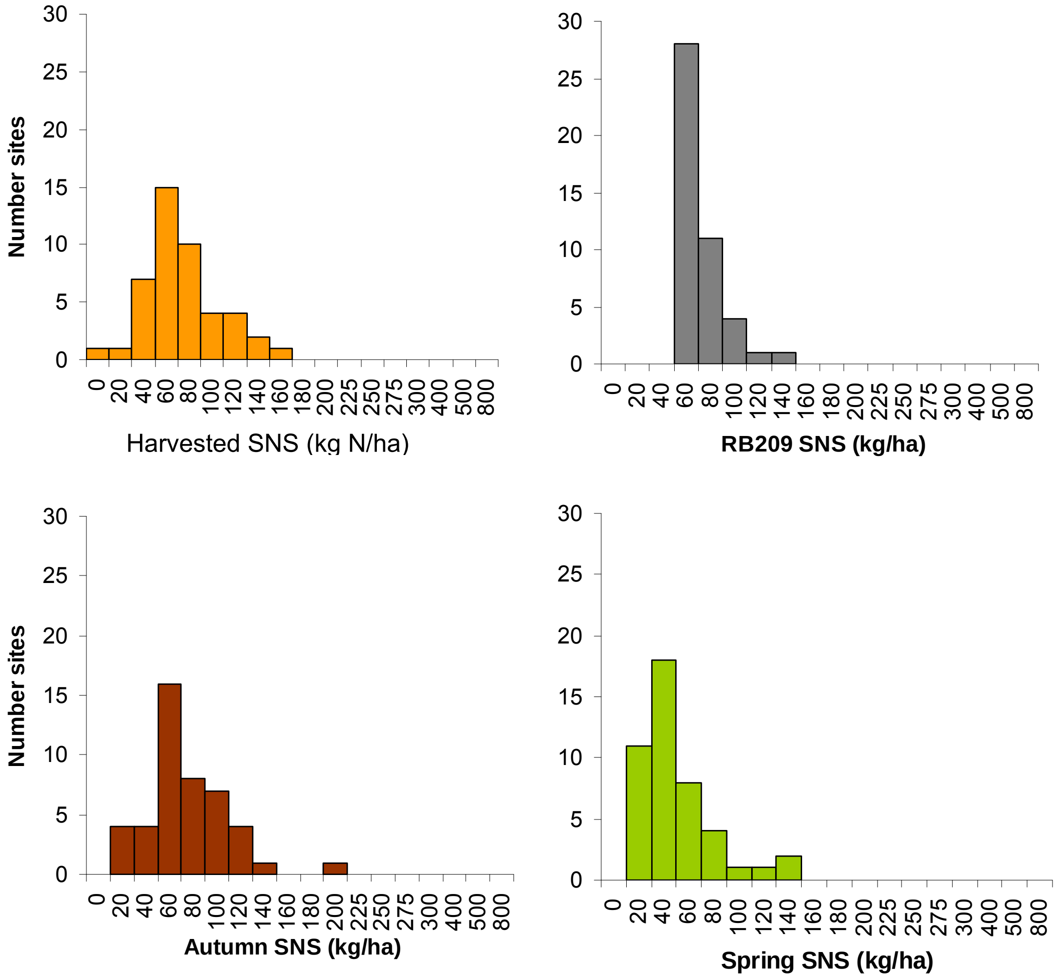


Figure 41. Frequency distributions of SNS on HIGH RAINFALL AREAS from a subset of 45 sites measured in 2008-2010. A) final harvested SNS by unfertilised crop at harvest; B) FAM estimate of SNS using RB209, including allowance for manures; C) SNS (SMN + Crop N) measured in autumn; D) SNS (SMN + Crop N) measured in spring.

Relationships with harvested SNS

The relationships between measured SNS in autumn or spring and harvested SNS are best described by broken stick functions with a horizontal line after the break point. Regression analyses were conducted in Genstat v12. Fitting curves was not found to explain sufficiently more of the variation to justify their use over the simpler split-line model. Based on this function, autumn SNS (Figure 42) explained 45% of the variation in harvested SNS, whereas spring SNS explained 49% of the variation. For both autumn and spring measured SNS, the breakpoint in harvested SNS occurred at around 200 kg/ha of uptake (209 vs 204 kg/ha for autumn and spring respectively). However, the x-axis breakpoint occurred at a considerably greater level for autumn SNS (313 kg/ha) than for spring (189 kg/ha). Whilst the intercept was similar between autumn and spring, the slope of the relationship was shallower for autumn SNS (0.50) than for spring SNS (0.85). This implies that for spring SNS, any measurement exceeding 200 kg/ha will relate to a final harvested SNS of around 200 kg/ha. However, a measure of 200 kg/ha SNS in autumn relates to an average harvested SNS of around 150 kg/ha, and measures of over 300 kg/ha autumn SNS can be expected to relate to a final harvested SNS of 200 kg/ha.

A straight line relationship was found between FAM estimated SNS and harvested SNS; as FAM estimates did not exceed 160 kg the breakpoint was not reached. The relationship with FAM SNS explained less variation (31%) than SMN-based SNS predictions.

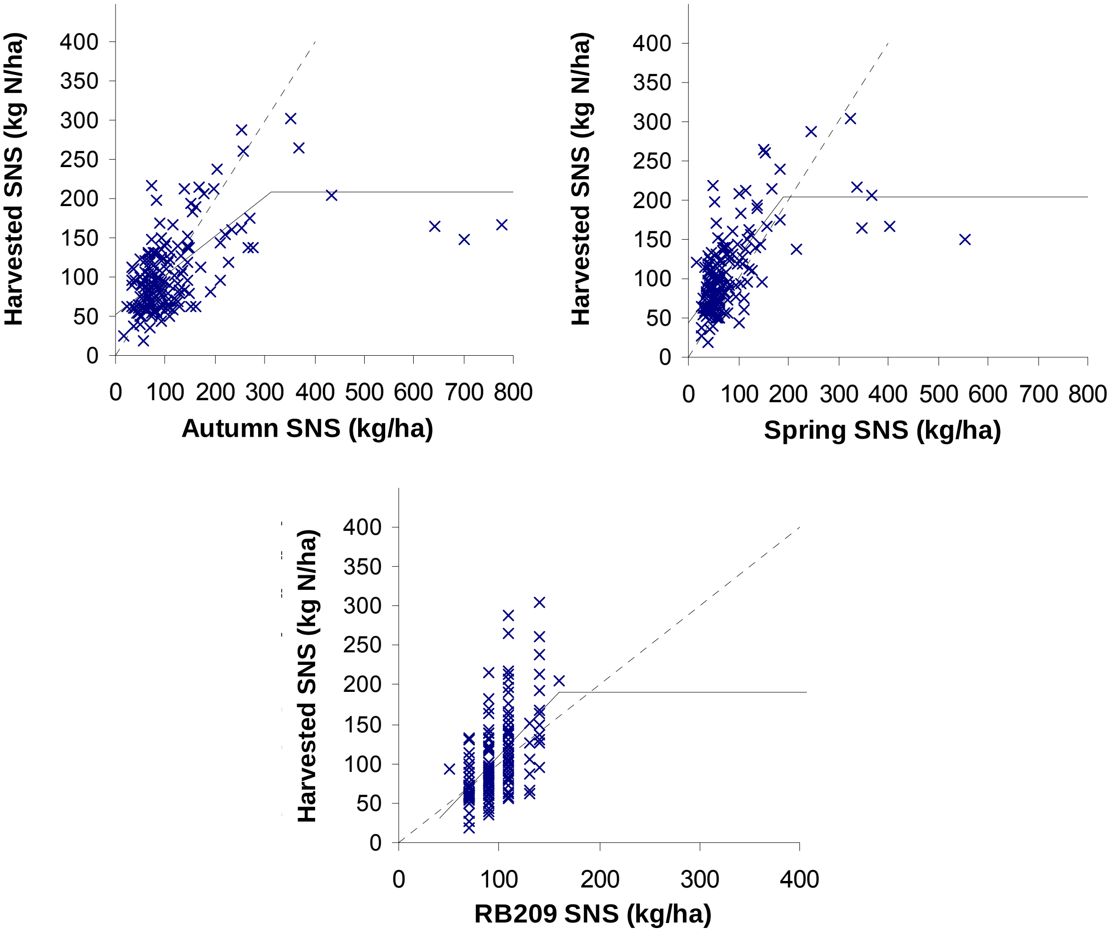


Figure 42. Relationships (with fitted broken stick functions; line) between SNS measured in Autumn (A), Spring (B) or (C) estimated by FAM (RB209) and harvested SNS for 164 sites in 2008-2010. Dotted line: y=x.

The strength of the relationship between estimated SNS and harvested SNS differed with soil type, rainfall area and previous cropping. Tables 32a and b shows variation explained by the relationships for different subsets of the data along with the parameters for intercepts, slopes and breakpoints. The relationships were best for clay and silt soils (Figure 43) and worst for light and shallow soils (Figure 45). Relationships for medium soils were less good (Figure 44), especially with autumn sampling, and worse on light and shallow soils, but the relationships were stronger for soil sampling than for FAM, except on shallow soils. Relationships with soil sampling were also better in low or moderate rainfall areas; the relationship in high rainfall areas with autumn sampling was especially poor (Figure 47).

Looking at previous crops, relationships were best following field vegetables and poorer following pulses. Dividing the sites into those with or without a history of grass or manure use made little difference to the strength of the relationship, but selecting out sites that represented ‘normal’ arable situations (clay, silt or medium soils only; no history of grass or manure, medium or low soil organic matters) showed the strength of the relationship to be considerably weaker (Figure 48) than with the full dataset. Similarly, relationships were stronger where SNS was expected to be high.

Table 32a. Percentage of variation explained by split-line regression of either autumn SNS, spring SNS or FAM SNS against harvested SNS for the new dataset 2007-2010, for different sub-groups. Also intercept (harvested SNS with zero measured SNS) and slope (kg harvested SNS/kg measured SNS). Values in italics are not statistically significant (P=0.05).

		% var. explained			**intercept**			**slope**		
Group	**# of sites**	**Aut**	**Spr**	**FAM**	**Aut**	**Spr**	**FAM**	**Aut**	**Spr**	**FAM**
All	164	45	49	31	52	44	-22	0.5	0.85	1.33
Silt soils	34	52	50	32	58	57	-76	0.66	0.89	1.89
Clay soils	33	58	62	30	31	33	-183	0.84	1.04	2.98
Medium soils	70	23	44	9	56	34	-6	0.37	0.95	1.18
Shallow soils	9	0	0	5	-	-	-33	-	-	1.32
Light sands	13	0	23	0	86	41	48	3.5	0.84	0.44
Silt & Clay soils	67	55	56	31	53	46	-99	0.64	0.96	2.13
Light & shallow soils	22	3	6	9	59	47	21	0.25	0.68	0.72
Soil depth <90cm	19	0	0	9	-	-	-97	-	-	2.30
Low rainfall areas	44	39	35	27	46	50	-16	0.69	0.86	1.3
Moderate rainfall	75	48	54	23	58	48	-39	0.43	0.80	1.49
High Rainfall	45	6	36	16	59	44	4	0.29	0.65	1
Previous crop:										
Cereals	43	51	53	13	27	32	0	0.65	0.87	1.08
Non-cereals	121	42	47	31	55	49	-29	0.52	0.82	1.39
OSR	50	18	33	18	65	48	0	0.37	0.74	1.03
Peas and Beans	35	26	26	29	71	31	-141	0.38	1.34	2.7
Field veg	12	58	70	25	60	44	-103	0.71	1.05	2.1
Grass or manure history	57	39	47	13	68	54	-50	0.39	0.78	1.65
No grass or manure history	107	42	48	39	43	39	-35	0.57	0.87	1.48
“Normal” arable sites*	52	22	5	14	1	-112	-7	0.75	5	1.11
Non-“normal” arable sites	112	46	59	34	52	40	-22	0.51	0.91	1.35
FAM SNS INDEX 0-2	97	25	33	5	50	49	17	0.38	0.56	0.84
FAM SNS INDEX 3-5	67	43	49	8	78	69	-	0.46	0.77	-
FAM SNS INDEX 1	41	1	27	-	61	32	-	0.16	0.80	-
FAM SNS INDEX 2	56	37	31	-	37	59	-	0.59	0.46	-
FAM SNS INDEX 3	48	38	44	-	78	69	-	0.46	0.77	-

* “Normal” arable sites are those on silt, clay or medium soils with no history of manure or grass and not following high N vegetables and not in high rainfall areas. Non-“normal” are the remainder.

Table 32b. Breakpoints from split-line regression of either autumn SNS, spring SNS or FAM SNS against harvested SNS for the new dataset 2007-2010, for different sub-groups. Values in italics are not statistically significant (P=0.05).

	Breakpoint harvested SNS			**breakpoint_measured SNS**		
Group	**Aut SNS**	**Spr SNS**	**FAM SNS**	**Aut SNS**	**Spr SNS**	**FAM SNS**
All	209	204	191	313	189	160
Silt soils	455	259	202	603	226	148
Clay soils	216	362	-	221	317	-
Medium soils	169	139	80	306	111	91
Shallow soils	70	70	122	34	32	117
Light sands	89	101	96	50	72	110
Silt and Clay soils	280	269	195	354	233	139
Light and shallow soils	96	95	100	146	70	110
Soil depth <90cm	77	-	147	34	-	81
Low rainfall areas	187	199	160	204	173	192
Moderate rainfall	209	214	172	348	207	142
High Rainfall	128	223	114	239	273	110
Previous crop:						
Cereals	143	190	151	179	181	140
Non-cereals	218	208	194	312	194	160
OSR	149	151	114	231	138	110
Peas and Beans	210	171	144	370	105	105
Field veg	255	255	206	275	200	146
Grass or manure history	212	199	130	369	186	110
No grass or manure history	205	208	-	282	194	-
“Normal” arable sites	110	99	171	82	42	160
Non-“normal” arable sites	209	204	194	308	181	160
FAM SNS INDEX 0-2	199	215	121	394	299	126
FAM SNS INDEX 3-5	204	204	192	252	165	160
FAM SNS INDEX 1	123	105	-	400	90	-
FAM SNS INDEX 2	137	216	-	168	341	-
FAM SNS INDEX 3	335	356	-	556	374	-

* “Normal” arable sites are those on silt, clay or medium soils with no history of manure or grass and not following high N vegetables and not in high rainfall areas. Non-“normal” are the remainder.

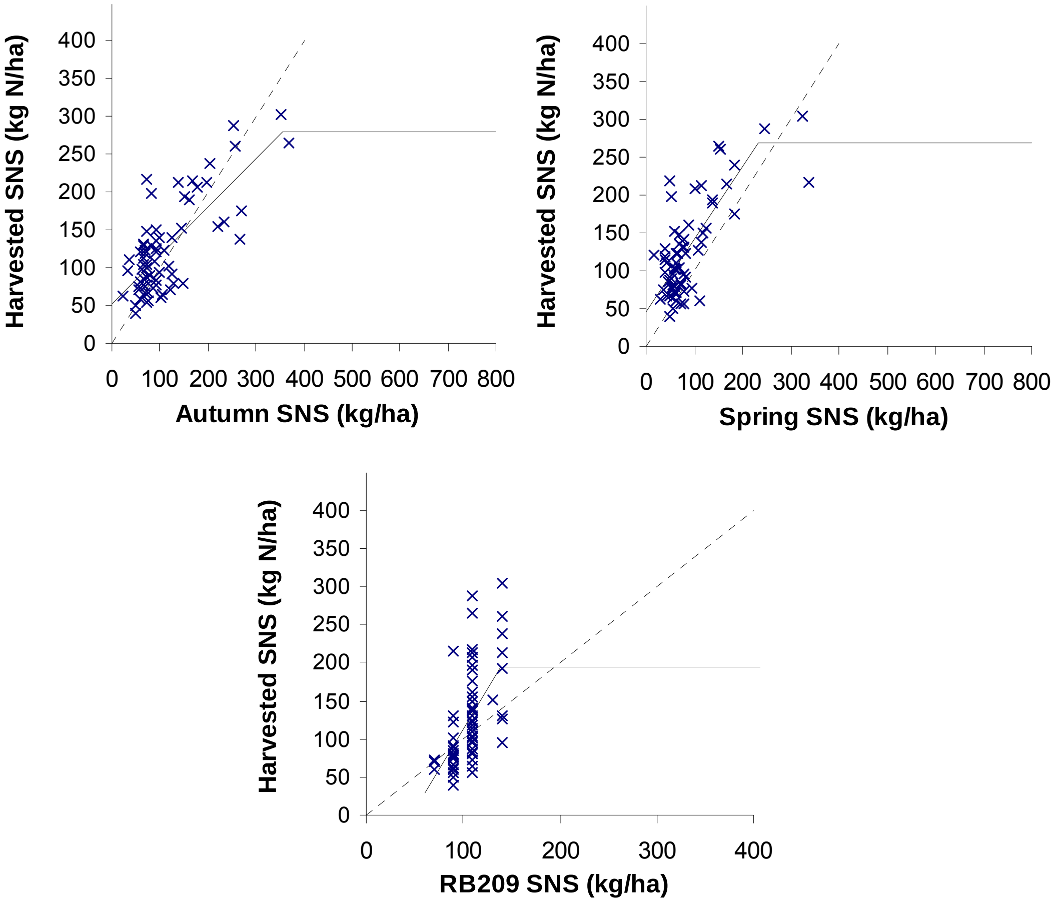


Figure 43. Relationships (with fitted broken stick functions; line) between SNS measured in Autumn (A), Spring (B) or (C) estimated by FAM (RB209) and harvested SNS for DEEP CLAYEY AND DEEP SILT SOILS in a subset of 67 sites 2008-2010. Dotted line: y=x.

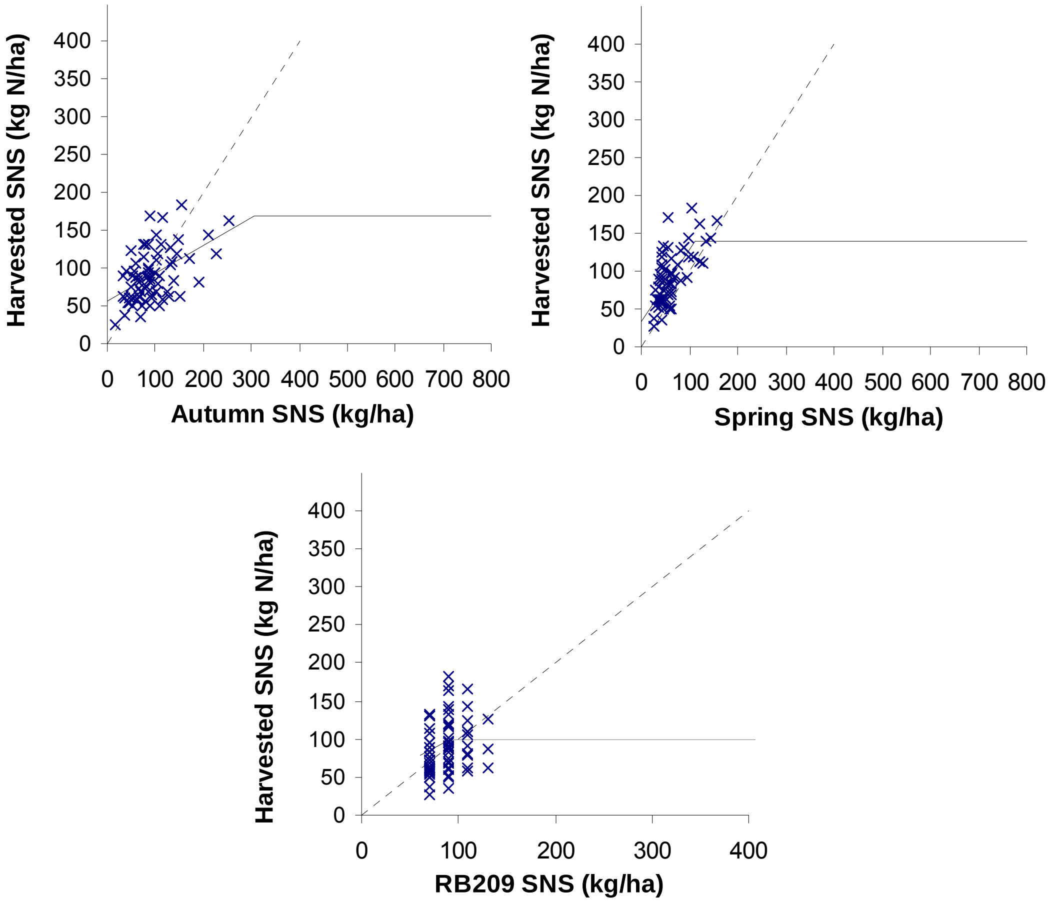


Figure 44. Relationships (with fitted broken stick functions; line) between SNS measured in Autumn (A), Spring (B) or (C) estimated by FAM (RB209) for MEDIUM SOILS in a subset of 70 sites 2008-2010. Dotted line: y=x.

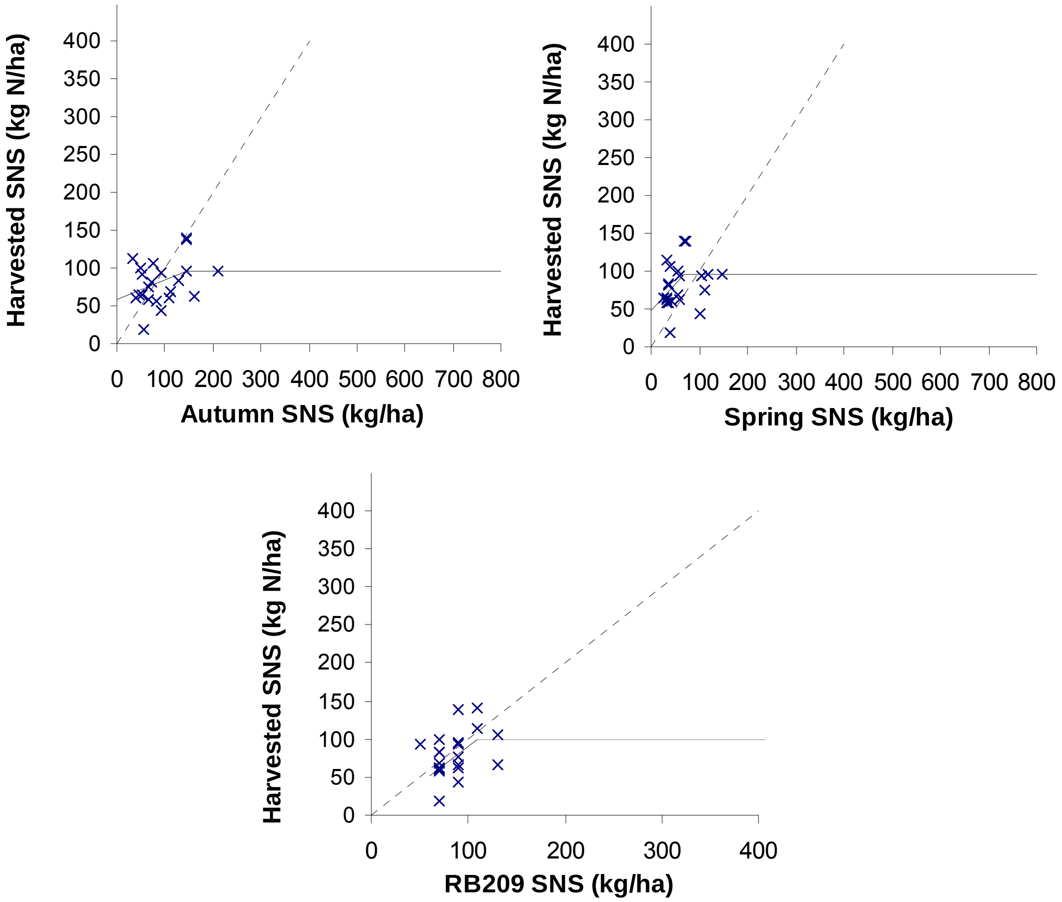


Figure 45. Relationships (with fitted broken stick functions; line) between SNS measured in Autumn (A), Spring (B) or (C) estimated by FAM (RB209) for LIGHT AND SHALLOW SOILS in a subset of 22 sites 2008-2010. Dotted line: y=x.

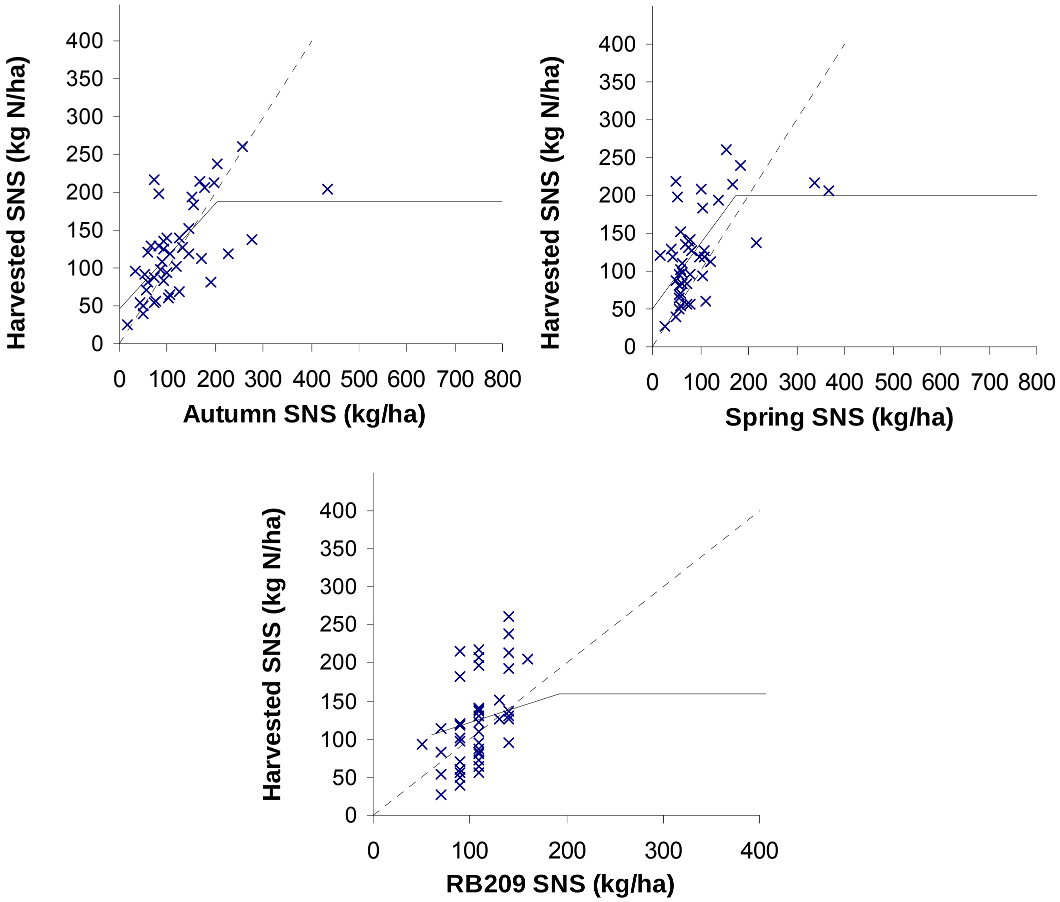


Figure 46. Relationships (with fitted broken stick functions; line) between SNS measured in Autumn (A), Spring (B) or (C) estimated by FAM (RB209) for LOW RAINFALL AREAS in a subset of 44 sites 2008-2010. Dotted line: y=x.

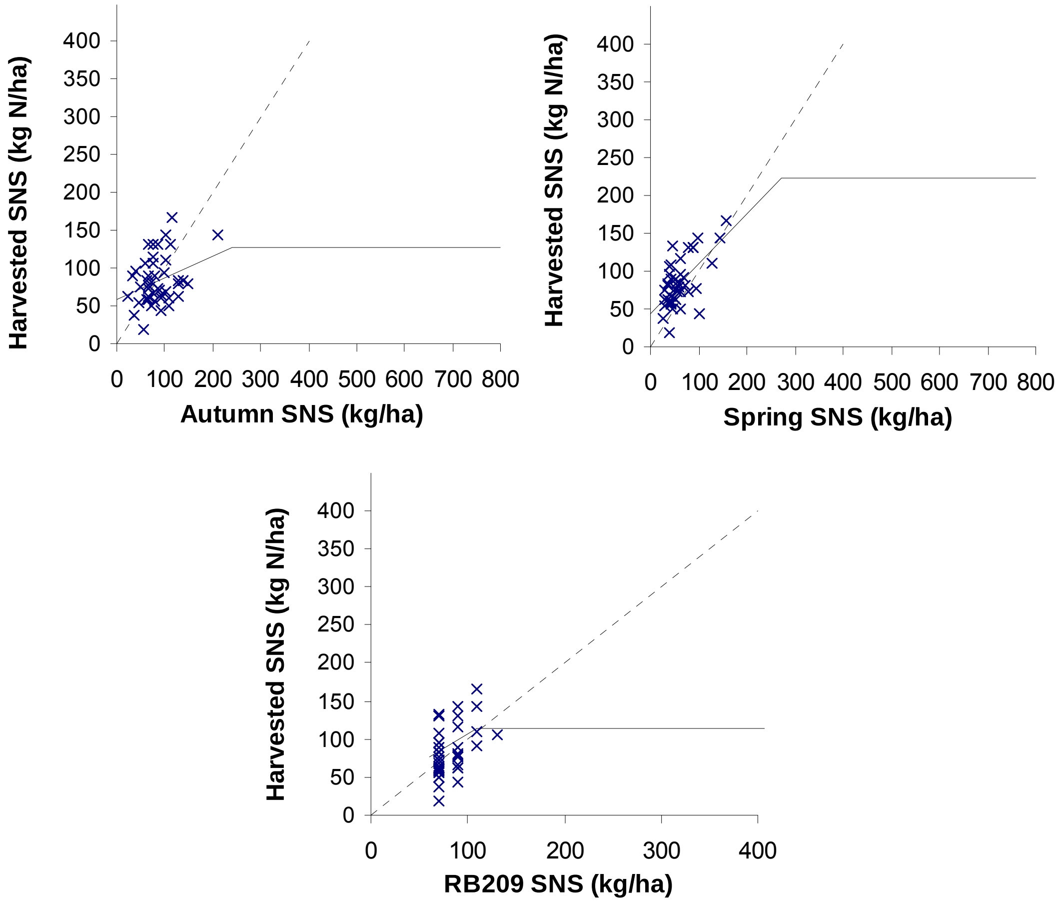


Figure 47. Relationships (with fitted broken stick functions; line) between SNS measured in Autumn (A), Spring (B) or (C) estimated by FAM (RB209) for HIGH RAINFALL AREAS in a subset of 45 sites 2008-2010. Dotted line: y=x.

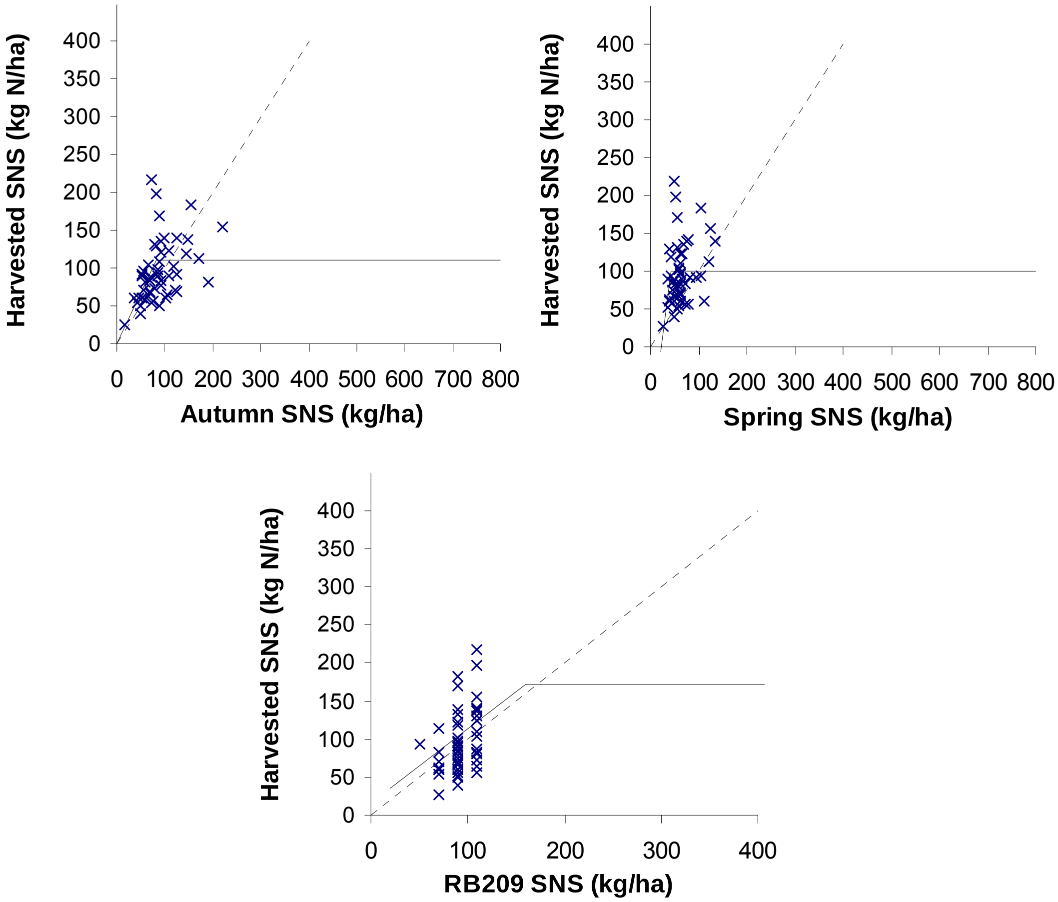


Figure 48. Relationships (with fitted broken stick functions; line) between SNS measured in Autumn (A), Spring (B) or (C) estimated by FAM (RB209) for 'NORMAL' ARABLE SITUATIONS (those on silt, clay or medium soils with no history of manure or grass and not following high N vegetables and not in high rainfall areas) in a subset of 52 sites 2008-2010. Dotted line: y=x.

Further regression analyses

In order to gain some insight into the most important factors influencing the estimation of harvested SNS further regression analyses were conducted in Genstat v12.

Multiple regression analyses

‘Stepwise multiple regression with groups’ was conducted in Genstat to assess which factors best explain variation in harvested SNS. A full range of factors was examined including soil group, rainfall area, previous crop, soil organic matter, soil total N%, soil C:N ratio, PMN, AAN, actual winter rainfall, actual post-sampling rainfall, IRRIGUIDE estimated drainage over winter, IRRIGUIDE estimated drainage after sampling, estimated N retention using generic rainfall area classification, estimated N retention using in-year classification, manure history, stone content and soil depth. Data were restricted to only sites where all this information was available. The results in Table 33 show that knowledge in both autumn and spring of soil group and previous crop provided the biggest improvement to the relationship with harvested SNS; manure history and C:N ratio of soil also giving useful information. In spring, measurement of AAN also provided a significant improvement.

Table 33. Percentage variation in harvested SNS explained by multiple linear regression models for autumn or spring measured SNS (0-90cm) with best additional factors.

Explanatory variable (Autumn)	Variation explained	Explanatory variable (Spring)	Variation explained
Autumn SNS by itself	43.6%	Spring SNS by itself	45.5%
+ RB209 Soil Group	52.2%	+ RB209 Soil Group	56.4%
+ Previous crop	55.9%	+ Previous Crop	59.0%
+ Manure history	57.1%	+ AAN	61.3%
+ soil C:N ratio	58.2%	+ Manure History	62.8%
		+ soil C:N ratio	63.7%

Measures of stone content did not add to the explanation. Measures of N retention improved the explanation (over autumn SNS by itself) to 46.5% of variation, however this was a smaller improvement than from other factors, and once these other factors had been accounted for the improvement due to N retention was not significant.

Table 34 shows model parameters from multiple regression analysis for autumn and spring SMN. This shows there was no significant difference between silt and clay soils (or medium soils in spring), but that SMN measures on organic soils over-estimated harvested SNS by around 60 kg/ha in autumn and 100 kg/ha in spring. SMN measures on light and shallow soils over-estimated harvested SNS by over 30 kg/ha in autumn and around 25 kg/ha in spring. There was no significant difference in the estimate of harvested SNS between cereals and oilseed rape as previous crops, but after pulses and field vegetables SMN measures under-estimated harvested SNS by around 25 and 35 kg/ha respectively. If the field had a known history of manure then harvested SNS tended to be around 17 kg/ha greater than predicted just by measured SMN. The soil C:N ratio explained more of the variation in harvested SNS than either SOM% or soil total N% alone, and harvested SNS was around 1.4 kg/ha greater for each unit increase in C:N ratio. This was opposite to what might be expected due to mineralisation. In spring, for each 10 kg increase in measured AAN the harvested SNS could be expected to increase by 2.5 kg/ha.

Table 34. Parameters from multiple linear regression analysis in explaining harvested SNS, the reference condition being with cereal as the previous crop and no manure history. Add or multiply parameter values for different conditions, as appropriate.

Explanatory variable (AUTUMN)	Parameter	S.E.	Explanatory variable (SPRING)	Parameter	S.E.
Autumn SNS 0-90	x 0.52	0.050	Spring SNS 0-90	x 0.68	0.064
+ Soil group			+ Soil Group		
Silts	+4.7	9.4	Silts	+6	8.8
Clay	+27	12.2	Clay	+19	11.5
Medium soil	-17	7.5	Medium soil	-8	7.1
Organic soils	-58	18.7	Organic soils	-105	19.3
Shallow soils	-32	13.0	Shallow soils	-22	12.2
Light sand	-47	12.2	Light sand	-28	11.8
+ Previous crop			+ Previous crop		
OSR	+12	7.4	OSR	+8	6.9
Pulse	+21	8.1	Pulse	+26	7.5
Field veg	+41	13.0	Field veg	+30	12.3
Other	+21	9.6	Other	+2	9.1
+ Manure history	+17	6.6	+ Manure history	+18	6.2
+ Soil C:N ratio	x 1.43	0.66	+ Soil C:N ratio	x 1.37	0.62
			+ AAN	x 0.253	0.103

Sampling date – autumn vs spring

Overall the relationship of harvested SNS with spring SNS was slightly better than with autumn SNS. However, there was a tendency for spring SNS to under-estimate harvested SNS, especially with small SMN levels; also autumn SNS tended to over-estimate harvested SNS, especially with large SMN levels. Figure 49 shows the relationship between SNS measured in autumn and spring, showing that autumn SNS was usually greater than spring. Whilst the difference between autumn and spring may be greatest on light and shallow soils in high rainfall areas, this was not exclusively the case; large differences between spring and autumn also occurred on retentive soils in moderate or low rainfall areas.

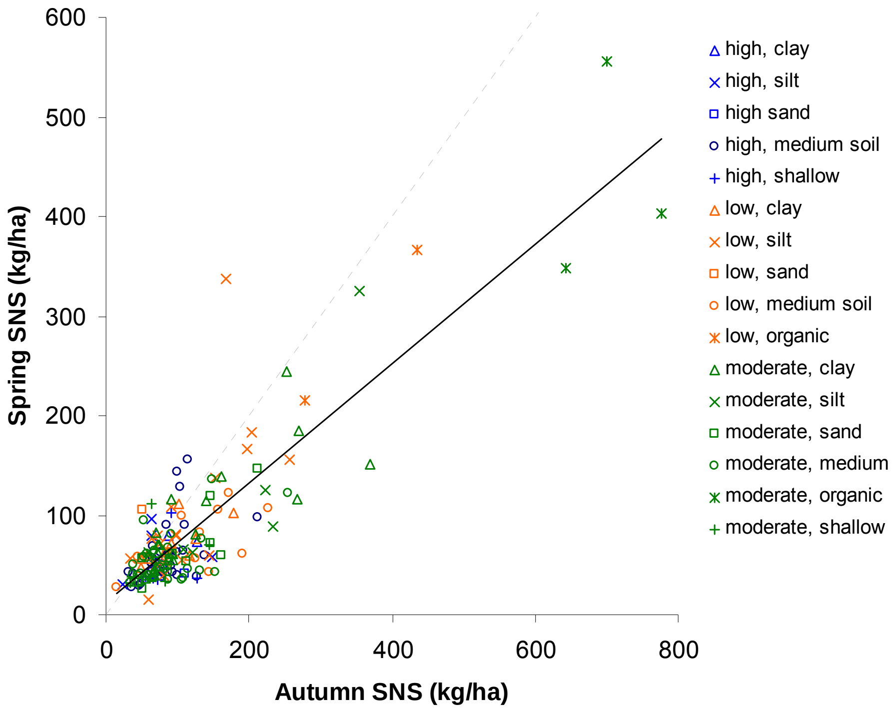


Figure 49. Relationship between autumn and spring SNS for 164 sites in 2008-2010, for low (orange), moderate (green) and high (blue) rainfall areas and different soil groups (see legend). Dashed line shows y=x, solid line is the regression line (y= 0.6x +12, r^2=0.75).

Repeated over-winter measurements

SMN measurements were repeated monthly over the winter of 2009/10 to gauge the variability in SNS measures over winter. The sites used were a shallow soil at Towthorpe (N Yorks), a deep silt soil following vegetables in Lincolnshire, a sandy clay loam medium soil in Aby (Lincolnshire) and a shallow soil in Hampshire. These all showed a decline in measured SNS from autumn to spring (Figure 50), but in three of the four sites final harvested SNS was higher than SNS measured in February. At two of the sites measured SMN increased from February to April, largely as a result of increasing ammonium in the topsoil, indicating mineralisation. At the Lincolnshire site following high N veg, SNS levels initially increased before falling dramatically through spring from over 300 kg/ha to less than 90 kg/ha, indicating initial mineralisation with subsequent leaching and/or immobilisation. Despite these large changes in soil N, in this instance the SNS measured in autumn gave an accurate estimate of harvested SNS, presumably because subsequent mineralisation through late spring matched that which was initially leached or immobilised. Exploration of whether autumn or spring sampling is ‘best’ continues in section 3.7.

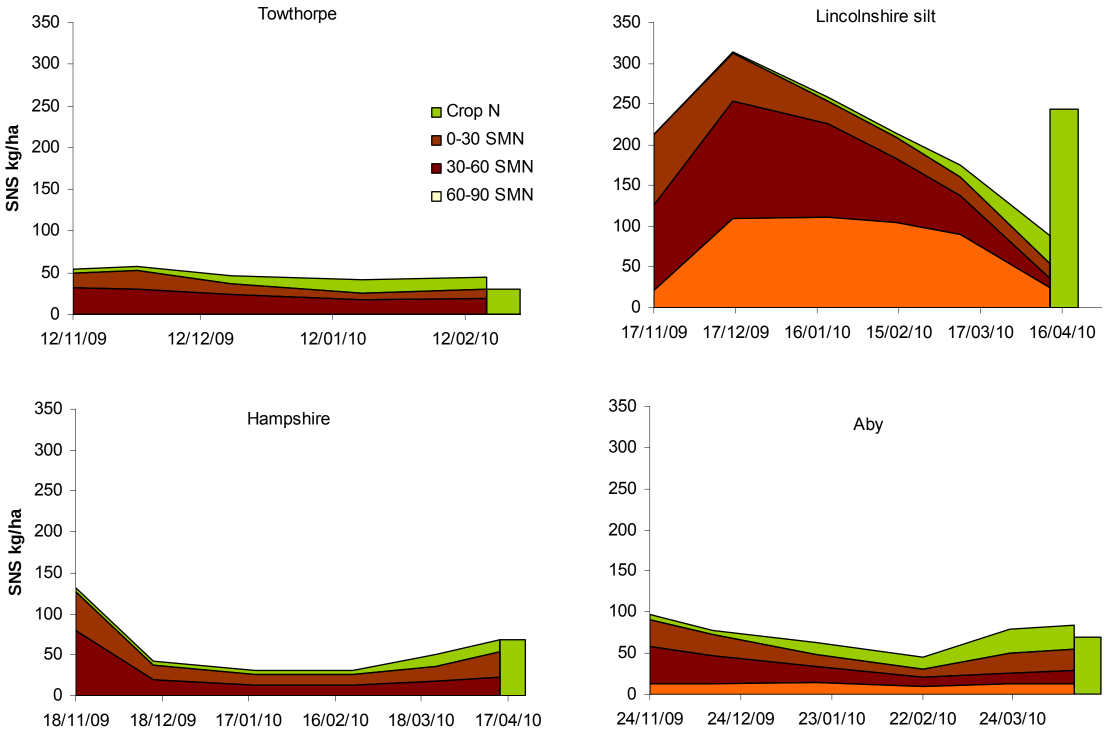


Figure 50. SNS measures from monthly SMN sampling at four sites, divided by depth and crop N. Final green bar shows harvested SNS at harvest.

Sampling depth

The strength of relationship between measured SNS and harvested SNS was assessed with SMN sampling at 0-30, 0-60 or 0-90 cm depth for spring and autumn (including crop N) using split-line regression analysis. Results in Table 35 show that in autumn there is a relatively small improvement in increasing depth of sampling beyond 30 cm, and no difference in explanatory power of harvested SNS between sampling to 60 or 90 cm; it seems that information from 60-90 cm is not useful in explaining the variation in harvested SNS. By contrast, increasing sampling depth in spring substantially improved the explanation of harvested SNS, with 0-90 cm giving substantially the best relationship. SMN depth also affected the intercept, slope and breakpoint of the relationship considerably. Choice of best depth is explored further in section 3.7.

Table 35. Results from split-line regression analysis for harvested SNS against SNS measured at different depths in autumn or spring.

Depth	% variation explained	Intercept	Slope	Breakpoint X	Breakpoint Y
Autumn 0-30	38.9	61	0.88	185	224
Autumn 0-60	41.8	55	0.59	263	209
Autumn 0-90	41.5	53	0.50	312	209
Spring 0-30	19.1	32	2.45	46	145
Spring 0-60	39.1	52	0.97	165	213
Spring 0-90	47.0	46	0.85	183	203

Mineralisation measures

Mineralisation after SMN measurement could be indicated by any of a range of measures. Multiple regression analysis showed that C:N ratio in soil explained more variation in harvested SNS than SOM% or total soil N%, when in combination with an SNS measurement and soil and previous crop information. However, this seemed to work inversely to the direction expected. The direct predictor of mineralisation, AAN, gave a significant improvement to the relationship in spring, but not in autumn.

Figure 51 shows the relationships between the various measures that relate to 'mineralisation' potential. It can be seen that SOM% and total soil N% were very closely related, and each was positively related to harvested SNS, as well as PMN. There was a more complex relationship with soil C:N ratio. On their own, the relationships between each of these measures and harvested SNS was weak, the maximum r^2 being 0.177 for PMN; r^2 was 0.13 for total soil N%, 0.15 for SOM%, 0.02 for soil C:N ratio and 0.173 for AAN. The value of mineralisation measures in predicting SNS is explored further in section 3.7.

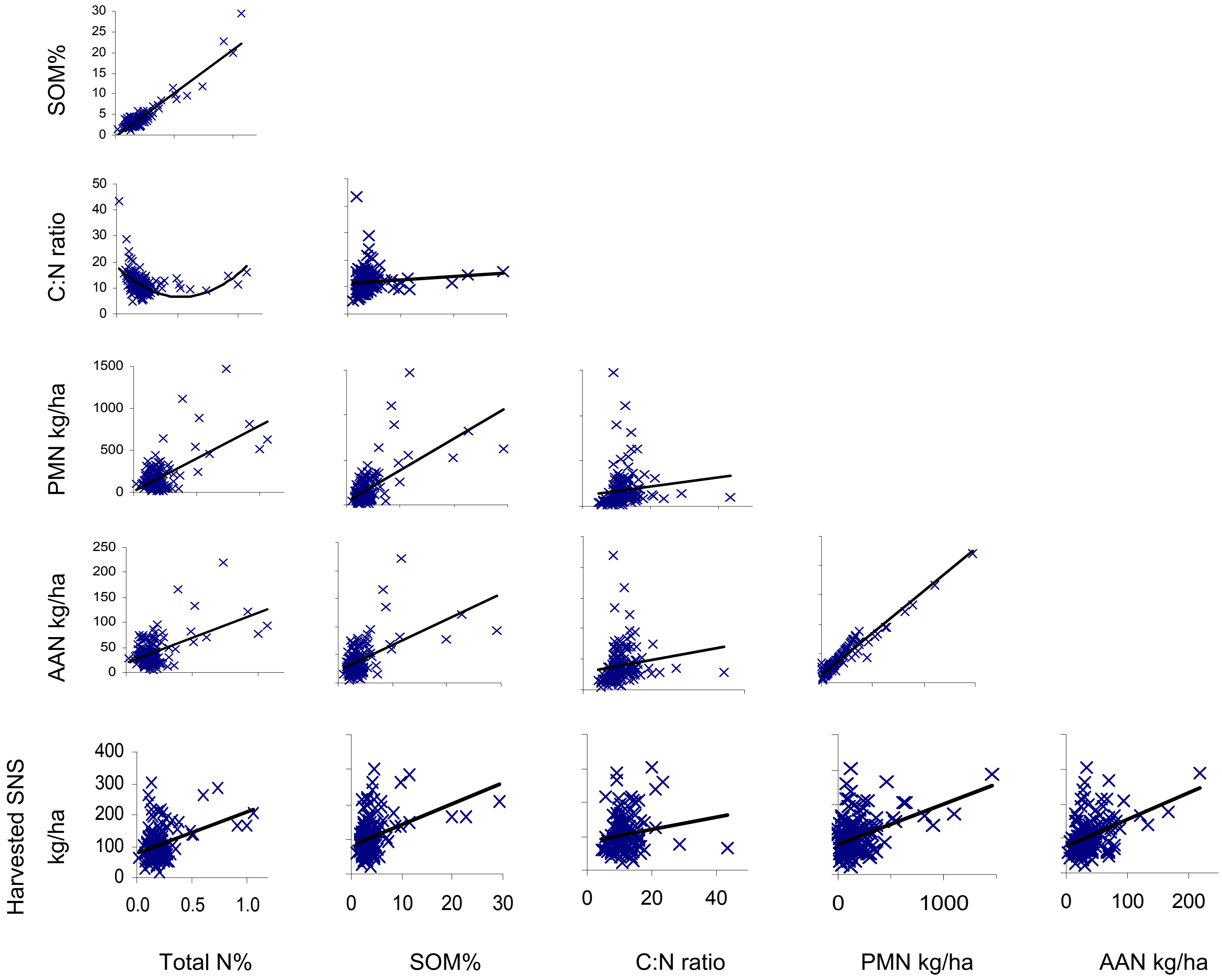


Figure 51. Inter-relationships between mineralisation measures, and relationships with harvested SNS for 164 sites between 2007 and 2010.

Bulk Density

There is some evidence in this dataset (Table 36) that using different estimates of bulk density based on different soil textures (as used by HCFR) could improve the relationship between measured SNS and harvested SNS. The advantage seemed to apply especially in spring, with an apparent disadvantage for clay soils measured in autumn.

Table 36. Comparisons of the relationship between soil measured SNS and harvested SNS using different bulk density assumptions. NB = no break; i.e. break exceeds maximum measurements.

Date	Bulk Density	% variation explained	Intercept	Slope	Breakpoint X	Breakpoint Y
All soils:						
Aut	1.33	41.5	53	0.50	312	209
Aut	HCFR	41.9	53	0.47	335	209
Spr	1.33	47.0	46	0.85	183	203
Spr	HCFR	50.1	49	0.72	232	215
Clay soils:						
Aut	1.33	56.7	44	0.80	225	216
Aut	HCFR	54.3	35	0.77	236	216
Spr	1.33	59.2	41	1.00	-	-
Spr	HCFR	62.1	33	1.00	254	287
Silty soils:						
Aut	1.33	52.6	57	0.67	NB	NB
Aut	HCFR	53.3	58	0.60	NB	NB
Spr	1.33	48.8	62	0.85	232	259
Spr	HCFR	53.0	62	0.72	275	259
Medium Soils:						
Aut	1.33	20.3	58	0.36	292	163
Aut	HCFR	21.4	48	0.47	147	117
Spr	1.33	37.9	45	0.78	152	164
Spr	HCFR	43.5	32	0.97	108	136
Light and Shallow soils:						
Aut	1.33	2.8	relationship not significant			
Aut	HCFR	1.2	relationship not significant			
Spr	1.33	0.0	relationship not significant			
Spr	HCFR	0.0	relationship not significant			

Stoniness

As shown by the multiple regression analysis, measured stone contents seemed to have no effect on the relationship with harvested SNS. Figure 52 shows that stone content did not explain variation in harvested SNS that was not explained by SNS measurement in spring or in autumn.

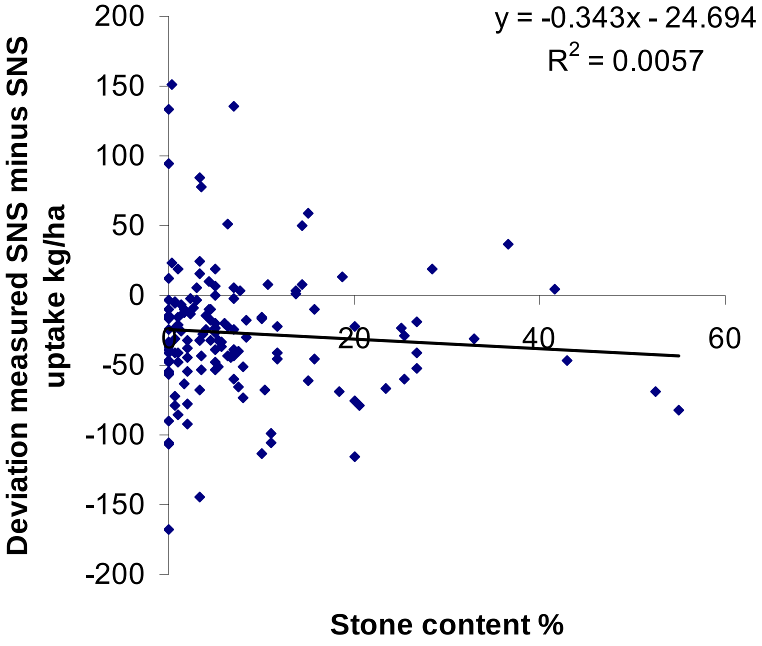


Figure 52. Relationship of stone content with deviations from the relationship between measured SNS and harvested SNS at 164 sites in 2007-2010.

Leaching

Various estimates were assessed to indicate possible N losses after sampling, both in autumn or in spring. Whilst there may be some very weak relationships with harvested SNS (Figure 53) these were not great enough to give a significant improvement in the multiple regression analysis once other factors were accounted for. Possible adjustments for leaching will be assessed further in section 3.7.

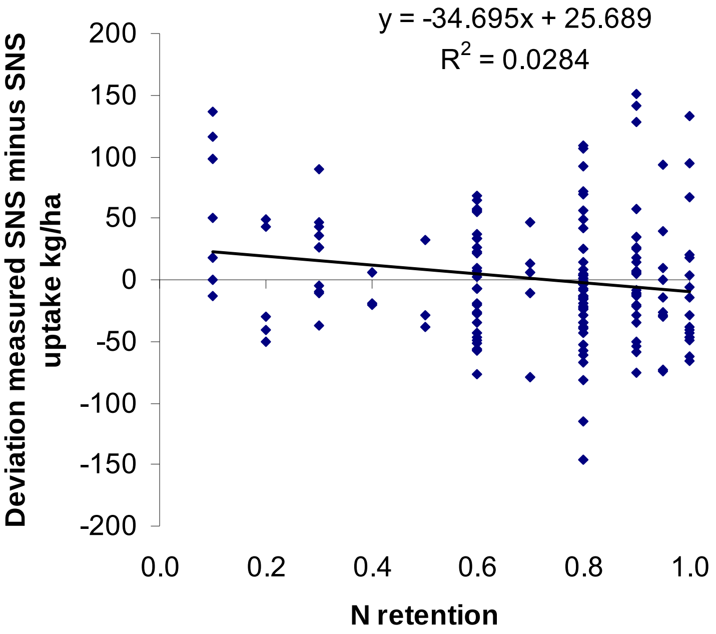


Figure 53. Relationship of estimated N retention with deviations from the relationship between measured SNS and harvested SNS at 164 sites in 2007-2010.

Crop N

For cereal crops, including an estimate of crop N with measured SMN made little difference to the prediction of harvested SNS in autumn, but it improved the r^2 value by around 2% for spring SMN measures (data not shown). The method of estimating crop N made little difference to the predictions for cereal crops, with the best methods perhaps being the simplest, using shoot numbers (or growth stage) with plant population to estimate crop N. Actual measures of crop N could be recommended where estimates exceed 30 kg/ha. Calibrations now exist for estimating GAI and N uptake of digital photos for cereal and oilseed rape crops, using the Canopy Assessment Tool (www.agricentre.basf.co.uk/agroportal/uk/en/e_tools/eTools.html) but this has not been tested in this project. Section 3.6 of this report considers how best to estimate and interpret crop N in oilseed rape.

3.5.5. Conclusions from SNS datasets

Analysis of past datasets and the newly generated dataset shows that, whilst there is a significant relationship between measured SNS in autumn or spring and harvested SNS, the relationship rarely explains more than 50% of the variation. This is less than has been observed in other studies (e.g. Sylvester-Bradley et al., 2008). Furthermore, it seems that the relationship is best characterised using intercepts, slopes and break-points, rather than as a simple 1:1 relationship. The implications of this for Best Practice in SNS prediction are explored further in section 3.7.

3.6. Considering crop N and SMN in oilseed rape

3.6.1. The problem

Most N fertiliser recommendation systems for oilseed rape work on the basis that the crop must take up a target amount of N by maturity to achieve its optimum yield. The N taken up by the crop can be supplied from mineralisation of organic residues in the soil and from inorganic fertiliser. Mineralised soil N is seldom enough to meet the crop's target N uptake on its own and most recommendation systems assess how much fertiliser N is required to make up the shortfall. This is usually done in late winter or early spring by estimating or measuring the amount of N that has already been taken up by the crop and the amount of mineral N in the soil. A few systems also estimate the N that will be mineralised during the remaining growth period.

Three assumptions are commonly used to estimate the amount of fertiliser N that is required; 1) the target N uptake can be reduced by the amount of N that the crop has taken up by spring, 2) the crop will take up an equivalent amount of soil N as is measured as SMN before spring growth, and 3) fertiliser N is taken up with 60% efficiency. The first assumption is reasonable when the spring crop N is small. However, over the last two seasons warm autumns and mild winters have resulted in large amounts of N taken up by spring. Some crops have been measured to take up over 150 kg/ha N over autumn and winter. These crops also often have a very small SMN supply by spring.

It is not certain whether all of the spring crop N in large crops should be subtracted from the target N uptake. This is because oilseed plants may not be 100% efficient at remobilising N from dying leaves. Recent unpublished data from LINK Project LK0979 showed that unfertilised crops yielding between 3 and 4 t/ha lost 15 kg/ha N in dead leaves between the start of stem extension and harvest. Greater losses are expected in larger fertilised crops. It is also not known how much of the N mineralised from the dropped leaves is re-captured by the plant. N loss from dead leaves may mean that fertiliser requirements are underestimated. For example, a crop with an N content in spring of 100 kg/ha and a targeted final N uptake of 200 kg/ha will require 165 kg N fertiliser if all of the spring crop N can be subtracted from the target N uptake. If for example 20% of the spring crop N is lost then the fertiliser N requirement increases to 200 kg/ha (assuming a fertiliser N uptake efficiency of 60%). Hence this project tested the extent to which extra crop N uptake by oilseed rape was reflected in extra harvested SNS.

3.6.2. Methods

Site selection and canopy management

In each of the three years ADAS and NIAB TAG selected five field sites where oilseed rape was the current crop. Sites were selected to give combinations of expected SNS levels, soil types and geographic situations (Table 37). Fields were avoided where the crop had received an autumn N fertiliser application, where manure had been applied or grass ploughed in the season prior to crop establishment, or where the soil was peaty (over 15% organic matter). In the first year (2007) fields in which the N fertiliser had been applied more than six weeks prior to autumn sampling were accepted.

First year – 2007/2008

At each site, two adjacent areas of contrasting crop size were selected in fields of already established oilseed rape. The large crop was selected to be as large as possible and the variation in crop size caused by variation in establishment or/and subsequent crop growth.

Years 2 (2008/2009) and 3 (2009/2010)

Three methods of canopy manipulation were used to create neighbouring small and large canopies; sowing date, plant population and fleece. See Table 37 for details of which method was used at each site. Fields with the earliest crop emergence were selected for the sowing date method. After plant emergence a 10m x 10m area was sprayed with glyphosate and three to four weeks later the area was re-sown with a broadcasting seed rate of 100 seeds/m^2. The plant population method for manipulating plant canopy size ideally required one 10m x 10m area to be sown with 25% of the seed rate used for the rest of the field. Where this was not practical a smaller plant population was created by hoeing out or glyphosating half of the plants at the second to third true leaf stage. This was preferably done by removing alternate 15 cm sections from within each row, as opposed to removing alternate rows, which may have created gaps that were too large for uniform sampling. The final method of crop size manipulation was achieved using fleece; once the crop had reached the second to third true leaf stage it was covered with fleece until February to create an area of crop with greater growth.

Field plot

The plot areas of 10m by 10m were marked out and surrounded by guard areas where no fertiliser N was applied. The size of this guard area was large enough to ensure that no fertiliser N from the surrounding commercial crop could encroach onto the plot area and its size depended on the particular fertiliser spreader used on the farm and the tramline width. Signs were erected on each tramline in the guard area stating “No N fertilisers” to mark the points where the fertiliser operator should turn off the spreader.

Table 37. Selected sites, soil types and the canopy manipulation methods used to compare effects on harvested SNS of different crop size over the three years.

Year	Site ID	Site	Top soil texture	Subsoil texture	Canopy manipulation method
2007/08	8A-R001/2	Boxworth	Clay	Clay	Field area selection
2007/08	8A-R003/4	Rivis, Leavening	Silty clay loam	Silty clay loam	Field area selection
2007/08	8A-R005/6	Evison	Silty clay loam	Silty clay loam with chalk	Field area selection
2007/08	8A-R007/8	Rosemaund	Silty clay loam	Silty clay loam	Field area selection
2007/08	8A-R09/10	Boothman, Brawby	Silty loam/Silty clay loam	Silty loam/Silty clay loam	Field area selection
2007/08	8T-R011/12	Morley	Sandy loam	Clay	Field area selection
2007/08	8T-R013/14	Biggleswade	Clay loam	Clay loam	Field area selection
2007/08	8T-R015/16	Aby	Sandy clay loam	Sandy clay loam	Field area selection
2007/08	8T-R017/18	Louth	Silty loam	Silty loam	Field area selection
2007/08	8T-R019/20	Wylye	Silty clay	Chalk	Field area selection
2008/09	9A-R021/22	High Mowthorpe	Sandy loam	Sandy clay loam	Sowing Date (Fleece)
2008/09	9A-R023/24	High Mowthorpe	Silty clay loam	Chalk	Plant pop’n (hoed)
2008/09	9A-R025/26	Boxworth	Clay	Clay	Plant pop’n (hoed)
2008/09	9A-R027/28	Terrington	Silt	Silt	Plant population
2008/09	9A-R029/30	Rosemaund	Sandy clay loam	Sandy clay loam	Plant population
2008/09	9T-R031/32	Morley	Sandy clay loam	Clay loam	Fleece
2008/09	9T-R033/34	Biggleswade	Clay loam	Clay loam	Fleece
2008/09	9T-R035/36	Aby	Sandy clay loam	Sandy clay loam	Sowing date
2008/09	9T-R037/38	Welton (Biscathorpe)	Sandy clay loam	Sandy clay loam	Sowing date
2008/09	9T-R039/40	Hants	Clay loam	Clay loam	Fleece
2009/10	10A-RO41/42	High Mowthorpe	Silty clay loam	Silty clay loam	Sowing date, seed rate, fleece
2009/10	10A-RO43/44	High Mowthorpe	Silty clay loam		Plant pop’n (hoed)
2009/10	Extra	High Mowthorpe			Plant pop’n (Drilled)
2009/10	10A-RO47/48	Terrington			Plant population

Year	Site ID	Site	Top soil texture	Subsoil texture	Canopy manipulation method
2009/10	10A-RO49/50	Rosemaund			Plant population
2009/10	10T-RO51/52	Morley	Sandy clay loam	Clay loam	Fleece
2009/10	10T-RO53/54	Ketteringham	Sandy caly loam	Sandy clay loam	Plant population
2009/10	10T-RO55/56	Biggleswade	Clay loam	Clay loam	Plant pop’n, fleece
2009/10	10T-RO57/58	Aby	Sandy clay loam	Clay loam	Fleece
2009/10	10T-RO59/60	Welton	Sandy clay loam	Clay loam	Plant population
2009/10	10T-RO61/62	Hill Farm	Sandy silty loam	Clay loam	Plant population

Measurements

Quadrat placement

Eighteen quadrat areas were marked out in each of the small and large crop areas for soil and plant sampling. Quadrats were positioned so that a plant row ran diagonally from one corner to the opposite corner. Six 0.25 m^2 quadrats were used for each of the autumn and spring sampling. Six 0.5 m^2 quadrats were used for the summer sampling.

Soil sampling

Soil samples were taken in autumn, between the first of November and the first of December (December 12th in the first year) and in spring, during the last two weeks in February, before stem extension. Soil cores were taken from 30 cm soil horizons to 90 cm depth (60 cm depth on shallow soils) from 12 sampling points, two from opposite corners of each of the six quadrats to be sampled. Where possible samples were taken using Eijkelkamp “stepwise” 30 mm soil corers for the top 30 cm and EJH Danish 22 mm and 19 mm corers for 30-60 cm and 60-90 cm depths respectively. Care was taken not to cross contaminate soil from one horizon to another, and to avoid any contamination from vegetation, removing the top 1 cm of soil if necessary.

Samples were dispatched to the lab in cool boxes with ice blocks as soon as possible after sampling. To avoid samples sitting in storage or transit over the weekend sampling was timed to avoid sending samples on a Thursday or Friday.

Assessments were taken of topsoil texture using the flow chart from RB209 (Annex 2) for each horizon. Stone content of the topsoil was assessed by digging one spit with a spade and visually assessing stone size and abundance using reference charts from the Soil

Survey Handbook (Annex 1). An estimate of stone content of the deeper soil layers was made, using Table 28.

Soil sample analysis

All soil samples were analysed by NRM for dry matter content (DM%) and SMN (nitrate N and ammonium N concentration, mg/kg). In spring 2010, topsoil samples were also analysed for potentially mineralisable N (PMN) by anaerobic incubation and total N% by Dumas or Kjeldahl.

Plant sampling in autumn and spring

Visual crop assessments were made at the time of sampling during autumn and spring to assess plant density, height, and GAI. At each of the six 0.25 m^2 quadrats the crop was classified as either ’thin’, ‘normal’, or ‘dense’ and crop height was measured. To assess GAI a digital photograph was taken of the crop, one metre above the crop looking vertically down onto the crop. This was then uploaded to the canopy GAI tool (http://www.agricentre.basf.co.uk/agroportal/uk/en/crops/osr/gai_tool/GAI_tool.html) to estimate the GAI of the crop.

All plants within the quadrat were cut to ground level and their fresh weight recorded. A 50% subsample was dried at 80°C for 24 hours weighed and bulked and dispatched to the lab for N analysis by Dumas.

Plant sampling in summer

Plant samples were taken at the end of seed filling when the crop would usually have been swathed or desiccated. Before sampling the discard area and farm crop were assessed visually to check for evidence that the discard area or plot had been fertilised by the farm spreader, and a photograph of the plot was taken. Quadrats were positioned so that a plant row ran diagonally from one corner to the opposite corner. All plants within each of the six 0.5 m^2 quadrats were cut to ground level, taking care not to lose seed. The total fresh weight of each sample and a 20% subsample was recorded. Then the plants in the sub-sample were separated into stems and pods, including any seed shed and oven dried separately and the dry weight recorded. The seed was threshed from the pods and the dry weight of the seeds and pod walls recorded. The pod walls and stems were combined and sent for N analysis, as were the seeds. Seed and straw/pod wall N% were determined by the Dumas method by NRM laboratories.

Two sites (RT-RO13/14 and RT-RO55/56) were removed from the analysis because the crop N measured in summer was more than 60 kg/ha less than the crop N measured in spring. It is extremely unlikely that this much N could have been lost from the canopy between spring and summer and it is possible that some seed may have been lost during crop sampling.

Statistical analysis

Two methods, linear regression analysis and paired *t* tests, were used to test whether canopy size is likely to have affected the relationship between measured SNS (in autumn or spring) and final N uptake by the unfertilised crop (described here as harvested SNS).

3.6.3. Results

Detailed results from this part of the project are presented in Annex 5.

The overall mean autumn SMN for the small treatment over the three years was 57 kg/ha, ranging from 20–106 kg/ha, whereas the overall mean autumn SMN for the large treatments was smaller at 44 kg/ha with a range of 17–98 kg/ha; this difference was not significant ($P>0.05$) (Figure 54). The overall mean autumn crop N for the small treatment over the three years was significantly ($P<0.001$) smaller at 19 kg/ha (range of 1–86 kg/ha) compared to the overall mean for the large treatment at 46 kg/ha with a 10–124 kg/ha range. The total autumn SNSs for small and large treatments over the three years were not significantly different $P>0.05$ at 76 kg/ha (25–123 kg/ha range) and 90 kg/ha (28–169 kg/ha range) respectively. Although not statistically significant the greater SNS of the large treatment may have been caused by larger crops taking up more N in the autumn before it was immobilised by soil micro-organisms.

In the spring the overall mean SMN for the small treatment over the three years was not significantly ($P>0.05$) larger at 40 kg/ha with a range of 12–90 kg/ha than the overall mean SMN for the large treatment at 34 kg/ha with a range of 15–84 kg/ha. The three year overall mean spring crop N of the small treatment was significantly ($P<0.001$) less at 29 kg/ha, 2–71 kg/ha range, than the overall spring crop N for the large treatment with a mean of 55 kg/ha, and a 19–125 kg/ha range. The three year overall mean total SNS for the small treatment was 69 kg/ha, with a 34–127 kg/ha range which was significantly ($P<0.01$) less than the spring overall mean SNS for the large treatment which was 89 kg/ha and ranged from 39–173 kg/ha. This difference may be partly explained by crops of the larger treatments taking up more N in the autumn before mineral N was either immobilised or leached over-winter.

The harvested SNSs for small and large treatments were not significantly different from each other (*P*>0.05), the small treatment had a mean crop N of 101 kg/ha and ranged from 34–207 kg/ha while the large treatment had 116 kg/ha with a 46 to 257 kg/ha range. There were also no significant (*P*>0.05) differences between the harvested SNS for the different treatments in individual years.

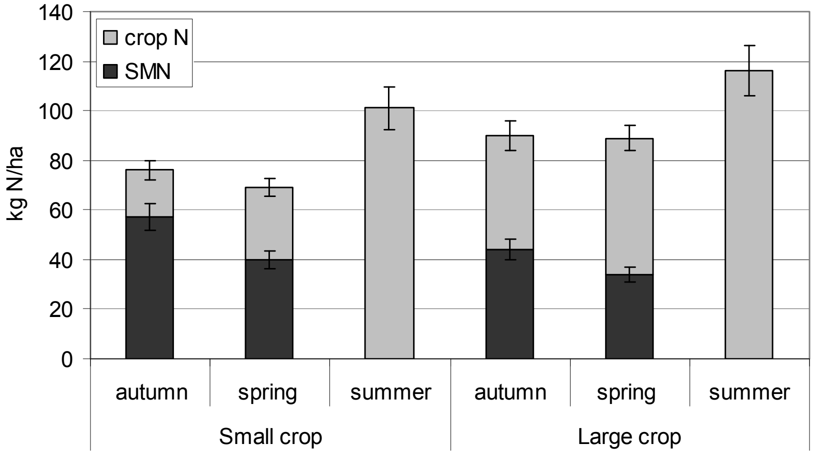


Figure 54. Overall mean SMN (kg/ha) and crop N (kg/ha) in autumn, spring and summer from 2007/08, 2008/09 and 2009/10 with small and large crop treatments. N=28 ± SEM per treatment.

Linear regression analyses revealed no significant differences in the relationships between autumn or spring SNS and harvested SNS between small and large crop treatments (Figure 55). This was the case when the regression analyses were performed for individual seasons or across all three seasons.

Harvested SNS as a proportion of the autumn or spring SNS was calculated for each site and a paired T-test was carried out to investigate whether there were any differences between the small and large crop treatments. Across all three seasons the average harvested SNS as a proportion of autumn SNS was 1.50 for the small treatment and 1.41 for the large treatment, however this difference was not significant. There was also no difference between for proportion of spring SNS taken up between the small (1.58) and large (1.38) treatments. Also, no differences were detected when the analysis was restricted to the 15 sites with the largest difference between the small and large treatments (average of 24 kg/ha N compared with 66 kg/ha N). Analyses for each individual season also showed no differences between the small and large treatments.

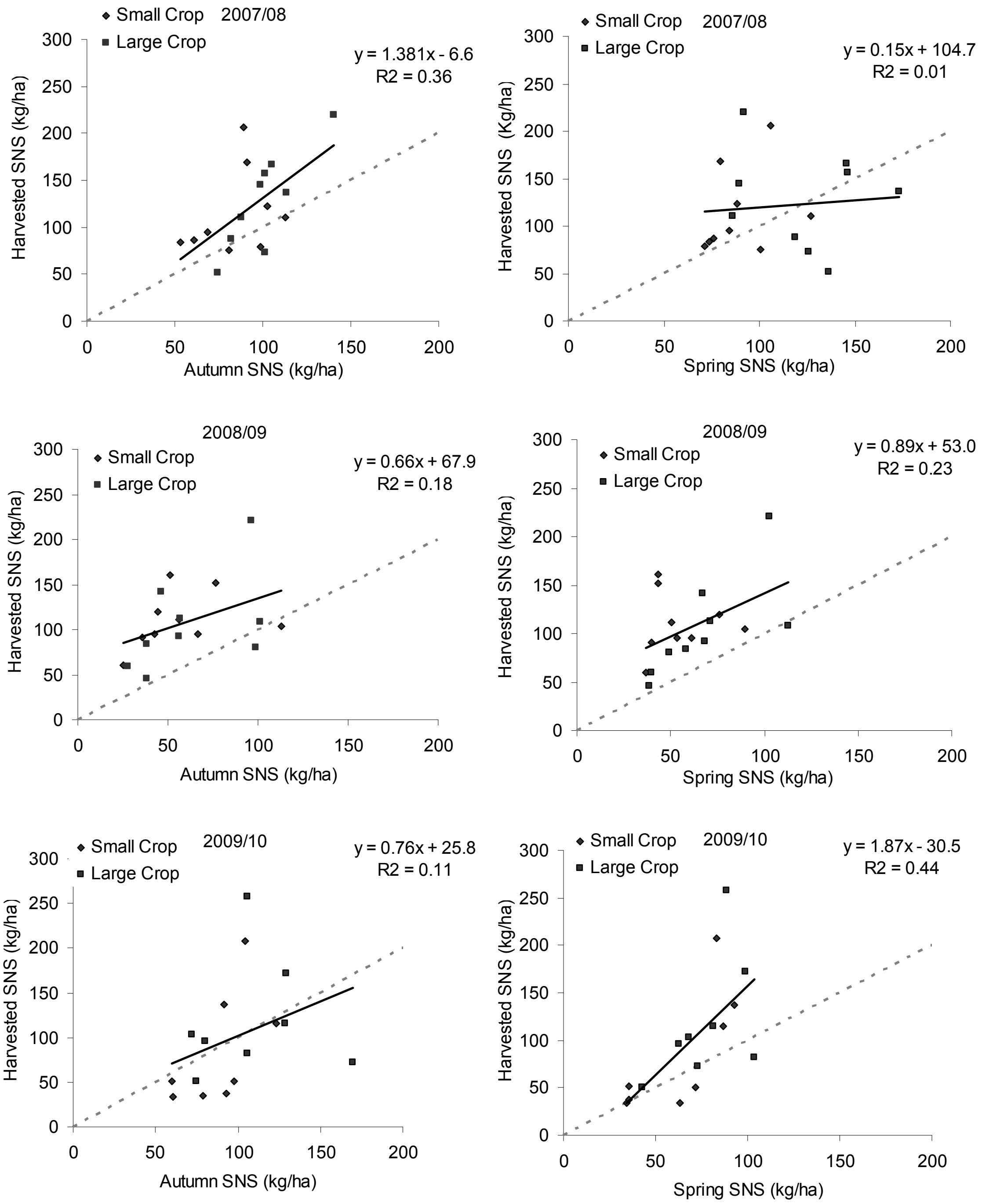


Figure 55. Comparison of autumn or spring SNS (SMN + crop N) with harvested SNS. There were no significant differences between the relationships for the small and large crop treatments.

3.6.4. Discussion and conclusions

This sub-project investigated 29 pairs of crops with treatments intended to provide small and large canopies across three seasons. In autumn the average crop N contents were 19 kg/ha for the small treatment and 46 kg/ha for the large treatment, and there was no significant difference in the overall SNS because the small treatments had a greater SMN. In spring, the small treatments contained 29 kg/ha and the large treatments contained 55 kg/ha. The large treatments also had a greater SNS because there was no difference in SMN between the treatments. There was no evidence that the size of the canopy measured in autumn or spring affected the relationship between autumn or spring SNS and harvested SNS. Even when the dataset was restricted to the sites with the largest contrast in canopy size the differences in harvested SNS remained non-significant. This indicates that SMN and crop N may be considered as equivalent in terms of how they are used to predict a crop's requirement for N fertiliser. The results indicate that oilseed rape is efficient at remobilising N from dying leaves and little N is lost in dropped leaves.

The average proportions of autumn and spring SNS taken up by summer were 1.45 and 1.48 respectively. These proportions appear greater than when the SNS prediction included N to be mineralised after the SMN was measured. On average, an additional 27 and 30 kg/ha was taken up respectively compared with the autumn and spring SNS. However, there were large seasonal variations, e.g. mean additional N uptake compared with the autumn SNS ranged from 3 kg/ha in 2009/10 to 48 kg/ha in 2008/9. Additional N uptake compared with spring SNS ranged from 14 kg/ha in 2009/10 to 46 kg/ha in 2008/9. These estimates of additional N uptake are similar to previous studies with PR447 (Berry & Spink 2009) showing 14 kg/ha of additional N uptake compared with spring SNS across 9 sites seasons. RD-2008-3578 (Berry et al., 2011) showed 37 kg/ha of additional N uptake compared with spring SNS across 6 site seasons.

The ability to predict harvested SNS from measured SNS in these oilseed rape crops appeared poor. Linear relationships between autumn or spring SNS with harvested SNS in summer accounted for between 1% and 44% of the variation. Similar predictive ability was found whether using autumn or spring SNS, which may indicate that soil measurements could be made earlier than February as is currently practised. However, there are really too few data to be able to draw such conclusions with confidence. Also, any autumn soil analyses would need to be interpreted carefully (if there was a high risk of over-winter leaching) or SNS could be over-estimated. This potential problem is smaller in oilseed rape than in cereals because oilseed rape takes up a greater proportion of SMN before winter. However, previous studies with oilseed rape (PR447 and RD-2008-3578) have shown that spring SNS gave a better prediction of harvested SNS than in this current study, with r^2 values from simple regression analyses of 0.75 and 0.52 respectively.

Considering the value of just measuring crop N (and not SMN), regression analysis with harvested SNS showed that that there was only a significant relationship for spring crop N in 2009/10 and in all cases the variation accounted for was less than when using SNS. This shows that it is important to include an estimate of SMN when predicting harvested SNS in oilseed rape.

Assessing oilseed rape crop N content

The N content of oilseed rape canopies can be estimated using several methods. Depending on the circumstances and the type of crop some methods are more appropriate than others as described below.

Method 1: Via crop height.

Canopy height has been related to crop N content as follows;

- 10 cm ≈ 35-45 kg N/ha
- 20 cm ≈ 55-65 kg N/ha
- 30 cm ≈ 75-85 kg N/ha

This method is appropriate for moderate sized canopies. However it has not been tested for semi-dwarf varieties and should not be used on crops which have been flattened by snow.

Method 2: Via green area index (GAI).

Each unit of green area index (metres square of green tissue per metre square of ground) has been shown to contain about 50 kg N/ha. In some cases it has been found that large canopies with a GAI of 2 or more contain closer to 40 kg N/ha per unit of GAI. GAI can be related to crop N content as follows:

- GAI 0.5 ≈ 25 kg N/ha
- GAI 1.0 ≈ 50 kg N/ha
- GAI 2.0 ≈ 80-100 kg N/ha

GAI can be estimated by uploading a digital photo of the crop onto www.totaloilseedcare.co.uk. This method is appropriate for crops with a GAI up to 3. GAI can also be estimated very crudely from an estimate of the fraction of ground covered by the crop. Crop covers of one third, one half and three quarters approximate to GAIs of 0.5, 1 and

2 respectively. Estimates of GAI using this method can vary widely for the same crop between assessors.

Method 3: Via crop fresh weight.

Cut the plants off at ground level from a 1m by 1m area, record the fresh weight in kg, then multiply this by 40 to estimate the crop N content (kg/ha).

- Crop fresh weight 1 kg/m2 ≈ 40 kg N/ha
- Crop fresh weight 2 kg/m2 ≈ 80 kg N/ha
- Crop fresh weight 3 kg/m2 ≈ 120 kg N/ha

This technique should be done when the crop foliage is dry and is useful for crops with large canopies.

Method 4: Via crop weight and the concentration of N in the plant

This method will give the most accurate estimate of crop N content, but requires an accurate set of weighing scales, facilities for drying the plant material and there is a cost for the N analysis.

- Cut the plants off at ground level from a 1m by 1m area.
- Record the fresh weight of the whole crop sample (in grammes)
- Take a sub-sample from the whole sample of about 500g and record the exact fresh weight (sub-sample may not be required for small crops)
- Dry the sub-sample in an oven at about 80°C (until no further weight loss) and record the weight of the dried sub-sample (in grammes).
- Send the dried sub-sample to an appropriate analytical lab to determine the percentage of N in the dried plant tissue by weight.
- Crop N content can then be calculated using the following steps
  1. Divide the fresh weight of the total sample by the fresh weight of the sub-sample
  2. Multiply the answer from 1 by the dry weight of the sub-sample
  3. Multiply the answer from 2 by the percentage N content of the dry plant material and divide by 100
  4. Multiply the answer from 3 by 10 to give crop N content in kg N/ha.

3.7. Estimating SNS on-farm: cost-effective approaches

3.7.1. Defining the 'best' prediction of SNS – methodology

We are looking for the estimate (a measure or an assessment) that can be made in spring or earlier that gives the best prediction of harvested SNS over all sites. We can consider a number of ways of evaluating possible predictors:

1. The co-efficient of determination (r^2) or % of variation in the observed values (harvested SNS) explained by the candidate predictor, allowing empirical adjustment of that predictor, as when a slope and intercept is derived in regression analysis
2. The co-efficient of determination (r^2) or % of variation in harvested SNS explained directly by the candidate predictor, without allowing any empirical adjustment, hence testing deviations from the y=x relationship.
3. Using this approach it is also useful to separate total error into bias (the difference between mean predicted SNS and mean harvested SNS) and imprecision (the average of all differences between predicted and harvested SNS, ignoring whether they were negative or positive).
4. The proportion of predicted values within x kg/ha of the observed value
5. The average difference between predicted and observed
6. The average cost of getting the prediction wrong (profit foregone)
7. The proportion of times that those costs are less than x £/ha

Up to now we have just considered the first method above for describing the relationships between, for example, autumn SNS and harvested SNS. We have seen that the r^2 or the % variation explained in these regressions is, for example, slightly higher for spring measured SNS than for autumn SNS. However, we have also noted in these relationships that there is usually an intercept which is different from zero, a slope which is different to one and often also a point at which the linear relationships breaks; the 'breakpoint' beyond which any increase in measured SNS does not correspond to a further increase in harvested SNS.

Co-efficient of determination (r^2)

Currently, when using SNS estimates to decide N fertiliser recommendations we assume the assessment is a prediction of the N that will be taken up by the crop from the soil, without making any adjustments for intercept or slope. We are therefore interested in how much variation in harvested SNS is explained by the SNS predictor, i.e. the extent to which the observed 'harvested SNS' values fall on the 1:1 or y=x line with the predictor, rather than on a regression line which has been fitted. This r^2 is calculated from the proportion of the regression sum of squares (the sum of the squared differences between predicted and observed values) of the total deviance (the sum of the squared differences between each observation and the overall mean) using the formulae below:

$$R^2 = 1 - \frac{SS_{\rm err}}{SS_{\rm tot}}.$$

Where $SS_{\rm err}$ = the sum of squares of residuals =

$$SS_{\rm err} = \sum_i (y_i - f_i)^2$$

f = predicted value
y = observed value
SS_{tot} = Total sum of squares =

$$SS_{\rm tot} = \sum_i (y_i - \bar{y})^2,$$

$\bar{y}$ = overall mean of observed values

Both the r^2 from a regression analysis and the r^2 from the y=x relationship have been calculated for each possible approach to predicting harvested SNS.

Errors in prediction

The simple difference between a SNS prediction and harvested SNS is the error. We have calculated these errors (subsequently termed $N_{\rm error}$) for each site such that positive values indicate that the SNS prediction underestimated actual SNS (hence N fertiliser applications would likely have been too generous) and negative values indicate that the SNS prediction over-estimated the actual SNS (hence N fertiliser applications would likely have been sub-optimal). To evaluate any SNS prediction approach over all sites, the errors can be usefully separated into mean bias (the difference between the mean of all predictions and the mean of all harvested SNSs) and mean imprecision (the average of all differences between predicted and harvested SNS, ignoring whether they were negative or positive, less the bias).

SNS predictions within x kg/ha of observed harvested SNS

Another way of deciding which SNS predictor is best is to assess how often it gets close to the correct answer, or how often it gets the answer very wrong. It is well known that predictions of SNS or N requirement cannot be expected to be accurate within +/- 20 kg/ha; Sylvester-Bradley et al. (2008) showed that, even using the best recommendation system with soil measurement, the N recommendation was within 50 kg/ha of the measured optimum in only 50% of cases. Their analysis also showed that the costs of getting the N recommendation wrong were relatively small when the error was less than ~25 kg/ha but much larger where errors exceeded 50 kg/ha.

For each approach to SNS prediction we have therefore calculated the proportion of sites where the prediction is (or is not) within 10, 20 or 50 kg/ha of the observed harvested SNS.

Costs of getting SNS prediction wrong

The most important comparison of approaches for a farmer is that which compares the financial costs or benefits of alternative approaches. By assuming a standard relationship between SNS and N requirement, or N optimum (see below), assuming that perfect knowledge of harvested SNS would allow N fertiliser to be applied at the optimum economic rate, and assuming that SNS can directly replace fertiliser N (kg/kg), we can calculate a financial cost of getting the SNS prediction wrong. This cost derives from lost yield (net of saved fertiliser) where predicted SNS is over-estimated (actual SNS less than predicted), and from wasted fertiliser (net of increased or decreased yields) where predicted SNS is under-estimated (actual SNS greater than predicted). These assumptions are not entirely realistic, because we know that crop recovery of fertiliser N is less than 100% whereas crop recovery of harvested SNS is 100% (by definition); also variation in N optima is not perfectly related to variation in SNS (there is also variation in crop N demand and fertiliser N recovery). However, for the sake of allowing economic comparisons between SNS prediction approaches, it is essential to make some common assumptions such as these. The resulting cost estimates should probably be regarded as underestimates; in practice fertiliser adjustments will be larger than these, hence more costly; however, the benefits of one approach over another would also probably be reduced because the poor predictabilities of crop N demand and fertiliser N recovery are not included.

A standardised N response curve (derived from many N response experiments) was used to determine effects on grain yield of applying less or more than the optimum (Figure 56). The parameters of the linear plus exponential curve adopted and the assumptions of grain price are given in Table 38. The economic N optimum (N_{opt}; kg/ha) is calculated from the equation:

$$N_{opt} = [\ln(k/1000 - c) - \ln(b(\ln(r)))]/\ln(r)$$

Where k is the break-even price ratio (BER: kg grain/kg N) and parameters *b*, *c* and *r* are parameters of the Linear plus Exponential function given in Table 38.

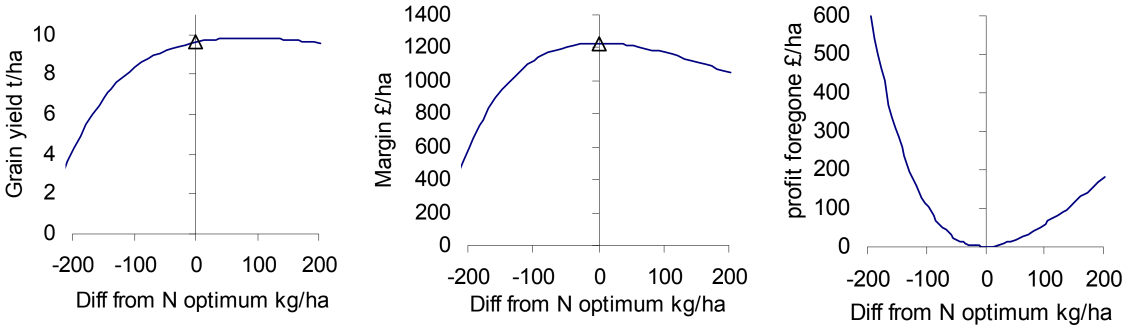


Figure 56. Response curves for grain yield, margin over fertiliser cost (ignoring other costs), thus profit foregone from non-optimal fertiliser use, as used to calculate costs of different approaches to SNS prediction.

It can be seen that the grain response shows little decrease at super-optimal N levels; it assumes that negative effects on yield of over-fertilising are unlikely, e.g. due to lodging. Hence the costs of over-estimating SNS and under predicting fertiliser N requirement are much greater than the costs of under-predicting SNS. This is because the costs of losing grain yield are greater than the costs of wasting N fertiliser. However, if soil sampling predicts a very high SNS (>150 kg/ha) which turns out to be a serious over-estimate, initial N applications in February / March and early April would likely be missed or seriously reduced. In this case, if the crop available SNS actually turns out to be much less than predicted by sampling (<80 kg/ha) it is likely that the crop would begin to look N stressed in time to alter the final N applications, and hence avoid very large yield losses. For this reason, losses of above ~2-3 t/ha due to over-prediction are probably unrealistic. The minimum profitability from over-predicting SNS at any site is that which would occur from applying no fertiliser and achieving unfertilised yields; the difference in the margin at the economic optimum and that with no applied N should therefore be used as the maximum 'profit foregone' from over prediction.

Table 38. Assumptions used in calculation of the costs of SNS errors for a wheat crop. The optimum is for the total supply of N from both soil and fertiliser.

Parameters for LpE curve:			Economic Assumptions:		
A		12	Grain price	150	£/t
B		-12	AN price	300	£/t
C		-0.005	N price	0.87	£/kg
R		0.9905	BER	5.8	
optimum *available* N (kg/ha)	N_{opt}	247			
Yield at optimum (t/ha)		9.6			

The grain yield (GY; t/ha) at the N optimum, is given by the equation:

$$GY = a + b.r\mathrm{N}_{\mathrm{opt}} + c.\mathrm{N}_{\mathrm{opt}}$$

The grain yield for any N rate greater than the optimum (as supposed from an under or over estimate of SNS), which we can term $\mathrm{N}_{\mathrm{error,}}$, is therefore given by the equation:

$$\mathrm{GY}_{\mathrm{error}} = \mathrm{a} + \mathrm{b.r}(\mathrm{N}_{\mathrm{opt}}+\mathrm{N}_{\mathrm{error}}) + \mathrm{c.}(\mathrm{N}_{\mathrm{opt}}+\mathrm{N}_{\mathrm{error}})$$

with the important proviso that $(\mathrm{N}_{\mathrm{opt}}+\mathrm{N}_{\mathrm{error}}) > \mathrm{SNS}_{\mathrm{uptake}}$, if not then $(\mathrm{N}_{\mathrm{opt}}+\mathrm{N}_{\mathrm{error}})$ is substituted for $\mathrm{SNS}_{\mathrm{uptake}}$ in the above equation.

The financial margin over N cost at the optimum ($\mathrm{Margin}_{\mathrm{opt}}$; £/ha) was calculated for each site from:

$$\mathrm{Margin}_{\mathrm{opt}} = (\mathrm{GY}_{\mathrm{opt}} \text{ x Grain price}) - ((\mathrm{N}_{\mathrm{opt}} - \mathrm{SNS}_{\mathrm{uptake}}) \text{ x N price})$$

The profit foregone for any N rate greater than the optimum ($\mathrm{N}_{\mathrm{error}}$) can therefore be estimated for each site from:

$$\text{Profit foregone} = \mathrm{Margin}_{\mathrm{opt}} - ((\mathrm{GY}_{\mathrm{error}} \text{ x Grain price}) - ((\mathrm{N}_{\mathrm{opt}} + \mathrm{N}_{\mathrm{error}}) \text{ x N price})))$$

with the important proviso that $(\mathrm{N}_{\mathrm{opt}}+\mathrm{N}_{\mathrm{error}}) > \mathrm{SNS}_{\mathrm{uptake}}$, if not then $(\mathrm{N}_{\mathrm{opt}}+\mathrm{N}_{\mathrm{error}})$ is substituted for zero in the above equation.

Profit foregone was calculated in this way for each site and for each SNS prediction approach. In order to compare between approaches, assessments can be considered of both the average profit foregone and the proportion of sites where profit foregone is less than £10/ha or greater than £40/ha.

Adjusting predictors to improve performance

Until now, SMN-based predictors have generally been used without adjustment; SNS has been calculated by summing in kg/ha N, SMN to 90 cm, crop N and an estimate of mineralisable N (though estimates of mineralisable are often taken as zero). SNS has then been used with an implicit assumption that harvested SNS will be directly equivalent to predicted SNS. However, SNS predictors inevitably have different average values, giving them different degrees of ‘bias’ compared to harvested SNS, as well as accounting for different proportions of the variation in harvested SNS (‘precision’). The average foregone profit (Section 3.7.1) arises due to bias as well as imprecision. Whilst the main aim of SMN sampling has been to improve predictive precision of SNS, the performance of SMN-based predictors is also influenced strongly by any bias that they may have. It can be argued that it would be easy to adjust a predictor for bias, so long as the bias of that predictor was known beforehand. If this is accepted, it will be important to recognise the extent to which the financial performance of a predictor arises from bias or from imprecision, and to compare only predictors that have similar and small bias, say from zero to -20 kg/ha.

The effect of bias on profit foregone, using a fixed SNS level as the predictor, is shown in Figure 57. As shown by Sylvester-Bradley et al. (1987; 2008) in previous similar exercises, any large bias seriously worsened performance. Performance maximised with an SNS prediction of about 95 kg/ha, less than the mean harvested SNS of 106 kg/ha. However, variation within a small range of negative bias (between -20 and 0 kg/ha of the mean) affected mean profit foregone by less than £1/ha. Hence, predictors are best compared if they are within this range, and this is the approach adopted in subsequent section in which predictors are developed and compared.

Consideration of bias can be taken one step further, viz. some predictors here tended to under-predict low values and over-predict high values of harvested SNS i.e. relationships between predicted and observed SNS deviated from equivalence across the full range and hence the slope differed significantly from 1:1. Just as bias of a predictor may be anticipated and counteracted, so slopes may also be predictable.

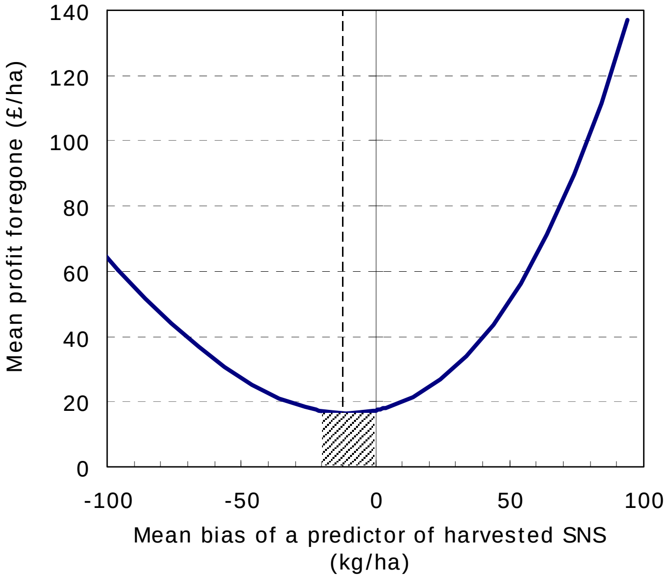


Figure 57. Effect of varying the mean bias of an example predictor (a fixed amount of SNS at all sites) on its mean financial performance (profit foregone) through its use in deciding use of fertiliser N. Dashed line: median harvested SNS. Shaded band: range for minimum profit foregone, ~£17/ha.

Section 3.7.8 therefore uses regression analysis to explore the need for adjustment of bias and/or slope of the various predictors developed through section 3.7. Note that in regression analysis the intercept (or constant) represents bias; also note that there is interdependence between the intercept and the slope. Hence regression analysis of a predictor will determine a slope which will depend on whether an intercept has been allowed or not; alternatively it will determine an intercept depending on whether the slope was allowed to differ from 1. In this report we examine adjustments to the most successful predictors using both intercepts and slopes. These analyses were conducted on the assumption that the values for slope and intercept could have been known in advance. However, it should be acknowledged that they were actually derived using knowledge of the new data being analysed here as well as of previously generated data (from section 3.3), so the predictive nature of the values chosen must be considered in subsequent discussion. It should be noted that there would probably be considerable difficulty in achieving full adoption by the industry of slope and intercept adjustments, so in any case their possible use must be considered with care.

3.7.2. Comparison of current approaches for predicting SNS

Table 39 (and Tables up to to 48) summarises results for different approaches to predicting SNS for the newly generated dataset as a whole. Note that all approaches based on soil measurement included an estimate of crop N made at the time of sampling, but unless AAN is specified, they excluded an explicit estimate of mineralisable N.

It can be seen that identity of the 'best' approach depended crucially on which assessment we used to determine 'best'; approaches that gave a good relationship with harvested SNS (i.e. fitting gave a high r^2 value) did not necessarily give a good direct prediction of harvested SNS (i.e. the unfitted predictor giving a high r^2 value; y=x). As explained in Section 3.7.1, as long as bias is within the range -20 to 0 kg/ha, the most telling measure of the success of an approach is probably profit foregone, as this is what would directly affect the farmer. Perhaps surprisingly differences in profit foregone between the approaches (without much bias) were not large; the difference between simply assuming 100 kg/ha SNS at all sites and the best possible prediction approach was just £8.60 /ha on average.

From this analysis, the FAM approach to SNS prediction generally performed well. Foregone profit was less with FAM than with a fixed SNS prediction (100 kg/ha at all sites) in almost all circumstances, and it was never seriously worse. However, it appears that direct use of measured SMN as a predictor for use in all circumstances gave worse returns than using the FAM; some SMN-based approaches were even worse than assuming SNS was fixed. These large average losses mainly arose from just a few sites where soil measurement substantially over-predicted harvested SNSs; e.g. more than ~250 kg/ha SNS was measured but less than ~150 kg/ha was taken up by the unfertilised crop. Such cases gave a potential to under-fertilize by over 100 kg/ha, which gave substantial losses in yield hence very large foregone profits. Such large over-predictions were not possible using the fixed SNS or using the FAM as these could not give predictions beyond ~150 kg/ha and harvested SNS was seldom less than ~50 kg/ha, making over predictions of more than ~100kg/ha, hence large losses, virtually impossible.

It has been shown using broken-stick regression analysis, both on past datasets and the newly generated dataset, that the linear relationship between measured SNS and harvested SNS did not hold beyond ~200 kg/ha harvested SNS; above this point further increases in predicted SNS could not be expected to yield greater increases in harvested SNS. It is therefore unreasonable to treat measures of SNS above ~200 kg/ha as *predictions* of harvested SNS of more than ~200kg/ha. Thus for the sake of making fair comparisons in the subsequent conclusions of this report, any SNS prediction exceeding 200 kg/ha was treated as a prediction of just 200 kg/ha SNS. This restriction only affected exceptional cases; it made little difference to profit foregone as N recommendations are likely to be small or zero where SNS is taken to be 200 kg/ha, and would be the same even if SNS was taken to be 300 kg/ha or more.

Even with using a maximum of 200 kg/ha, predictions derived from SMN measurements still gave worse returns than using FAM when all sites were considered together. Only when adjustments to measured SNS were made, either by adding another measurement (i.e. AAN) or by assuming a slope and intercept, did soil measurement-derived estimates of SNS outperform the FAM. These adjustments are discussed in greater detail in section 3.7.2. First we look at the situations where SMN measurement may be more (or less) worthwhile.

Table 39. Comparison of approaches for SNS prediction, using all data from 164 sites 2007-2010. # Negative r^2 values indicate the extent to which predictor values provided worse deviations than a constant i.e. the mean. 'Best' predictors are developed through section 3.7 and defined in section 3.7.8.

	Coefficients of determination		Accuracy and Precision				Profit foregone		
SNS prediction approach	r^2 linear regression	r^2 y=x #	Mean bias, kg/ha	Mean imprec'n, kg/ha	% within 20 kg/ha	% outside 50 kg/ha	Mean £/ha	% <£10/ha	% >£40/ha
Constant 100 kg/ha	0.00	0.00	-5.8	32	34%	20%	16.61	44%	10%
FAM	0.27	0.14	-17.5	15	45%	20%	13.27	68%	7%
FAM incl. manure	0.31	0.26	-9.6	21	48%	18%	12.20	69%	8%
Autumn SNS 0-90	0.27	-2.08	+0.9	37	37%	27%	18.13	57%	12%
Autumn SNS 0-60	0.31	-0.81	-11.2	32	30%	28%	15.90	57%	10%
Spring SNS 0-90	0.35	-0.57	-24.4	20	30%	31%	15.97	54%	10%
Autumn SNS 0-90 (max 200)	0.39	0.26	-5.7	29	63%	15%	14.65	57%	7%
Spring SNS 0-90 (max 200)	0.49	0.08	-31.7	7	32%	30%	14.93	55%	9%
Spring SNS 0-90 + AAN$_{90}$	0.52	0.47	-9.0	19	42%	14%	9.61	74%	4%
Spring SNS 0-60 + AAN$_{60}$	0.44	0.38	-10.1	20	43%	16%	11.07	70%	5%
Aut SNS 0-90 + leach adj	0.49	0.06	-29.7	11	29%	32%	15.75	52%	8%
Spr SNS 0-90 + leach adj	0.54	0.04	-35.9	4	29%	32%	15.49	54%	9%
Aut SNS 0-90 int and slope	0.42	0.41	-2.6	28	40%	21%	11.13	65%	5%
Spr SNS 0-90 int and slope	0.49	0.46	-9.6	18	49%	16%	9.69	72%	7%
Autumn 'Best'	0.49	0.47	-5.0	25	37%	15%	10.06	68%	4%
Spring 'Best'	0.57	0.57	-3.4	23	46%	12%	8.01	75%	3%

Table 40. Comparison of approaches for SNS prediction on 67 clay and silt soil sites 2007-2010. # Negative r^2 values indicate the extent to which predictor values provided worse deviations than a constant i.e. the mean. 'Best' predictors are developed through section 3.7 and defined in section 3.7.8.

	Coefficients of determination		Accuracy and Precision				Profit foregone		
SNS prediction approach	r^2 linear regression	r^2 y=x #	Mean bias, kg/ha	Mean imprec'n, kg/ha	% within 20 kg/ha	% outside 50 kg/ha	Mean £/ha	% <£10/ha	% >£40/ha
Constant 100 kg/ha	0.00	0.00	-26	22	27%	28%	24.62	43%	19%
FAM	0.14	-0.05	-27	18	36%	28%	22.03	55%	16%
FAM incl. manure	0.33	0.14	-20	20	42%	24%	18.65	61%	15%
Autumn SNS 0-90	0.56	0.33	-14	24	34%	24%	16.20	54%	10%
Autumn SNS 0-60	0.60	0.26	-31	12	28%	36%	17.39	48%	9%
Spring SNS 0-90	0.53	0.06	-39	9	24%	40%	20.00	45%	13%
Autumn SNS 0-90 (max 200)	0.53	0.39	-22	17	58%	22%	14.96	51%	7%
Spring SNS 0-90 (max 200)	0.57	0.06	-44	4	25%	42%	21.00	45%	16%
Spring SNS 0-90 + AAN_{90}	0.59	0.47	-20	14	37%	19%	12.52	69%	7%
Spring SNS 0-60 + AAN_{60}	0.50	0.36	-23	14	33%	22%	14.97	58%	9%
Aut SNS 0-90 + leach adj	0.55	0.28	-31	11	22%	31%	16.92	51%	7%
Spr SNS 0-90 + leach adj	0.57	0.04	-45	4	24%	42%	21.31	43%	16%
Aut SNS 0-90 int and slope	0.54	0.43	-19	17	34%	28%	13.80	57%	7%
Spr SNS 0-90 int and slope	0.56	0.41	-22	13	42%	22%	13.89	63%	12%
Autumn 'Best'	0.55	0.51	-9	26	25%	18%	12.60	66%	6%
Spring 'Best'	0.61	0.56	-11	20	37%	19%	10.88	72%	6%

Table 41. Comparison of approaches for SNS prediction on 70 medium soil sites 2007-2010. # Negative r^2 values indicate the extent to which predictor values provided worse deviations than a constant i.e. the mean. ‘Best’ predictors are developed through section 3.7 and defined in section 3.7.8.

	Coefficients of determination		Accuracy and Precision				Profit foregone		
SNS prediction approach	r^2 linear regression	r^2 y=x #	Mean bias, kg/ha	Mean imprec’n, kg/ha	% within 20 kg/ha	% outside 50 kg/ha	Mean £/ha	% <£10/ha	% >£40/ha
Constant 100 kg/ha	0.00	0.00	+10	20	40%	11%	10.06	40%	3%
FAM	0.12	0.02	-10	15	53%	14%	7.66	76%	1%
FAM incl. manure	0.07	0.01	-3	22	51%	16%	8.27	73%	3%
Autumn SNS 0-90	0.25	-0.48	+3	29	41%	26%	14.76	67%	9%
Autumn SNS 0-60	0.22	-0.43	-13	18	37%	20%	11.99	70%	9%
Spring SNS 0-90	0.45	-0.29	-29	2	41%	19%	9.54	67%	4%
Autumn SNS 0-90 (max 200)	0.24	-0.31	+1	29	71%	9%	12.77	67%	6%
Spring SNS 0-90 (max 200)	0.45	-0.29	-29	2	41%	19%	9.54	67%	4%
Spring SNS 0-90 + AAN_{90}	0.37	0.21	-5	18	49%	9%	6.57	80%	1%
Spring SNS 0-60 + AAN_{60}	0.26	0.05	-5	21	50%	10%	7.88	77%	1%
Aut SNS 0-90 + leach adj	0.26	-0.63	-24	10	41%	26%	12.44	63%	6%
Spr SNS 0-90 + leach adj	0.46	-0.49	-33	1	33%	23%	10.95	63%	4%
Aut SNS 0-90 int and slope	0.25	0.13	+6	20	47%	13%	8.11	73%	3%
Spr SNS 0-90 int and slope	0.45	0.42	-5	15	60%	9%	4.64	87%	1%
Autumn 'Best'	0.26	0.16	+6	20	40%	7%	7.80	74%	1%
Spring 'Best'	0.36	0.32	-0	22	53%	6%	5.79	77%	1%

Table 42. Comparison of approaches for SNS prediction on 22 shallow and light sandy soil sites 2007-2010. # Negative r^2 values indicate the extent to which predictor values provided worse deviations than a constant i.e. the mean. 'Best' predictors are developed through section 3.7 and defined in section 3.7.8.

	Coefficients of determination		**Accuracy and Precision**				**Profit foregone**		
SNS prediction approach	**r^2 linear regression**	**r^2 y=x #**	**Mean bias, kg/ha**	**Mean imprec'n, kg/ha**	**% within 20 kg/ha**	**% outside 50 kg/ha**	**Mean £/ha**	**% <£10/ha**	**% >£40/ha**
Constant 100 kg/ha	0.00	0.00	+19	9	41%	9%	10.34	50%	5%
FAM	0.18	0.02	-11	13	50%	14%	5.72	77%	0%
FAM incl. manure	0.13	-0.01	+4	18	55%	9%	6.73	77%	5%
Autumn SNS 0-90	0.10	-1.77	+11	25	36%	23%	20.86	50%	9%
Autumn SNS 0-60	0.07	-1.27	-1	35	18%	18%	14.75	55%	5%
Spring SNS 0-90	0.05	-1.37	-20	18	23%	27%	13.26	50%	5%
Autumn SNS 0-90 (max 200)	0.10	-1.62	+11	25	55%	14%	19.27	50%	9%
Spring SNS 0-90 (max 200)	0.05	-1.37	-20	18	23%	27%	13.26	50%	5%
Spring SNS 0-90 + AAN$_{90}$	0.21	-0.27	+3	23	41%	9%	8.84	77%	5%
Spring SNS 0-60 + AAN$_{60}$	0.16	-0.28	+6.3	17	55%	14%	9.59	82%	5%
Aut SNS 0-90 + leach adj	0.20	-3.12	-51	0	14%	50%	20.63	27%	14%
Spr SNS 0-90 + leach adj	0.16	-1.40	-33	4	27%	32%	12.43	59%	5%
Aut SNS 0-90 int and slope	0.10	-0.60	+14	14	41%	23%	11.39	68%	9%
Spr SNS 0-90 int and slope	0.05	-0.67	+4	25	41%	18%	11.41	59%	9%
Autumn 'Best'	0.20	0.07	-10	12	50%	0%	5.42	77%	0%
Spring 'Best'	0.40	0.34	+3	16	55%	0%	4.35	86%	0%

Table 43. Comparison of approaches for SNS prediction on 62 low FAM SNS Index (0-1) sites 2007-2010. # Negative r^2 values indicate the extent to which predictor values provided worse deviations than a constant i.e. the mean. 'Best' predictors are developed through section 3.7 and defined in section 3.7.8.

	Coefficients of determination		Accuracy and Precision				Profit foregone		
SNS prediction approach	r^2 linear regression	r^2 y=x #	Mean bias, kg/ha	Mean imprec'n, kg/ha	% within 20 kg/ha	% outside 50 kg/ha	Mean £/ha	% <£10/ha	% >£40/ha
Constant 100 kg/ha	0.00	0.00	+26	6	29%	7%	11.94	46%	5%
FAM	0.00	-0.14	-6	15	71%	12%	5.16	80%	0%
FAM incl. manure	0.01	-0.07	-4	15	71%	10%	4.88	83%	0%
Autumn SNS 0-90	0.06	-1.77	+9	24	37%	24%	15.66	56%	5%
Autumn SNS 0-60	0.05	-0.91	-6	22	44%	20%	8.98	71%	2%
Spring SNS 0-90	0.29	-0.49	-21	3	51%	7%	6.25	76%	2%
Autumn SNS 0-90 (max 200)	0.06	-1.77	+9	24	59%	7%	15.66	56%	5%
Spring SNS 0-90 (max 200)	0.29	-0.49	-21	3	51%	7%	6.25	76%	2%
Spring SNS 0-90 + AAN$_{90}$	0.24	0.00	-0	20	54%	5%	4.81	88%	0%
Spring SNS 0-60 + AAN$_{60}$	0.16	-0.25	+0.7	22	56%	10%	6.30	80%	0%
Aut SNS 0-90 + leach adj	0.06	-1.78	-23	10	44%	24%	11.76	61%	7%
Spr SNS 0-90 + leach adj	0.28	-0.86	-26	1	39%	12%	7.72	73%	2%
Aut SNS 0-90 int and slope	0.06	-0.82	+16	13	32%	12%	9.97	71%	5%
Spr SNS 0-90 int and slope	0.29	0.23	+4	14	59%	2%	3.75	90%	0%
Autumn 'Best'	0.06	-0.56	+12	15	32%	2%	8.29	71%	2%
Spring 'Best'	0.20	-0.03	+6	15	51%	5%	5.18	83%	0%

Table 44. Comparison of approaches for SNS prediction on 89 medium FAM SNS Index (2-3) sites 2007-2010. # Negative r^2 values indicate the extent to which predictor values provided worse deviations than a constant i.e. the mean. 'Best' predictors are developed through section 3.7 and defined in section 3.7.8.

	Coefficients of determination		Accuracy and Precision				Profit foregone		
SNS prediction approach	r^2 linear regression	r^2 y=x #	Mean bias, kg/ha	Mean imprec'n, kg/ha	% within 20 kg/ha	% outside 50 kg/ha	Mean £/ha	% <£10/ha	% >£40/ha
Constant 100 kg/ha	0.00	0.00	-11	24	35%	20%	13.98	42%	9%
FAM	0.03	-0.11	-16	19	38%	22%	14.05	64%	9%
FAM incl. manure	0.06	0.01	-10	23	40%	20%	13.25	63%	10%
Autumn SNS 0-90	0.37	-0.11	-9	27	37%	26%	15.67	61%	12%
Autumn SNS 0-60	0.34	-0.29	-25	15	28%	31%	16.93	58%	12%
Spring SNS 0-90	0.31	-0.55	-38	7	27%	35%	18.10	49%	12%
Autumn SNS 0-90 (max 200)	0.33	0.08	-13	21	67%	16%	13.15	61%	7%
Spring SNS 0-90 (max 200)	0.33	-0.47	-39	4	28%	34%	18.02	49%	12%
Spring SNS 0-90 + AAN$_{90}$	0.40	0.25	-15	15	40%	15%	9.98	73%	3%
Spring SNS 0-60 + AAN$_{60}$	0.34	0.22	-12	20	39%	15%	11.78	67%	5%
Aut SNS 0-90 + leach adj	0.37	-0.25	-31	10	26%	29%	16.00	54%	8%
Spr SNS 0-90 + leach adj	0.37	-0.54	-42	3	26%	37%	18.84	47%	12%
Aut SNS 0-90 int and slope	0.34	0.27	-10	19	46%	19%	10.07	65%	4%
Spr SNS 0-90 int and slope	0.33	0.18	-17	14	48%	20%	10.87	67%	7%
Autumn 'Best'	0.38	0.35	-5	24	39%	12%	9.45	69%	2%
Spring 'Best'	0.46	0.41	-9	17	48%	12%	8.03	75%	3%

Table 45. Comparison of approaches for SNS prediction on 13 high FAM SNS Index (4+) sites 2007-2010. # Negative r^2 values indicate the extent to which predictor values gave worse deviations than a constant i.e. the mean. 'Best' predictors are developed through section 3.7 and defined in section 3.7.8.

	Coefficients of determination		Accuracy and Precision				Profit foregone		
SNS prediction approach	r^2 linear regression	r^2 y=x #	Mean bias, kg/ha	Mean imprec'n, kg/ha	% within 20 kg/ha	% outside 50 kg/ha	Mean £/ha	% <£10/ha	% >£40/ha
Constant 100 kg/ha	0.00	0.00	-83	1	8%	62%	52.92	69%	46%
FAM	0.00	-0.57	-43	11	31%	46%	28.92	46%	23%
FAM incl. manure	0.01	-0.52	-42	11	31%	38%	27.90	46%	23%
Autumn SNS 0-90	0.00	-22.06	+36	30	31%	46%	36.58	38%	31%
Autumn SNS 0-60	0.02	-9.44	+71	48	15%	38%	31.12	15%	23%
Spring SNS 0-90	0.02	-6.24	+57	54	15%	69%	36.98	15%	38%
Autumn SNS 0-90 (max 200)	0.36	0.25	-14	29	54%	31%	17.44	38%	8%
Spring SNS 0-90 (max 200)	0.23	0.01	-21	28	23%	54%	21.88	31%	15%
Spring SNS 0-90 + AAN_{90}	0.29	0.27	-7	33	23%	31%	16.86	46%	15%
Spring SNS 0-60 + AAN_{60}	0.09	-0.13	-19	28	31%	38%	22.63	46%	23%
Aut SNS 0-90 + leach adj	0.33	-0.12	-29	23	23%	62%	24.26	31%	15%
Spr SNS 0-90 + leach adj	0.29	0.02	-26	23	23%	54%	21.40	38%	15%
Aut SNS 0-90 int and slope	0.26	0.06	-20	29	15%	62%	21.19	31%	8%
Spr SNS 0-90 int and slope	0.27	0.22	-12	30	23%	31%	17.79	46%	15%
Autumn 'Best'	0.30	0.12	-21	26	8%	46%	19.81	54%	8%
Spring 'Best'	0.39	0.39	-1	35	31%	31%	14.59	54%	8%

Table 46. Comparison of approaches for SNS prediction on 58 sites with manure or grass history 2007-2010. # Negative r^2 values indicate the extent to which predictor values gave worse deviations than a constant i.e. the mean. 'Best' predictors are developed through section 3.7 and defined in section 3.7.8.

	Coefficients of determination		Accuracy and Precision				Profit foregone		
SNS prediction approach	r^2 linear regression	r^2 y=x #	Mean bias, kg/ha	Mean imprec'n, kg/ha	% within 20 kg/ha	% outside 50 kg/ha	Mean £/ha	% <£10/ha	% >£40/ha
Constant 100 kg/ha	0.00	0.00	-16	23	40%	24%	17.38	48%	10%
FAM	0.22	-0.23	-34	8	31%	31%	18.21	60%	9%
FAM incl. manure	0.13	0.08	-11	23	38%	24%	15.19	64%	10%
Autumn SNS 0-90	0.44	-0.45	+3	40	26%	36%	23.32	52%	16%
Autumn SNS 0-60	0.43	-0.11	-14	33	14%	40%	19.83	41%	12%
Spring SNS 0-90	0.48	-0.13	-33	12	22%	36%	16.46	43%	10%
Autumn SNS 0-90 (max 200)	0.37	0.16	-6	33	59%	21%	17.93	53%	9%
Spring SNS 0-90 (max 200)	0.54	0.00	-37	6	24%	36%	16.76	45%	12%
Spring SNS 0-90 + AAN$_{90}$	0.56	0.49	-11	19	34%	16%	9.95	69%	3%
Spring SNS 0-60 + AAN$_{60}$	0.51	0.45	-11	19	34%	16%	10.81	74%	3%
Aut SNS 0-90 + leach adj	0.59	-0.09	-38	8	19%	41%	18.59	41%	10%
Spr SNS 0-90 + leach adj	0.63	-0.02	-41	2	24%	40%	16.85	45%	12%
Aut SNS 0-90 int and slope	0.41	0.38	-5	28	40%	29%	12.36	62%	9%
Spr SNS 0-90 int and slope	0.53	0.44	-15	14	47%	21%	10.30	69%	9%
Autumn 'Best'	0.60	0.55	-11	17	41%	12%	8.46	71%	2%
Spring 'Best'	0.63	0.61	-8	18	40%	14%	7.53	74%	2%

Table 47. Comparison of approaches for SNS prediction on 56 sites where SMN would be recommended (with manure or grass history or after vegetables, on clay or silt soils) 2007-2010. # Negative r^2 values indicate the extent to which predictor values gave worse deviations than a constant i.e. the mean. 'Best' predictors are developed through section 3.7 and defined in section 3.7.8.

	Coefficients of determination		Accuracy and Precision				Profit foregone		
SNS prediction approach	r^2 linear regression	r^2 y=x #	Mean bias, kg/ha	Mean imprec'n, kg/ha	% within 20 kg/ha	% outside 50 kg/ha	Mean £/ha	% <£10/ha	% >£40/ha
Constant 100 kg/ha	0.00	0.00	-43	12	25%	38%	29.11	52%	23%
FAM	0.08	-0.28	-35	14	30%	38%	24.87	54%	18%
FAM incl. manure	0.17	-0.05	-26	18	32%	32%	21.35	55%	16%
Autumn SNS 0-90	0.19	-4.86	+2	50	23%	39%	27.09	46%	21%
Autumn SNS 0-60	0.24	-2.09	-5	62	18%	45%	24.74	38%	18%
Spring SNS 0-90	0.25	-1.50	-26	40	20%	46%	27.00	34%	25%
Autumn SNS 0-90 (max 200)	0.42	0.24	-17	25	54%	27%	17.79	46%	9%
Spring SNS 0-90 (max 200)	0.47	-0.16	-45	8	21%	45%	24.08	38%	21%
Spring SNS 0-90 + AAN_{90}	0.50	0.33	-22	16	30%	27%	14.94	61%	9%
Spring SNS 0-60 + AAN_{60}	0.42	0.17	-27	15	29%	32%	17.81	55%	11%
Aut SNS 0-90 + leach adj	0.45	0.07	-30	17	18%	39%	20.53	45%	11%
Spr SNS 0-90 + leach adj	0.49	-0.18	-47	6	21%	48%	24.49	38%	21%
Aut SNS 0-90 int and slope	0.41	0.29	-18	23	30%	38%	16.53	48%	9%
Spr SNS 0-90 int and slope	0.48	0.28	-26	13	38%	29%	15.70	57%	13%
Autumn 'Best'	0.44	0.39	-12	25	29%	25%	14.46	61%	7%
Spring 'Best'	0.51	0.44	-15	19	39%	29%	12.86	61%	7%

Table 48. Comparison of approaches for SNS prediction on 49 ‘normal’ arable sites 2007-2010. # Negative r^2 values indicate the extent to which predictor values provided worse deviations than a constant i.e. the mean. ‘Best’ predictors are developed through section 3.7 and defined in section 3.7.8.

	Coefficients of determination		Accuracy and Precision				Profit foregone		
SNS prediction approach	r^2 linear regression	r^2 y=x #	Mean bias, kg/ha	Mean imprec’n, kg/ha	% within 20 kg/ha	% outside 50 kg/ha	Mean £/ha	% <£10/ha	% >£40/ha
Constant 100 kg/ha	0.00	0.00	+4	28	37%	15%	12.00	40%	8%
FAM	0.16	0.15	-3	25	42%	10%	9.52	67%	6%
FAM incl. manure	0.16	0.15	-3	25	42%	10%	9.52	67%	6%
Autumn SNS 0-90	0.19	-0.13	-6	25	48%	15%	13.28	65%	10%
Autumn SNS 0-60	0.20	-0.25	-24	9	42%	19%	12.39	75%	8%
Spring SNS 0-90	0.09	-0.62	-32	5	40%	29%	15.32	63%	8%
Autumn SNS 0-90 (max 200)	0.19	-0.10	-7	24	73%	8%	12.79	65%	8%
Spring SNS 0-90 (max 200)	0.09	-0.62	-32	5	40%	29%	15.32	63%	8%
Spring SNS 0-90 + AAN_{90}	0.14	-0.01	-11	17	50%	13%	10.12	79%	6%
Spring SNS 0-60 + AAN_{60}	0.06	-0.21	-14	14	55%	14%	10.75	73%	6%
Aut SNS 0-90 + leach adj	0.17	-0.36	-21	14	35%	19%	13.73	65%	8%
Spr SNS 0-90 + leach adj	0.09	-0.71	-35	4	37%	29%	16.17	62%	8%
Aut SNS 0-90 int and slope	0.19	0.16	-2	25	50%	8%	9.21	73%	6%
Spr SNS 0-90 int and slope	0.09	-0.01	-8	21	48%	15%	10.50	75%	8%
Autumn 'Best'	0.17	0.09	+7	24	35%	12%	10.98	69%	6%
Spring 'Best'	0.19	0.17	-3	23	52%	8%	8.78	75%	6%

SNS prediction in different situations

Soil type

Tables 40, 41 and 42 show results from different SNS prediction approaches for clay and silt soils, medium soils and light and shallow soils respectively. These show soil measurement to be most advantageous (compared to FAM) on clay and silt soils and least so on light and shallow soils. Average benefits of soil measurement on medium soils (over all levels of expected SNS) were generally marginal or non-existent.

SNS Index level

Tables 43, 44 and 45 show results from SNS prediction approaches in low, medium and high expected SNS situations respectively. Benefits from soil measurement were marginal or non-existent in the low expected SNS situations, but became worthwhile where SNS expectations were high.

Situations where SMN would be expected to be worthwhile

Table 46 shows results from sites where there was a history of grass or manure use so SMN measurement might be advised as worthwhile. In these situations benefits did accrue from the knowledge gained by SMN sampling, although if FAM included estimated extra N from manure use it still financially outperformed unadjusted predictions based on sampling.

Table 47 shows results only from sites where SMN measurement was expected to be worthwhile, so where there was a history of grass or manure use, or vegetables had been grown previously, and excluding light or shallow soils. Here SNS was expected to be high and predicted SNS from soil measurement (adjusted by AAN, leaching, and / or intercepts and slopes) gave considerable returns; however, the maximum average benefit of the ‘best’ method over FAM at these sites was still only around £9/ha.

‘Normal’ arable situations

Table 47 shows the results from SNS prediction approaches for ‘normal’ arable situations, on medium, clay and silt soils where there was no history of manure or grass, so SNS levels were expected to be Index 3 or less and SOM was below 5%. In these situations, FAM gave a considerably better financial return than a fixed assuption of 100 kg/ha, but there was no apparent benefit from any prediction approach based on SMN sampling.

3.7.3. Field Assessment Method (FAM)

Using the FAM in RB209 (2010) consistently gave better predictions of harvested SNS than simply assuming 100 kg/ha across the board. Overall, the FAM predictions performed relatively well. Whilst they rarely give the highest r^2 value for the regression relationship with harvested SNS, they did generally give good r^2 values for the absolute prediction of harvested SNS. On average, the FAM predictions were about right, and on average the relationship between FAM prediction and harvested SNS was relatively close to 1:1 (i.e. the intercept was close to zero and the slope was close to 1).

It should be noted however that making the prediction of SNS using RB209 proved to be subject to interpretation, particularly with regard to classifying soil groups. Within this dataset soils had been grouped initially on the basis of soil texture, from determinations at the lab. However, these inevitably were not always consistent between autumn and spring assessments, due to soil textural analysis being somewhat subjective and due to the inherent variability in soils, metre by metre. Knowledge of the soil series was also used to inform the classification of soil group, although for several sites there proved to be differences between the RB209 soil group expected from soil series information and from soil texture, and there it should be noted that uncertainties about subsoils could affect RB209 classifications. Correct classification of soil group proved to be important in correctly predicting harvested SNS. This was especially true for organic soils; some clay and silty soils in this dataset had soil organic matter contents close to or exceeding 10%, so therefore could be classed as organic soils. However, (contrary to the case in this dataset) SOM on most fields would not normally be known, so some soils classed as organic here would not normally have been so. Conversely, there were soils for which soil series information would suggest they were organic soils, but soil analysis showed SOM to be less than 10%. Within this dataset the classification of a small number of fields as being organic or not made a large difference to how well the FAM approach predicted SNS, largely due to a few high SOM sites which give high harvested SNS.

Correctly accounting for grass and manure history in the FAM approach also proved to be important in predicting harvested SNS. Where sites had been in grass within the past three years, Table D of RB209 (p94) was used to assess whether mineralisation of grass residues would cause SNS to exceed that expected from previous crop information. Table 46 shows a small benefit in the prediction of SNS by including this grass history information.

Advice for dealing with manure history in RB209 predictions of SNS is to increase the SNS Index value by one or two levels depending on manure type, application rate and frequency of application. In Table 49 two approaches were compared; in Approach 1 the predicted SNS was increased by 20kg/ha where previous manure applications were moderate and by 40kg/ha where previous manure applications were heavy and frequent; in Approach 2 predicted SNS was only increased by 20 kg/ha where manure had been used within the past 7 years, whatever the amount or frequency of its application. In this case the simpler approach appeared to be better. A range of more complex approaches was also explored, but none outperformed this simple approach.

Table 49. Comparison of FAM (RB209) approaches of predicting harvested SNS, involving consideration of grass in the history of the fields, and two different approaches to manure use (superscripts; see text).

	Coefficients of determination		Accuracy and Precision		Profit foregone	
SNS Prediction approach	r^2 linear regression	r^2 y=x	Mean bias (kg/ha)	% outside 50 kg/ha	Average £/ha	% >£40 /ha
Constant 100 kg/ha	0.00	0.00	-6	20%	16.61	10%
FAM excluding grass	0.24	0.11	-18	21%	13.77	8%
FAM incl grass	0.27	0.14	-17	20%	13.27	7%
FAM incl manure[1]	0.31	0.26	-10	18%	12.20	8%
FAM incl manure[2]	0.34	0.26	-11	16%	11.90	7%

3.7.4. Predictions based on SMN measurement

Whilst SNS predictions based on SMN measurement frequently gave better r^2 values for the regression relationship with harvested SNS than FAM predictions, the r^2 for the absolute prediction (without fitting) of harvested SNS was often worse. This shows that whilst SMN measurement provided good precision, SMN results themselves (without consideration of mineralisation or recovery) included some consistent bias. This is shown by both the overall means (average harvested SNS is 106 kg/ha compared to 116 kg/ha for autumn measured SNS and 81 kg/ha for spring measured SNS) and in the linear relationship with harvested SNS, where the intercept was large (76 and 72 kg/ha for autumn and spring respectively) and the slope was small (0.26 and 0.42 for autumn and spring respectively). It was concluded that an upper limit on the prediction of ~200 kg/ha was required to avoid the largest errors, as discussed above. Including this constraint substantially improved the r^2 values for absolute prediction of harvested SNS, reduced the intercepts (41 and 45 kg/ha for autumn and spring respectively) and increased the slopes (0.65 and 0.82 respectively) of the relationship with harvested SNS. The average constrained prediction for both autumn and spring SNS (100 and 74 kg/ha respectively) fell below the mean harvested SNS (106 kg/ha). Autumn SNS gave a better r^2 for the y=x relationship and a marginally better profitability than spring SNS because it was closer on average to harvested SNS. Spring SNS predictions were improved dramatically by inclusion of an additional factor to account for this shortfall, either a constant (intercept) or the AAN measure. Both spring and autumn SNS predictions were also improved further by adjusting for slope. These adjustments were informed by average intercepts and slopes of relationships in past datasets (intercept 40 kg/ha slope 0.6

and 0.9 for autumn and spring respectively) so their use could be seen as independent of the current dataset. Such intercept and slope adjustments are not however currently used by the industry; the case for their adoption will be discussed later in the report.

Best sampling time – Autumn vs spring

Tables 39 to 44 show that spring measurement based predictions generally explained more of the variation in harvested SNS than autumn predictions, but only gave better absolute predictions of harvested SNS (higher r^2 from y=x) if appropriate adjustments (see above) were made. Despite this, spring sampling often gave similar or better profitability than autumn sampling, because spring sampling tended to under-estimate harvested SNS whereas autumn sampling more often over-estimated harvested SNS; we saw in section 3.7.1 that over-estimating SNS was more costly than under-estimating it. For this reason, autumn sampling to 60 cm gave smaller foregone profits than sampling to 90 cm, because incidences of over-estimating harvested SNS were reduced.

Best sampling depth

SNS predictions based on different sampling depths (each restricted to a max SNS of 200 kg/ha) are shown in Table 50. In autumn, the difference in prediction between 0-90 cm and 0-60 cm was marginal. Even using 0-30 cm explained a similar proportion of the variation in harvested SNS to using deeper depths, though, without adjustment, the absolute predictions were obviously more biased. A simple adjustment, assuming full depth SNS was 2x 0-30 cm SNS seemed to give a reasonable estimate of harvested SNS, though financially this was £2/ha worse than using a 0-60 cm estimate.

In spring there was a larger fall-off in predictive performance from reducing sampling depth from 90 cm to 60 or 30 cm, and consequently there were much larger financial costs. Despite this, use of the GrowHow N-Min calibrated method (which uses 0-30 cm sampling and regionally calibrated adjustments to account for SMN below sampling depth, plus a measure of AAN) performed relatively well.

Table 50. Comparison of SNS prediction approaches derived from SMN to different sampling depths (all constrained to a maximum of 200 kg/ha). For ‘SNS 0-30 adj’ see text.

Prediction approach	Coefficients of determination		Accuracy and Precision		Profit foregone	
	r^2 linear regression	r^2 y=x	Mean bias kg/ha	% outside 50 kg/ha	Average £/ha	% >£40 /ha
Autumn SNS 0-90	0.39	0.26	-6	15%	14.65	7%
Autumn SNS 0-60	0.41	0.16	-20	27%	14.74	9%
Autumn SNS 0-30	0.40	-0.67	-53	43%	25.43	22%
Autumn SNS 0-30 adj	0.36	0.11	-15	27%	16.73	11%
Spring SNS 0-90	0.49	0.08	-32	30%	14.93	9%
Spring SNS 0-60	0.39	-0.45	-46	40%	22.21	20%
Spring SNS 0-30	0.15	-1.71	-70	60%	38.03	30%

3.7.5. Mineralisation adjustments

A range of approaches is possible to account for mineralised soil N and hence to improve the performance of SNS predictions. Results of some approaches are shown in Table 51. Including AAN in estimates of SNS improved the prediction of harvested SNS for spring-measured SMN, but not for autumn.

Table 51. Comparison of different approaches for estimating mineralisation to improve prediction of harvested SNS.

Prediction approach	Coefficients of determination		Accuracy and Precision		Profit foregone	
	r^2 linear regression	r^2 y=x	Mean bias kg/ha	% outside 50 kg/ha	Average £/ha	% >£40/ha
FAM incl manure[2]	0.34	0.26	-11	16%	11.90	7%
Autumn SNS						
0-90	0.39	0.26	-6	15%	14.65	7%
0-90 + AAN_{90}	0.37	0.21	+14	27%	18.33	7%
+ min totalN	0.39	0.27	-5	25%	14.63	7%
+ min SOM%	0.40	0.27	-4	26%	14.60	7%
+ min manure N	0.39	0.28	0	24%	15.20	9%
+ min prev crop	0.39	0.29	-1	20%	14.92	8%
0-60	0.41	0.16	-20	27%	14.74	9%
0-60 + AAN_{60}	0.38	0.25	+11	26%	16.82	13%
0-60 + min total N	0.41	0.16	-19	27%	14.85	9%
0-60 + min SOM%	0.41	0.18	-18	27%	14.53	9%
Spring SNS						
0-90	0.49	0.08	-32	30%	14.93	9%
0-90 + AAN_{90}	0.52	0.47	-9	14%	9.61	4%
0-60	0.39	-0.45	-46	40%	22.21	20%
0-60 + AAN_{60}	0.44	0.38	-10	16%	11.07	5%
0-90 + min total N%	0.50	0.11	-30	29%	14.61	9%
0-90 + min SOM%	0.50	0.14	-29	28%	14.15	9%
0-90 + min manure N	0.45	0.15	-26	27%	14.20	10%
0-90 + min prev crop	0.50	0.19	-27	27%	13.30	6%
0-90 + 20kg/ha standard	0.49	0.42	-13	17%	10.22	7%
0-90 + 20kg + min SOM	0.48	0.43	-10	16%	10.19	7%

Total N% of soil can give an indication of likely mineralisation; for example, soils with total N% greater than ~0.25 may be expected to provide some extra N through mineralisation of organic matter, perhaps at a rate of around 1.5 kg/ha for each 0.01% increase in total N%. Similarly, SOM% can indicate likely mineralisation, with perhaps, soils with SOM% greater than around 4% likely to provide some extra N through mineralisation, perhaps at a rate of around 10 kg/ha for each 1% increase in SOM%. Careful calibration could improve the parameters here, but these were used as a starting point to calculate SNS predictions using additional mineralisation estimates for results in Table 51. Improvements to prediction of harvested SNS were apparent for mineralisation estimates from both total N% and SOM% in spring measured SNS, but not to the same degree as with using AAN. In autumn, any benefits of using total N% or SOM% seemed too small to be worthwhile. Adding a standard estimate of 20 kg/ha for deposition/mineralisation to all spring soil measures improved prediction of harvested SNS and gave a lower profit foregone. Combining this with the SOM based mineralisation adjustment above gave a very slight further improvement. Such an overall adjustment would not improve performance for autumn measures as these are already close to underpredicting harvested SNS. It is possible that this 20 kg/ha is a reflection of cold winters in the years of the project, giving reduced mineralisation over winter and lower spring SNS estimates. It is not certain that such an adjustment would be appropriate following warm dry winters where mineralisation over winter would be greater and spring SNS estimates higher. It is not certain whether such differences in mineralisation over winter simply delay mineralisation until later in the spring, so that harvested SNS is unaffected, or whether total mineralisation is reduced and harvested SNS would be lower.

The multiple linear regression analyses in section 3.5 (e.g. Table 33) showed that inclusion of both previous cropping and manure history could improve predictions of harvested SNS. We might therefore be able to include this information in the form of additional mineralisation estimates to improve SNS predictions. Using results from the multiple regression analysis we could assume that SNS after OSR is 10 kg/ha greater than the SNS measure, after pulses is 20 kg/ha greater and after field veg is ~30 kg/ha greater. Adding these values to SNS predictions in autumn or spring gave a marginal increase in variation explained, but seemingly not sufficient to be worthwhile (Table 51). Similarly, adding 20 kg/ha where the site had a known history of manure did not substantially improve predictions, neither did knowledge of grass history (data not shown).

It can be seen from Table 51 that, whilst mineralisation estimates improved predictions of harvested SNS based on spring SMN measures, it did not for autumn measures. This may have arisen because autumn SMN measures were already influenced by mineralisation potential over the autumn period, whereas spring SMN measurements, following the cold winter, were less influenced by the mineralisation potential of the soil.

3.7.6. Leaching adjustments

Multiple regression analyses (section 3.5) revealed soil type to be an important factor in explaining variation in harvested SNS. The reason for this may be different amounts of N lost following soil sampling in autumn or spring for different soil types in different regions. Table 52 shows results of including ‘N retention’ estimates in SNS predictions, based on soil group and rainfall area, as described in section 3.5. These adjustments did improve the variation explained, but predictions could also be made worse. This suggests that the adjustments are affecting the slope and intercept of the relationship with SNS, so that the adjustments need refinement to prove useful, probably requiring slope or intercept corrections. The exception to this was where leaching adjusted spring SNS 0-90 was combined with AAN; here the relationship with and prediction of harvested SNS were improved considerably.

Table 52. Comparison of SNS prediction approaches with different leaching adjustments. Shaded rows are taken from previous tables, for comparison.

	Coefficients of determination		Accuracy and Precision		Profit foregone	
Prediction approach	r^2 linear regression	r^2 y=x	Mean bias kg/ha	% outside 50 kg/ha	Average £/ha	% >£40/ ha
Autumn SNS						
0-90	0.39	0.26	-6	15%	14.65	7%
0-60	0.41	0.16	-20	27%	14.74	9%
0-90 leach adj generic rainfall	0.47	0.13	-24	27%	15.22	9%
0-90 leach adj in-year rainfall	0.49	0.06	-30	32%	15.75	8%
0-90 + min SOM% + leach adj	0.48	0.00	-24	30%	17.02	11%
Spring SNS						
0-90	0.49	0.08	-32	30%	14.93	9%
0-90 leach adj generic rainfall	0.53	-0.07	-39	35%	17.13	12%
0-90 leach adj in-year rainfall	0.54	0.04	-36	32%	15.49	9%
0-90 + AAN_{90} + leach adj	0.56	0.48	-13	13%	8.99	4%

3.7.7. Adjustments for bulk density and stoniness

As discussed in section 3.5, SNS can be calculated from SMN analyses using either a standard bulk density figure of 1.33 kg/l, or different bulk density estimates for different soil types and depths. Table 53 shows the effects on SNS prediction of using these different bulk density approaches. It seems that adjustment for soil types and depths had little effect on prediction performance; possibly, performance in autumn worsened compared to use of standard 1.33 values, and possibly in spring there may have been small benefits. However, it is likely that these effects occurred by chance.

Table 53. Comparison of SNS prediction approaches with different bulk density assumptions. Shaded rows are taken from previous tables, for comparison.

Prediction approach	Coefficients of determination		Accuracy and Precision		Profit foregone	
	r^2 linear regression	r^2 y=x	Mean bias kg/ha	% outside 50 kg/ha	Average £/ha	% >£40/ha
Autumn SNS						
0-90	0.39	0.26	-6	15%	14.65	7%
0-60	0.41	0.16	-20	27%	14.74	9%
0-90 HCFR BD	0.37	0.24	-2	28%	16.03	9%
0-60 HCFR BD	0.39	0.15	-18	27%	15.40	11%
Spring SNS						
0-90	0.49	0.08	-32	30%	14.93	9%
0-90 + AAN_{90}	0.52	0.47	-9	14%	9.61	4%
0-90 + AAN_{90} leach adj	0.56	0.48	-13	13%	8.99	4%
0-90 HCFR BD	0.50	0.17	-27	24%	13.78	10%
0-90 + AAN_{90} HCFR BD	0.52	0.48	-6	15%	9.77	4%
0-90 + AAN_{90} leach adj HCFR BD	0.56	0.51	-10	13%	8.63	3%

Attempts to adjust SNS values for stone content in this dataset led to worse rather than better predictions of harvested SNS (data not shown). Adjusting for stone content is worthy of further exploration, but is complicated by the difficulties in assessing stone content accurately whether by weight or by volume. Different behaviour of porous and non-porous stones may also need to be considered. As soils with high stone content often also tend to be shallow, and definition of soil depth is uncertain, soil sampling is always likely to perform poorly in predicting SNS on stony sites.

3.7.8. Slope and intercept adjustments for N recovery and deposition

The differences between r^2 values for the linear regression relationship with harvested SNS and for the direct prediction of harvested SNS (y=x) justify inclusion of intercept and/or slope adjustments for many of the SNS predictors examined here. This is not surprising; there are grounds to expect this. We know that 35-40 kg/ha N is deposited from the atmosphere each year (Goulding, 1990), in addition to that mineralised after SMN sampling occurs; even if measured SNS was zero we would still expect some N to become available through the season and be taken into the crop. Knight et al. (2008) proposed that ‘efficiency’ (or recovery) of measured soil N might be considered to differ from 100%; they did not consider an intercept, so their ‘efficiency’ term decreased as SMN increased. Here we take an intercept to indicate or predict likely deposition, and a slope to indicate or predict mineralisation plus recovery of SMN by the crop. Mineralisation is likely to be related to measured SMN because, except where leaching is large and variable, mineralisation before SMN measurement is what mainly governs variation in SMN, and mineralisation after SMN measurement will almost certainly be related to this also.

Table 54. Effect of adjusting SNS predictions with intercepts and slopes (determined as described in section 3.7.1) for the whole dataset (164 sites). All predictions are constrained to 200kg N/ha. Shaded rows are taken from previous tables, for comparison.

Prediction approach	Adjustments		Coefficient of determination		Mean bias kg/ha	Profit foregone £/ha
	intercept	slope	r^2 linear regr'n	r^2 y=x		
Constant 100 kg/ha	0	1	0.00	0.00	-6	16.61
FAM	0	1	0.31	0.26	-10	12.20
Autumn SNS (SMN and crop N)						
0-90	0	1	0.39	0.26	-6	14.65
0-60	0	1	0.41	0.16	-20	14.74
0-90 + leach adj	0	1	0.49	0.06	-30	15.75
0-60	20	1	0.39	0.33	-1	13.58
0-60	40	0.7	0.41	0.40	-6	11.05
0-90	40	0.6	0.42	0.41	-3	11.13
0-90 + leach adj	40	0.8	0.49	0.47	-5	10.06
Spring SNS (SMN and crop N)						
0-60	0	1	0.39	-0.45	-46	22.21
0-90	0	1	0.50	0.17	-27	13.78
0-90 + AAN_{90}	0	1	0.52	0.48	-6	9.77
0-90 + AAN_{90} +leach adj	0	1	0.56	0.51	-10	8.63
0-60 + AAN_{60}	0	1	0.44	0.38	-10	11.07
0-60	40	1	0.41	0.39	-8	10.87
0-90	30	1	0.49	0.48	-3	9.85
0-90	40	0.85	0.49	0.49	-3	9.50
0-90 + AAN_{90}	20	0.85	0.52	0.51	-3	9.05
0-90 + AAN_{90} + lch adj	20	0.85	0.57	0.57	-3	8.01

Appropriate slopes and intercepts were added to the most promising SNS predictions in Table 54. Results show that such adjustments make a substantial difference to the prediction and the profit foregone, especially for autumn sampling. In spring, the slope of the direct relationship was closer to unity, but the negative bias was greater, especially for 0-60 SMN. Thus any adjustment (AAN, 60-90 cm SMN, or an intercept) that increased predicted SNS decreased bias and therefore increased profit. It is possible that SNS predictions could be improved by using different slope and intercept adjustments for different soil types and situations, but this was not explored further here.

The various predictions in Table 54 represent the best that measurement-based prediction approaches can be expected to achieve, assuming that appropriate values for slopes and intercepts can be set in advance. Many different values were tested of just intercepts (with slope still 1) or intercepts plus slopes (different to 1) to find any improvements in predictive performance. No improvements were found by altering slope alone. Intercepts provided some improvement, but not quite as much as with a slope also. The best approaches found were the final rows for autumn and spring SNS in Table 54. These involved adjustments for leaching and (in spring) incorporation of AAN as well as intercepts and slopes, and these are the approaches labelled as 'Best' in Tables 39 to 48. For the dataset as a whole therefore, the maximum average saving possible (over all sites) from using autumn SNS sampling over using FAM was just £2/ha, before any sampling and analysis costs were accounted for. For spring sampling, savings reached £4/ha on average. For sites where SMN was expected to be helpful (Table 47) these benefits were on average ~£7/ha and ~£8/ha respectively.

3.7.9. Barometer fields and estimating seasonal variation

Rather than using SMN testing for single field decisions, growers often use SMN testing on a few fields each year to gauge differences in SNS through the rotation and from year to year. Given that the value of SNS testing on 'normal' arable fields is small, and that SMN testing is relatively expensive, it makes sense that any information gained from SNS measurement should be used over as wide an area as possible. No existing datasets are really suitable for testing the value of barometer fields properly, as measures of SMN and harvested SNS would be needed in each of the fields that the barometer was to represent. However, data on spatial variation in SMN have been analysed and modelled (Marchant, personal communication; see section 3.4.1 and Annex 6) to show that optimal core numbers vary between 5 and 20, and that 15 cores is a reasonable compromise for most field situations. This work also showed that the economic benefits of SMN testing appeared to maximise at high (175 kg/ha) but not very high levels of expected SNS.

The Marchant study (Annex 6) also showed the extra return from SMN sampling, using a 10 ha barometer field, was almost as large as when a larger area was sampled (60 ha). In the more practical multi-field context, it must be logical that the value of a barometer field approach will maximise where there are many similar fields and where these fields are relatively uniform. One difficulty is that rotational effects on any single field are confounded with seasonal effects. Hence rotational effects are best monitored using several fields in each season, or if conclusions are only drawn from paired fields after several seasons.

Although using barometer fields may seem valuable, it is possible that this approach will sometimes worsen SNS predictions. For example, if barometer measurements follow a cold winter, spring SMN may be generally low due to reduced mineralisation in early spring, even after average over-winter rainfall; as has been seen in these circumstances, mineralisation may simply be delayed rather than reduced, so spring measurements may give an unrealistic under-estimate of harvested SNS.

The value of SMN measures in quantifying seasonal differences may be greater in other years however, for example, on heavy soils after a very wet winter, or after a low yielding year when fertiliser was applied in a dry spring, such as in 2011. Knowledge of seasonal effects will also have increased importance when grain and fertiliser prices are high.

3.7.10. Conclusions on cost-effective SNS prediction

- The FAM performed better than a fixed prediction of SNS, even on normal arable sites (Table 48).
- Average financial benefits of soil measurement-based predictions over FAM were small, and sometimes soil measurement predictions could be less profitable than FAM, even before sampling costs are accounted for.
- Worthwhile benefits from soil measurement were only evident in situations where SNS was expected to be high, for example at sites with a history of grass or manure use, or after vegetables, and on clay and silt soils.
- On light and shallow soils and in situations where SNS was expected to be low, FAM gave better predictions of SNS than soil measurement, even without accounting for sampling costs.
- Correct classification of soil type and manure history was important in getting best SNS predictions from the FAM.
- Harvested SNS rarely exceeds 200 kg/ha, so in judging prediction systems SNS estimates above 200 kg/ha are best treated as predictions of 200kg/ha and no more.
- Spring measures of SNS generally gave better predictions of harvested SNS than autumn measures, although differences were often not large, and on clay and silty soils autumn SMN performed as well as spring.
- If using autumn SNS measurements, sampling to 60 cm was as effective as sampling to 0-90 cm, but slope and intercept adjustments were required to avoid bias. Adjustment for over-winter leaching proved to be worth considering, but there was little benefit in including any measure of potential mineralisation in autumn.
- If using spring SNS measurements there was benefit in sampling to 90 cm, slope and intercept adjustments appeared worthwhile if measurements of mineralisation were

not made. Mineralisation measures gave worthwhile improvements in the SNS prediction, the best of which was AAN. Use of total soil N% or SOM% in improving SNS estimates showed potential, but further calibrations would be required to enable their adoption.

- Whether a standard bulk density of 1.33 kg/l was used, or specific bulk density values according to soil texture and depth, made little difference to the performance of SNS predictions.
- No convincing evidence was found to show that adjustments for stone content were worthwhile.
- Inclusion of a crop N estimate within the estimate of SNS proved important to achieve accurate predictions of SNS; the method used to estimate crop N had little impact on the performance of SNS predictions.
- Mineralisation
- Slope and intercept etc

3.8. Using SMN when growing cereals after vegetable or pulse crops

3.8.1. Implications for vegetable growers

Of the 12 sites tested following vegetables 10 were on deep silty soils in Lincolnshire, where the vegetable residues were incorporated in the autumn, before the establishment of the cereal crop.

Relationships between measured SNS and harvested SNS were relatively strong, both for autumn and spring measures (Figure 58). If the data were restricted to silt soils only, r^2 increased to 0.93 and 0.79 for autumn and spring measures respectively. The benefit of SMN sampling predictions over RB209 exceeded £15/ha in these cases.

Table 55 provides a comparison of the various approaches to SNS prediction for the sites after vegetables. Clearly all these approaches had a negative bias which was considerable in some cases; this needs to be taken into account when predictors are compared. Nevertheless, referring to Figure 39, improving a negative bias from -40 to -20 kg/ha SNS only improved foregone profit by ~£6/ha, so most of the £20/ha advantage of the ‘best’ SMN predictor over FAM can be attributed to improved precision rather than reduced bias.

On the basis of this evidence it therefore appears that SMN sampling can improve prediction of SNS after vegetable crops on retentive soils.

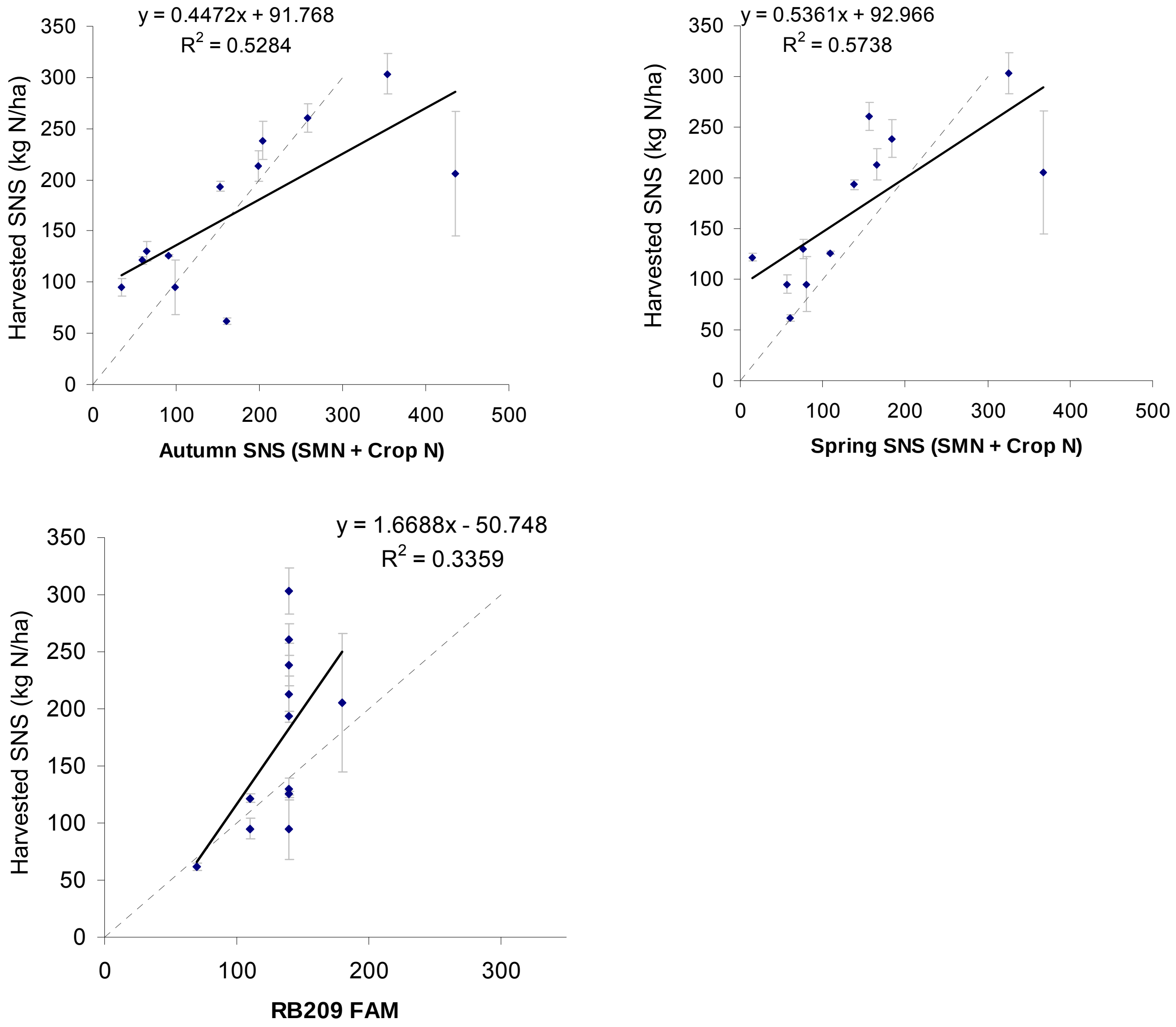


Figure 58. Linear regression for FAM and SMN-based predictions of harvested SNS for cereal crops following vegetable crops in 2008-2010. The dotted line shows y=x.

Table 55. Comparison of approaches for SNS prediction on 12 sites with field vegetables 2008-2010. # Negative r^2 values indicate the extent to which predictor values gave worse deviations than a constant i.e. the mean. 'Best' predictors are developed through section 3.7 and defined in section 3.7.8.

	Coefficients of determination		SNS errors kg/ha				Profit foregone		
SNS prediction approach	r^2 linear regression	r^2 y=x #	Mean bias	Mean imprecision	% within 20 kg/ha	% outside 50kg/ha	Mean £/ha	% <£10/ha	% >£40/ha
Constant 100 kg/ha	0.00	0.00	-70	8	17%	50%	52.05	58%	50%
FAM	0.36	-0.05	-43	14	42%	50%	30.83	42%	25%
FAM incl. manure	0.38	-0.01	-40	15	42%	42%	29.68	42%	25%
Autumn SNS 0-90	0.53	-0.28	-10	33	33%	42%	20.67	42%	8%
Autumn SNS 0-60	0.64	0.25	-25	29	17%	42%	22.23	17%	8%
Spring SNS 0-90	0.57	0.02	-26	31	25%	50%	20.91	25%	17%
Autumn SNS 0-90 (max 200)	0.56	0.36	-32	17	42%	50%	24.81	33%	17%
Spring SNS 0-90 (max 200)	0.75	0.27	-50	0	33%	50%	23.02	33%	25%
Spring SNS 0-90 + AAN_{90}	0.75	0.57	-30	6	33%	25%	14.00	58%	17%
Spring SNS 0-60 + AAN_{60}	0.56	0.28	-38	7	42%	33%	21.93	50%	25%
Autumn SNS (leach adj)	0.83	0.35	-50	1	25%	58%	21.39	25%	8%
Spring SNS (leach adj)	0.76	0.26	-51	0	25%	50%	23.29	33%	25%
Autumn SNS 0-90 int and slope	0.65	0.37	-38	13	17%	58%	22.52	33%	17%
Spring SNS 0-90 int and slope	0.75	0.54	-30	8	33%	25%	15.00	67%	17%
Autumn 'Best'	0.83	0.58	-34	4	25%	25%	13.74	58%	8%
Spring 'Best'	0.78	0.67	-19	11	42%	25%	10.86	67%	8%

3.8.2. Implications for crops following peas and beans

A total of 20 sites followed beans and 15 site followed peas, with 20 of these sites in 2010 provided by PGRO. Relationships of harvested SNS to SMN-based SNS estimates after peas and beans reflected the relationships seen for sites in general. However, spring sampling often substantially underpredicted harvested SNS following beans (Figure 59), and to a lesser extent peas (Figure 60). It is unclear how much of this result is a seasonal effect, with the cold winter in 2009 delaying mineralisation of crop residues.

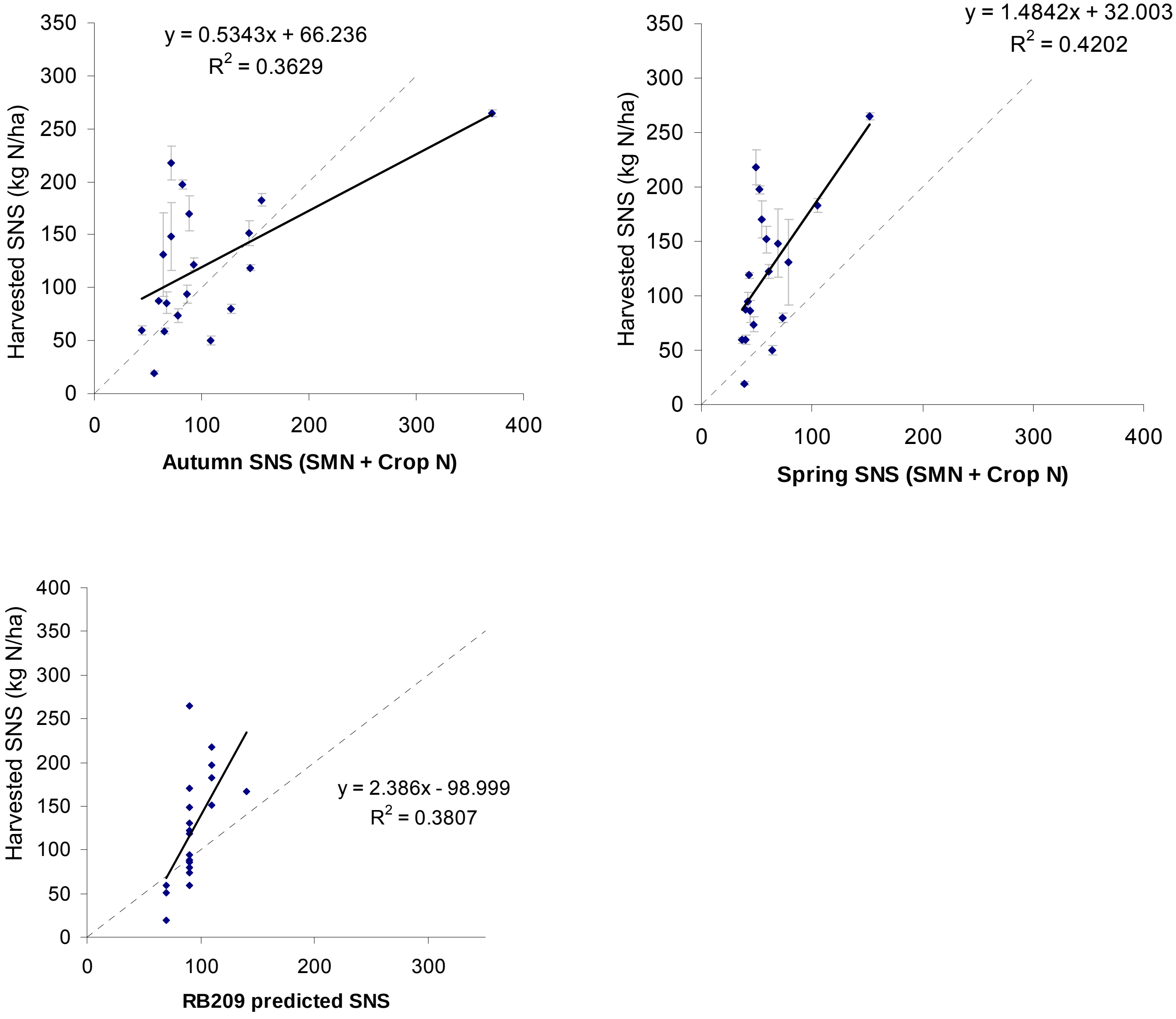


Figure 59. Predictions of harvested SNS for cereal crops following beans.

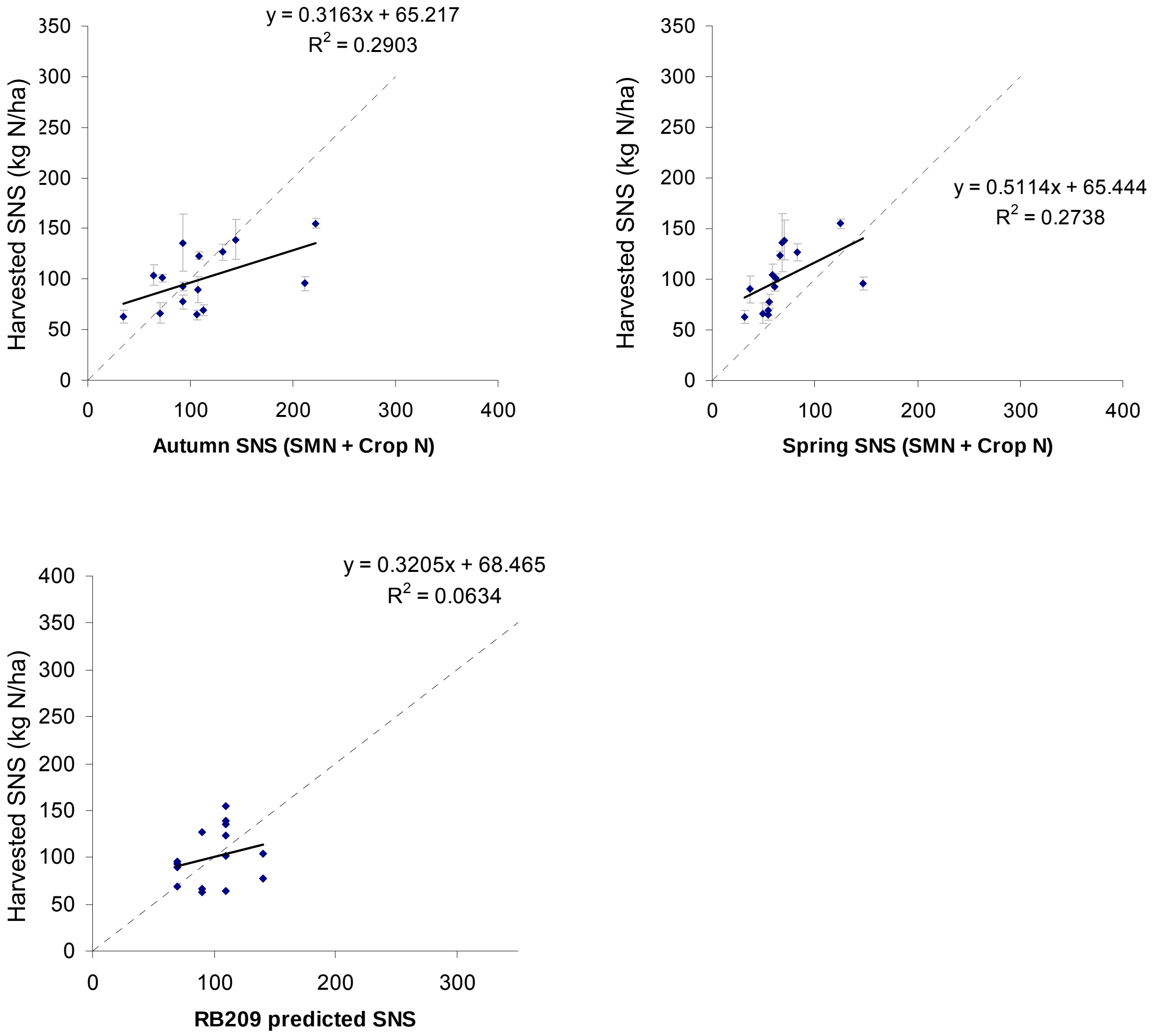


Figure 60. Predictions of harvested SNS for cereal crops following peas

If these results are representative of 'normal' years, it may imply that N residues are greater following beans than would be suggested by spring SMN measures, and perhaps from RB209 or SAC-TN625. However, the number of sites here was quite limited. It has been reported previously (Sylvester-Bradley & Cross, 1991) that N residues from beans appear to be mineralised more slowly than those from peas.

In 2011 PGRO have undertaken further measurements of paired sites following peas or beans, compared with adjacent fields, in order to test these findings. It will be useful to combine these with previous data before drawing firm conclusions about SNS prediction methods following grain legumes.

3.9. Discussion

Estimating SNS is important as it is crucial part of N fertiliser decision making. The most meaningful ultimate measure of SNS we have is harvested SNS; the N that gets into an unfertilised crop by harvest. Harvested SNS explains around 60% of the variation in N requirement, whereas the other components (crop N demand and fertiliser recovery) are less predictable and have weaker relationships (partly because they are correlated positively).

3.9.1. Relationships between measured SNS and harvested SNS

This project has explored in detail the relationships between various assessments of SNS, whether FAM or soil measurement based, with final harvested SNS of an unfertilised crop. In general these relationships are weak, the best estimates only explaining around 40-57% of variation in harvested SNS. This appears worse than was seen in more restricted previous studies (e.g. Sylvester-Bradley et al., 2008) but it appears to support others which found little relationship between measured SNS and N optima (e.g. Orson, 2010). The relationship between ‘predicted’ SNS and harvested SNS was strongest on silt and clay soils where the spread in expected SNS values was large. It was weakest on light and shallow soils and where the spread in expected SNS values was small.

It is likely that weaker relationships seen in this study arose through the extent of conditions and methods included. Past data were collated from extensive studies where operations were not necessarily standardised, the quality of data could not always be ascertained, and methods may have differed. Similarly, the new data were intentionally collected from widely different sites. However, the data were explored thoroughly and although there was more uncertainty, the strength of the relationship was fairly consistent no matter what subsets were left in or out.

In generating the new data, it should be noted that quadrat samples were used to measure harvest yield and N uptake from a single plot, whereas in previous datasets yield was measured by plot combine harvester, usually from a minimum of three replicated plots, and crop N uptake was derived from this. Whilst every effort was made to ensure that the quadrat measures made in this project were as representative, accurate and precise as possible, they cannot be expected to be as accurate or precise as measures based on replicated plot combine yields.

In relation to precision, SMN and harvest measures in this project were made on, as near as possible, exactly the same piece of ground. In other datasets SMN and harvest measures will have been made across a larger experimental area, so if there was any small scale spatial variation the relationship between measured SNS and harvested SNS may be expected to be less good.

In relation to accuracy, it should be noted that quadrat sampling tends to over-estimate yields in relation to plot combine harvesters (Bloom 1985). There may therefore be some bias in the average harvested SNS measured in this project, with comparable combine harvested SNS measures perhaps being ~10% less.

Thus, some caution is needed in drawing conclusions from the newly generated dataset. However, there is no evident difference in the accuracy or precision of the relationships, whether they are based on past or new data (e.g. compare Figure 29 with Figure 42). Hence sampling methodology cannot be the sole cause of the generally weak predictions. Indeed, if the data are restricted to very retentive silt soils following vegetables, the relationship between measured SNS and harvested SNS explained close to 90% of the variation, indicating that quadrat measurements used in this project can be both accurate and precise.

The weak relationship between measured SNS, whether measured in autumn or spring, and harvested SNS on light and shallow soils can be explained by the ‘leaky’ nature of these soils. Not only does the loss of N through leaching contribute to variability in harvested SNS, but also it means that these soils rarely, if ever, achieve very high levels of harvested SNS. Because we have not seen harvested SNS greater than ~150 kg/ha on these soils, the relationship with measured SNS is bound to be weak because the stretch of variation is small compared to the inherent errors and variability. Some caution is required here however due to the small number of light and shallow soil sites examined (22; Table 42); it is possible that situations do exist on these soil types where harvested SNS would be higher, so relationships with SMN measures would be stronger, but we have little evidence of this from past or current datasets.

Perhaps more perplexing is the relatively weak relationship for all SNS determinations seen for medium soils, which constitute an important share of arable soils generally (perhaps 40%), and which were represented by 70 sites in the new dataset (Table 41). It seems likely that much of this variability is real, and that the various attempts to account for variability in leaching, mineralisation, etc. were inadequate on this more variable soil group.

The relationships between predicted SNS and harvested SNS were undoubtedly affected by errors in sampling, handling, storage and analysis. Past data and new studies in this project showed that inherent spatial variability in soils, and hence within samples, puts the minimum possible confidence limit in measured SMN at around 20%. Sampling studies have shown that serious inconsistencies in storage duration and / or temperature could also add a bias of 50 kg/ha SNS or more. Differences between labs in analysis are not now much greater than differences within labs, but greater differences between labs may have occurred in the past; the repeatability of lab analysis cannot easily be separated from the variability between the samples tested. Indications from standardisation studies are to expect a minimum confidence limit in SMN measures of around 20%.

Further uncertainty arises from issues of interpretation: crop N in spring can only be estimated to within 5-10 kg/ha, actual bulk density of a soil may differ considerably from that assumed, stoniness of the soil can lead to over-estimates of SNS if no adjustments are made, and can cause under-estimates of SNS if inaccurate adjustments are made.

So there is plenty of cause for uncertainty in the relationship between predicted SNS and harvested SNS even before considering the different dynamic processes that change SNS on a temporal and spatial basis. Some of these uncertainties can be addressed by adopting best practice: effective sampling methods, minimising storage duration, keeping samples cool, effective sub-sampling and standardised lab analysis. There will however always be unavoidable variation and uncertainty in measured SMN due to spatial and temporal variability. This variability may be greater on light, shallow and medium soils where N losses by leaching may be substantial and where the relative contribution to final harvested SNS from mineralisable N may be greater. SNS predictions in these situations therefore appear less reliable than where N is largely retained in the soil, in clay and silt soils in low rainfall areas. It is possible that mineralisation measures would give better predictions of harvested SNS on light and shallow soils than measured SMN *per se.* However, the small range in harvested SNS in the datasets examined here, and the relatively small number of sites tested light and shallow soils, makes testing such conclusions difficult.

Certainly the datasets explored in this project confirm that SMN sampling is most worthwhile with silt or clay soils, in low rainfall areas, where SNS is expected to be large or uncertain, for example in sites after vegetables, or with a history of grass or manure. This finding is not new; it forms the basis for recommendations in both RB209 and the HGCA nitrogen for winter wheat management guidelines.

The HGCA guidelines also state that sampling is seldom worthwhile in low SNS situations. What is perhaps surprising is the finding that adjusting N decision making on the basis of soil sampling in such low SNS situations can actually lead to a worse average financial performance, even before the costs of SMN sampling and analysis are taken into account. This is because SMN sampling can sometimes give incorrect high SNS predictions which, if followed in N decision making, would lead to crops being significantly under-fertilised, hence sub-optimal yields being achieved, giving a large profit foregone. There is much less scope for large over-prediction of SNS using FAM, because the range of possible SNS estimates is effectively constrained to a minimum of ~50 kg/ha (RB209 has Index 1 as “<60 kg/ha”) and a maximum of 140 kg/ha for most situations (RB209 has

Index 4 as “121-160”)[1]. This points to the importance, if high SNS values are observed, of monitoring the crop through spring and reacting if the crop begins to look N-stressed.

3.9.2. Adjustments for prediction of harvested SNS

It seems that, for measured SNS to predict harvested SNS accurately, adjustments may be required for slope (recovery and mineralisation) and intercept (deposition). After thorough analysis of both past and new datasets here, it appears that the values of the best slopes and intercepts (to bring average bias between -20 and zero kg/ha SNS, and to minimise profit foregone; Table 54) were fairly consistent between datasets. Previous work has questioned the 100% equivalence for SNS used in fertiliser recommendation systems (Knight 2006; Knight et al. 2008; Orson, 2010) and has suggested that adjustments should be made for N recovery. Such adjustments have not featured in recommendations before, as it has previously been considered that additional N supplied through deposition and mineralisation after SMN sampling tends to offset the fact that not all the actual SMN measured will be taken up by the crop. For the sake of simplicity a recovery of SMN plus crop N of 100% has therefore been assumed, and contributions from deposition in recommendation systems have been implicitly ignored until recently. (Deposition of 20 kg/ha N is accounted for in the HGCA nitrogen for winter wheat management guidelines.) The findings in this study suggest however that accounting for deposition and recovery separately would give more accurate assessments of harvested SNS. Whilst this would make little or no difference to the predictions made at the average SNS (~100 kg/ha), it would alter predictions at the extremes. It would give a lower limit to SNS prediction of around 50 kg/ha, no matter how small was measured SNS. It would also tend to reduce predictions where measured SNS is high; it would be assumed that only 60-90% of SNS at high levels is recovered; for instance a measured SNS of 200 kg/ha with a 60% recovery would give an SNS prediction of 120 + 40 = 160 kg/ha, including the intercept adjustment. Predictions would be unchanged with SNS measures of 100 kg/ha (100 * 60% = 60, + 40 = 100), would be slightly higher with SNS measures of 80 kg/ha (80 * 60% = 48, + 40 = 88), and would be slightly lower with SNS measures of 120 kg/ha (120 * 60% = 72, +40 = 112). Given the size of the variability encountered in SNS prediction and N decision making generally, these adjustments are relatively small, and their value may be questioned in relation to the added complexity introduced. Nevertheless, even for SMN measurements within the range 60-100 kg N/ha, the difference between an assumption of 100% recovery and an assumption of 70% recovery plus intercept could make a difference of 30 kg N/ha in the amount of fertiliser N considered to be optimal. It is possible that different intercepts and recoveries may be required for different situations and prediction approaches (e.g. autumn vs spring sampling; Table 54). Using

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[1] Note that in RB209 previous crop and rainfall information only affects the SNS Index up to Index 4. Index 5 and Index 6 relate to organic soils only (or fields immediately after ploughing up high N leys, >3 years old, or for high N veg with incorporated residues in low rainfall areas).

different intercepts and recoveries can have large implications on the final predictions, and on predictions at average SNS levels. For example, using a recovery of 90% (as seems appropriate for spring SNS), without reducing the intercept, would give SNS predictions of 130 kg/ha from a measured SNS of 100 kg/ha, hence over-estimating on average by around 30 kg/ha. A simpler way of incorporating these conclusions into SNS predictions would be to apply upper and lower limits to any prediction, for example 50 kg/ha as a minimum and 160 kg/ha as a maximum for most circumstances, so that predictions are constrained to the same extent that they are in RB209. Also, the need for slope and intercept adjustments seems to be avoided if an AAN mineralisation measure is used in spring.

Autumn SNS measures tend to over-predict harvested SNS, especially with SMN measured to 90 cm rather than 60 cm. Adjustments with intercepts, or intercepts and slopes, or estimated leaching (from soil type and rainfall) were required to mitigate this (Table 54). A bias correction (intercept) of 20 kg/ha to the 0-60 cm prediction was not as useful as the 0-90 cm prediction with leaching adjustments, plus slope and intercepts corrections. Leaching adjustments appeared to increase precision, but slopes still also seemed to improve accuracy.

Unadjusted spring SNS predictions (SMN + Crop N) tend to under-predict harvested SNS by around 30kg/ha on average. Measures of likely mineralisation or inclusion of a ‘deposition’ estimate helped to mitigate this (Table 54).

The GrowHow AAN measure improved both precision and accuracy, and seemed to negate the need for slope and intercept adjustments. To get *accurate* predictions of harvested SNS from spring measurement it seems necessary to either use an AAN measure or add a mineralisation/deposition estimate. This is not the case with autumn measurement unless an adjustment for N recovery is also made. In order to give similar predictions on average to FAM an addition of 20 kg/ha is required to spring SNS measurements (i.e. under-predicting harvested SNS by ~10 kg/ha on average). It is not clear whether this represents N becoming available from mineralisation, deposition or both. There are implications from this for the use of RB209 N fertiliser recommendations, as adding 20kg to any SMN measure would increase the SNS Index by 1 and reduce N fertiliser recommendations accordingly. It is important to be clear whether such an adjustment is in keeping with the principles on which RB209 recommendations are based. The difficulty is that SNS Indices in RB209 are derived predominantly from SMN measures, not harvested SNS. FAM predictions of underestimated harvested SNS by 10 kg/ha on average in this project, whereas spring SMN measurement underestimated harvested SNS by 30 kg/ha on average. There are several possible explanations for this discrepancy. Perhaps the explanation of most concern would be that conditions in the three years of this study were markedly different to ‘normal’ years underpinning past datasets; i.e. that the cold winters experienced in each year of this project slowed mineralisation giving lower SMN measures in spring, but this mineralisation was delayed rather than reduced such that harvested SNS was unaffected. In this case, the 20 kg/ha difference simply reflects delayed mineralisation following cold winters which may not universally apply in all situations. Looking at the past dataset, spring measured SNS underpredicts harvested SNS by 17 kg/ha on average. This discrepancy requires careful consideration when fertiliser recommendations are revised. The issue is complicated by the fact that the SNS Indices in FAM do not include an estimate of N from deposition, which is typically 20-30 kg/ha per year. Instead, this is implicitly accounted for in the N recommendation tables, The HGCA Wheat N management guidelines includes an adjustment of 20kg/ha when calculating N requirement to account for this. This means that FAM estimates should be expected to underpredict harvested SNS by around 20 kg/ha. Within this dataset, the underprediction averages around 10kg/ha. It is important that any approach of predicting SNS gives results which are meaningful in relation to fertiliser recommendations which are drawn from experiments and measures of SMN conducted over the past 30 years. At this time, the best evidence from the project data is that adding a 20 kg/ha estimate to measured spring SNS estimates to account for likely mineralisation improves the prediction of harvested SNS and would, on average, give better financial performance. However, the uncertainty over whether this would apply in all situations, for example following warm dry winters, and the uncertainty in its relation to recommendation tables (i.e. whether there would be double counting of mineralisation/deposition) precludes us making a definitive recommendation at this time to using a blanket mineralisation estimate for spring SNS measures. To an extent, the same argument applies to the use of AAN estimates, as their use effectively increases SNS estimates by at least 1 index, reducing fertiliser recommendations accordingly.

The performance of FAM in predicting harvested SNS was comparatively good compared to unadjusted SNS. Whilst FAM was not precise (regression equations explained less of the variation in harvested SNS than soil sampling, around 31%), it was relatively accurate and r^2 for the the y = x relationship was 26%. It must be stressed however that these are the results of using RB209 with some skill and care; inaccurate use of RB209 or SAC-TN625 with regard to determining soil groups etc. proved likely to give poor predictions.

That results of SMN testing without appropriate adjustments for mineralisation or mineralisation and leaching were little better than FAM seems to go somewhat against the relatively long experience of using SMN testing in ADAS, especially for siting and managing N response experiments; sites with low SNS are targeted for such experiments to maximise the chances of getting a good response to N fertiliser. SMN testing has proved an invaluable tool in this regard; whilst considerable variation is observed, the SMN estimates of harvested SNS are rarely seen to fail altogether, and are often close to expected. SMN testing has also been used successfully by ADAS to inform N recommendations on a commercial basis for farmers, initially in the UK and more recently for cereal farmers in New Zealand. Many other organisations in the UK and elsewhere offer successful commercial services measuring SMN, and indications are that farmer customers are generally pleased with these services. SMN testing is also currently considered a useful tool in good nutrient management, and has been seen as playing an important role in justifying N management strategies for NVZ requirements. So SMN testing is important to farmers, the wider industry and to other stakeholders, including government. Consideration of the value of SMN testing is therefore not a trivial exercise, and the full consequences of any conclusions drawn need to be carefully thought through.

3.9.3. Where, when and how to measure SMN

Given the relatively small (or sometimes negative) financial benefits found from use of SMN to ‘improve’ SNS predictions over FAM, even before the costs of sampling are accounted for, consideration needs to be given to where, when and how SMN sampling should be advised.

It is clear that SMN sampling cannot be advocated as a tool to be used to determine N recommendations for every field in every year; as well as being prohibitively expensive this would most likely also lead to spurious minor adjustments to N recommendations which risk, on average, delivering worse financial returns than following RB209, SAC-TN625 or from following ‘farmer experience’. It seems that SMN testing cannot be advised as profitable for minor ‘fine-tuning’ of recommendations on a field by field basis, except where expected SNS on all those fields is very high and uncertain.

There are two important errors in N management that can lead to large costs from estimating SNS levels wrongly:

1. Getting *average* estimates of SNS prediction wrong across the whole farm or a management block (e.g. crop type on a certain soil in certain part of the rotation). Because N rates are often set across a large area of land, getting the average rate more than ~20 kg/ha out from the average ‘actual’ optima can add up to a large cost.
2. Getting estimates of SNS prediction very wrong on particular fields. Large over-predictions of actual harvested SNS are possible, hence under-applications of N fertiliser, since N optima can exceed 300 kg/ha. There is a reasonable chance of large over-predictions being noticed and corrected since signs of deficiency (paleness and lack of tillering) will become evident. Conversely, large under-predictions of SNS may go unnoticed since, in the absence of lodging, an over-fertilised crop may look normal throughout the growing season. In this case there is the potential to save 100 kg/ha fertiliser without a yield penalty. Given that recovery of fertiliser averages only 60%, the saving in fertiliser N from a 100 kg/ha difference in harvested SNS could be as much as 170 kg/ha.

According to the results in this project there therefore appear to be two main ways in which SMN sampling can help deliver improvements to N management on the farm:

1. Helping to get *average* estimates of SNS prediction right, so that N applications are right across the farm, or across a management block.
2. Identifying fields where SNS levels are very different to the average.

Using SMN testing to inform average SNS predictions

Given the variability in SMN it would seem unsafe to base fertiliser decisions on a few SMN measures in a single year. However, used in conjunction with RB209 or other FAM approaches, SMN may be a useful tool in decision making, particularly to help understand how SNS on a farm relates to expected SNS using the FAM, or to detect differences in SNS between years or rotational positions. It could be especially useful when also combined with grain protein content.

SMN testing should therefore not be considered as an approach to N decision making *per se*, but rather as a useful tool in a systematic approach to N management where experience of lodging, yields and grain proteins, as well as in-season crop monitoring, are integrated with SMN in a comprehensive monitoring strategy that could be called “soil-N profiling”. The use of an N balance approach (assessing SNS from the difference between N additions and N off-takes) could be developed here.

As an example, “soil N profiling” could be instructive where SNS of a block of land is thought to be higher than indicated by a FAM. SMN could be measured on some barometer fields, but results only acted upon if corroborated by frequent high grain N%s, or high total soil N%, or lodging, or if (with early applications of N fertiliser avoided for as long as possible) the crops do not look N deficient in spring. The converse could also apply.

Using SMN testing to identify deviant fields

We know that fields with high levels of harvested SNS do exist in large numbers on farms; over 20% of fields in the past dataset showed harvested SNS greater than 150 kg/ha; over 30% did in the new dataset. Experience of N response work in both the 1980s and 2000s is that around 20% of trials on previously untested sites don’t show responses to N fertiliser (Bloom PhD thesis, 1986; Sylvester-Bradley et al., 2008). Identifying these fields is important because economically and environmentally significant quantities of N fertiliser could be saved; the potential savings from improving N management on a few fields which are highly deviant can be much greater than improvements in N accuracy on a large number of fields which are already fertilised near-optimally. SMN testing by itself is unlikely to identify such fields without sampling every field on the farm. However, other information such as regular high grain proteins, regular lodging, high soil organic matter, a known past history of grass or manure use or old meadow land may give cause for suspicion; SMN testing can then usefully validate the suspicion.

In terms of using SMN testing to help inform appropriate ‘average’ SNS predictions, or to identify deviant fields, it is likely that the most value will be obtained the first time the measures are made, perhaps in the period after land is acquired, or after a farming system is changed. It is at this point we first learn how our fields relate to expectations in terms of SNS estimates. Subsequent analyses refine and validate this experience if results are similar, or may help to show the scale of rotational and seasonal variation if results are very different. However, it is likely that after several years of SMN testing we will have learnt the levels of SNS that are likely to be experienced, so that subsequent analyses will become less valuable.

3.9.4. Conclusions

This project has successfully amassed and interrogated large volumes of data to investigate the major issues surrounding estimation of SNS for use in N fertiliser recommendations. Greater clarity has been sought for each of these issues, and tighter ‘Best Practice’ guidelines for SNS estimation have been developed from them. It has been shown that soil measurement can only be expected to give more cost-effective estimates of SNS than FAM in a minority of cases where SNS levels are expected to be high and uncertain. FAM gives the most cost-effective estimates of SNS in the majority of arable situations. Despite this, the precision with which FAM predicts harvested SNS is poor, and there may be farms where SNS levels are consistently higher or lower than would be expected from FAM; measurement of soil mineral N remains one of the few tools available to help check this.

Autumn sampling to 60 cm depth has been shown to be adequate for clay and silt soils but spring sampling to 90 cm gives the best results overall. Better guidance has been given for how many soil cores are required per field, with 10-15 cores being adequate in most situations. The importance of keeping samples cool and getting them to the lab quickly has been demonstrated. The value of inter-laboratory ring-tests has also been shown and these should continue into the future.

The importance of accounting for crop N has been shown in both wheat and oilseed rape.

Measures of mineralisation can help improve predictions of harvested SNS, especially using AAN in spring. However, the improvements largely come from getting a closer prediction of harvested SNS on average (i.e. reducing the extent to which spring SNS measures underpredict harvested SNS), rather than by explaining a substantial amount of the variability in harvested SNS. The extent for measurements or approaches to further predict this variability in apparent mineralisation (or N loss) seems limited.

Wider consideration of standard adjustments for mineralisation/deposition and of recovery of measured SNS is required. In particular it is necessary to consider how any changes to estimating SNS in this way would relate to recommendation systems.

Overall, the uncertainties in SNS prediction remain very large. The project has shown that, whilst a small part of these uncertainties can be removed by applying best practice, in large part they reflect variability in the natural system which we will have to learn to live with. Whatever method of estimating SNS is used, our confidence in the prediction can never be absolute. This points to the importance of monitoring crops and learning from experience on the farm.

The project has largely confirmed the advice given in RB209 Appendix 2 and the HGCA nitrogen for winter wheat management guidelines regarding sampling for soil mineral nitrogen. The aspects which could be updated are:

- From a cost:benefit perspective the requirement for 15-20 soil cores for a 10 ha field is excessive. For most fields 10 cores is sufficient, more are only required where fields are variable, large (>30 ha) or SNS is expected to be high (>150 kg/ha).
- Taking separate SMN samples from smaller blocks in larger fields (>10 ha) is unlikely to be cost-effective, unless areas of the field are known to differ in ways that will affect likely SNS (e.g. previous cropping, manure or fertiliser applications, soil type)
- Thorough mixing of soil samples has been shown to lead to enhanced mineralisation within the soil sample, so should be avoided. Ideally, whole bulk samples should be sent to laboratory to avoid the need for sub-sampling. If bulk samples are too large and sub-sampling is required then this is best achieved by taking many small portions of soil from the bulk sample in a representative manner.
- Samples should be kept cool and analysed within three days of sampling.
- Analytical laboratories used should participate in ring tests
- Crop N content in wheat is best estimated using Table 29. In oilseed rape it is best estimated from an assessment of GAI, each unit of GAI giving 50 kg/ha N, rather than crop height.
- With regard to estimating mineralisation, evidence from this project suggests that an estimate should only be made with spring measurements of SMN. The best estimate of mineralisation is given by AAN, which is available commercially. Alternatively, spring SMN measures in the project dataset are improved by including an overall estimate of 20 kg/ha for mineralisation/deposition. However, it is not certain whether such an estimate would be appropriate in years with warm dry winters.
- The HGCA nitrogen for winter wheat management guidelines give detailed advice about best periods for sampling (Table 6). The evidence from this project would not support SMN sampling of sandy or shallow soils in any situation. For any soil type or rainfall class better

results would be expected in spring than autumn, but acceptable results can be obtained from autumn sampling on clay and silt soils.

- Results from this project support adjustments for leaching advocated in the N management guide.
- Some notes of caution should be added, warning that using SMN based measures of SNS can give worse economic performance than FAM. To counter this, very high SNS estimates (>160 kg N/ha) and very low estimates (<50 kg N/ha) should only be taken as greater than 160 kg/ha or less than 50 kg/ha respectively in terms of altering N management decisions if these results are confidently expected. Crops should be monitored through the season to judge whether changes to management were appropriate.

There are a number of recommendations regarding SMN measurement that have not been explicitly addressed in this project, but for which there is widespread support from past experience. These include:

- Not to take SMN measurements within six weeks of manure or fertiliser application, within a month of sowing (because of likely mineralisation flush following cultivation), in the same season as grass is ploughed out (due to highly variable patterns of mineralisation and immobilisation) or on peat soils (again due to variability in mineralisation and immobilisation through the season.
- To take samples from areas of fields with differing management history (cropping, fertiliser and manure applications) separately.
- Unrepresentative areas such as headlands and past manure heaps should be avoided when sampling for SMN.

3.9.5. Recommendations for further research

Used carefully, the FAM in RB209 gives 93% of fields with margins over N cost within £40/ha of the maximum (and 69% of fields within £10/ha of maximum; Table 39). This could be improved to 97% (and 75%) if SMN analysis was used everywhere, and the best method of interpretation was employed. However, the extra average advantage of £5/ha from using SMN on every field would not cover SMN costs, so the FAM is best used to identify the subset of fields where SMN analysis offers a larger average advantage e.g. ~£8/ha (Table 47). This approach would achieve ~98% of fields with N margins within £40/ha of maximum, and in addition, avoids SMN costs on a large majority of fields. This result may seem satisfactory from an economic point of view, and it is questionable whether further experimentation specifically on measurement of SNS would be worthwhile following this project. This is not to say that FAM predictions of SNS could not be improved. One area of uncertainty that may warrant further investigation is the harvested SNS in high N situations on light and shallow soils. Within this dataset there were very few fields with high harvested SNS; it is not clear whether this is because high levels of SNS are genuinely unavailable for crop uptake on these soils, or simply that insufficient fields were investigated in this study to find instances of high harvested SNS.

From the data, the maximum of the variation in harvested SNS that could be explained was only 57%, but this does not translate into large economic losses, and it seems doubtful whether this could be improved, even in the medium term, without good long-range weather forecasts and a large research programme to achieve substantially better characterisation of soils, soil organic matter and soil processes.

It is possible that some aspects of the predictions explored here could be improved by further data analysis, particularly including further analysis of the extensive and valuable new dataset generated here. For example, it should be possible to develop usable and useful predictions of AAN using measures of soil N% and total N%, which conventionally are considered as much more stable (thus need analysing less frequently) than measures of PMN by anaerobic incubation. Similarly, refinements could be made to predictions of N retention after sampling, based on soil type and rainfall, and further work on adjustments for stone content may also be helpful. Further development and validation of mechanistic models such as Sundial (Smith *et al*. 1997), and EU-Rotate_N (Rahn et al. 2010) using this dataset may also lead to marginally superior predictions of harvested SNS. However, whether such work could or would really lead to a step change in the power of the predictions is doubtful. Given that the normal cost of fertiliser N for most arable crops is now close to £200/ha, the normal return in crop response is now well over £500/ha – sometimes over £1,000/ha – it is dubious whether extensive research specifically on SNS (as a sub-component of crop N requirement) prediction systems, which could only save an average of ~£10/ha, could be considered worthwhile.

What may prove more beneficial is the development and validation of a more holistic approach to managing N fertiliser decision-making on the farm, which addresses crop N requirements directly, and which acknowledges multiple aspects of the farming systems. There is evidence from other projects (HGCA projects 3211 and 3530) that a significant proportion of the field to field variation as studied in this project is due to variation *between* farms rather than variation between fields *within* farms. Farm to farm variation includes some factors addressed here (e.g. soil type, soil organic matter), but also several factors which were only partially addressed here (e.g. yield and protein levels, previous fertiliser use – N, P & K, soil management, fate of crop residues, farmer experience and farmer attitudes). These farm to farm differences are seldom explicit in multi-site experimentation, yet they are open to assessment and analysis, and a more comprehensive approach involving monitoring of key indicators of field N status (yield, grain protein, SOM, SMN, canopy expansion, lodging) holds promise in quantifying and resolving them. 'Farm N profiling' that integrates a wide range of information sources, including farmer experience, to build a picture of farm N status as it relates to optimal N management is advocated in the HGCA nitrogen for winter wheat management guidelines, but has not been properly tested. Farm N profiling could be supported by modelling, for example using N balances to estimate SNS. Unfortunately there are no obvious sources of the comprehensive information that would be needed to validate farm N profiling. Of course, any approach that monitors the whole farm system should not become overly burdensome in management time or analysis costs, but it seems likely that a monitoring system could make use of information and technology already used for other important purposes (e.g. crop yields, grain N%, soil organic matter, previous crops), perhaps adopting an N balance approach. Thus, we suggest here that future work should address the variation in crop N requirements holistically, by assessing all its components (harvested SNS, crop N demand, and fertiliser N efficiency) and examining the variation experienced at different levels: farm to farm, between rotational positions, between years between fields, and within fields; and it should develop and evaluate targeted approaches for monitoring, predicting and managing each level of variability, since these may differ substantially.

3.9.6. Messages and recommendations

Assessment of harvested SNS

- Harvested SNS, the N (kg/ha) taken up by a crop receiving nil fertiliser N, is the most telling measure of soil nitrogen supply (SNS). Together with crop N demand (CND) and fertiliser N recovery (FNR) it determines fertiliser N requirement, in that:

  Fertiliser N requirement = [CND – SNS] / FNR
- Harvested SNS forms an important part of observed differences in N requirements, explaining around 60% of the variation in N optima seen across sites.
- A prediction of harvested SNS should always be made as part of decision making on N for arable crops, whether by FAM or by soil measurement.
- Current methods of predicting harvested SNS are poor, generally explaining less than 50% of its variation. Hence fertiliser decision-making should employ concomitant caution e.g. double-checking.
- Using the Field Assessment Method in RB209 or SAC-TN625 to estimate SNS is not precise in its predictions of harvested SNS, but it is accurate on average. The RB209 or SAC-TN625 methods should be used with care, paying particular attention to accurate description of soil type, assessment of soil organic matter content if this is likely to be more than low, and acknowledgement of field history, especially if grass or manures have been involved at least in the last decade.
- Soil sampling measures of SNS can explain more of the variation in harvested SNS than FAM, but absolute predictions of harvested SNS without adjustments can be worse on average than FAM.

- FAM gives best predictions of SNS where SNS is likely to be moderate or small e.g. in arable rotations without grass or manures in a field's history, and in high rainfall areas. In most arable situations FAM is the most cost effective method for estimating SNS.
- Measuring SMN becomes progressively more worthwhile as SNS (as predicted by the FAM) increases beyond 120 kg/ha, or where SNS is uncertain. This includes situations where organic manures have regularly been used in the past, where there is a history of long term grass and following vegetable crops which have left N-rich residues. SMN measurement gives best predictions on deep retentive (clay and silt) soils, in low rainfall areas where expected SNS levels are uncertain and likely to be high (>160 kg/ha), for example after high-N vegetables, or where manures have previously been used or grass grown (though SMN measures should not be made in the season immediately after applying manure or ploughing out grass). Conversely, SMN measurement can give very poor predictions of harvested SNS on light and shallow soils, or where SNS is expected to be small. SMN measurement can only be expected to give more cost-effective estimates of SNS than FAM in situations where SNS is expected to be high (>120 kg/ha).
- SMN measurement may prove useful as part of a more comprehensive N monitoring approach (e.g. including FAM, crop growth, lodging, grain yield and grain N%) and when assessing average SNS levels of large areas across a farm. In particular, SMN measures can provide a check of how SNS levels on the farm compare to RB209 expectations.

Sampling methods for SMN determination

- Sampling in spring tends to give slightly better predictions of harvested SNS than sampling in autumn, though the difference on clay and silt soils is small.
- Autumn SMN measurements have the advantage that soils only need to be sampled to 60 cm, whereas spring sampling should be to 90 cm.
- The number of samples per field that should be taken depends upon the level of SNS expected, the variability expected and the size of the field. Generally 10-15 samples is sufficient; taking more than this is unlikely to be cost effective, except where fields are highly variable or are large (<20 ha) and SNS is expected to be high (<160 kg/ha).
- Sampling in a W pattern or in a grid (as opposed to more complex arrangements) is adequate to give representative samples.
- Ideally sub-sampling in the field should be avoided. If bulk samples are too large for dispatch to the labs, then representative sub-sampling is required. Excessive mixing of samples should be avoided as this can stimulate mineralisation. The best approach is to take many small portions of soil from the bulk sample to form the sub-sample.
- It is crucial that samples are analysed as soon as possible after sampling (ideally within three days), and that samples are kept cool (<4°C) during storage and transport. Freezing is not appropriate except in research.

- Laboratory ‘ring-tests’ are important to ensure that any systematic differences between analytical laboratories are identified and corrected. There have been inconsistencies in the past.
- Whether standard bulk density figures (1.33 kg/l) or soil type and depth specific bulk density figures are used to calculate SNS on a per ha basis makes little difference to the performance of prediction of harvested SNS.
- No evidence has been found to show value in adjusting for stone content. If adjustments are made, care is needed to ensure that stone contents are not over-estimated.
- It is important that crop N at the time of SMN sampling is estimated and included in the estimate of SNS. Visual estimation methods are usually adequate. A number of approaches for estimating crop N in wheat and oilseed rape are available, estimates from shoot counts of GAI in wheat are satisfactory (e.g. Table 29), in oilseed rape assessment of GAI gives the best estimate of crop N. There is no evidence that crop N in OSR should be treated differently to that in other crops when estimating SNS.

Mineralisation tests

- Indicators of mineralisation do not seem to add predictive power to SNS estimates made in autumn.
- Measures of AAN (calibrated PMN from anaerobic incubation) improve the prediction of SNS in spring.
- Measures of soil total N% and SOM% are also useful indicators of mineralisation in spring, and they might overcome the need for annual measurements of AAN, but they have not yet been properly calibrated to give useful predictions of additionally available N. The implied relationship within RB209 of 10kg/ha N being mineralised for each 1% increase in SOM% above 4% provides a sensible basis for judging mineralisation, but does not perform as well as a predictor of mineralisation as AAN.
- Using a mineralisation/deposition estimate of 20kg/ha across the board improves predictions from spring SMN measurements in this dataset. There is some uncertainty whether such an adjustment would still be appropriate following a dry mild winter is spring SMN measures were generally high. The implications for such an adjustment on fertiliser recommendations need to be carefully considered.

Interpretation issues

We suggest that organisations offering N advice based on SMN testing should jointly consider the following points in order to standardise their approaches and hence improve the confidence of their clients in SMN testing:

- Crops have a maximum capacity for N uptake so estimates of SNS by SMN testing have the potential to exceed this. For the sake of making N recommendations, measures above 160 kg/ha could be treated as predictions of 160 kg/ha and no more, except in cases where past experience shows that more SNS than this can confidently be expected to become available, for example on retentive silts in low rainfall areas following high residue crops such as high N vegetables. Recommending zero N fertiliser should be avoided in all but the rarest situations.
- Estimates of SNS from small SMN values can under-predict harvested SNS. SNS estimates of less than 50 kg/ha could be treated as predictions of 50 kg/ha, not less, except where past experience shows that levels of SNS that will become available are very low, for example on very light soils with low organic matter.
- SMN measures in autumn can over-predict harvested SNS at high SNS levels, so require adjustments to make predictions more accurate on average. Adjustments for over-winter rainfall, as in Tables 31and 32, should be considered, as well as possible adjustments for recovery (i.e. slope). Alternatively, upper and lower limits to SNS prediction (~50 kg/ha to ~160 kg/ha) should be considered.
- SMN measures in spring tend to under-estimate harvested SNS. This can be rectified by inclusion of AAN measures, or by an estimate of deposition/mineralisation.
- Consideration is needed as to whether such mineralisation adjustments are appropriate in all situations (e.g. after warm winters when measured SNS may be higher). Detailed consideration is needed with regard to how such adjustments relate to fertiliser recommendation tables; Given that SNS indices in RB209 are based on SMN measurements, but N optima are derived from N response experiments, the effects of mineralisation and deposition on harvested SNS are somewhat confounded in relation to N recommendations. This should be considered when fertiliser recommendations are next revised.
- Because SMN sampling can on occasion give excessively high predictions of harvested SNS, extreme SMN results should be treated with caution. This is especially so if SMN measures do not tally with knowledge of the field history. Where SNS predictions are very high, and fertiliser N rates are cut back, the crop should be monitored through spring for signs of N deficiency. Where necessary, adjustments to planned N strategy should be made.

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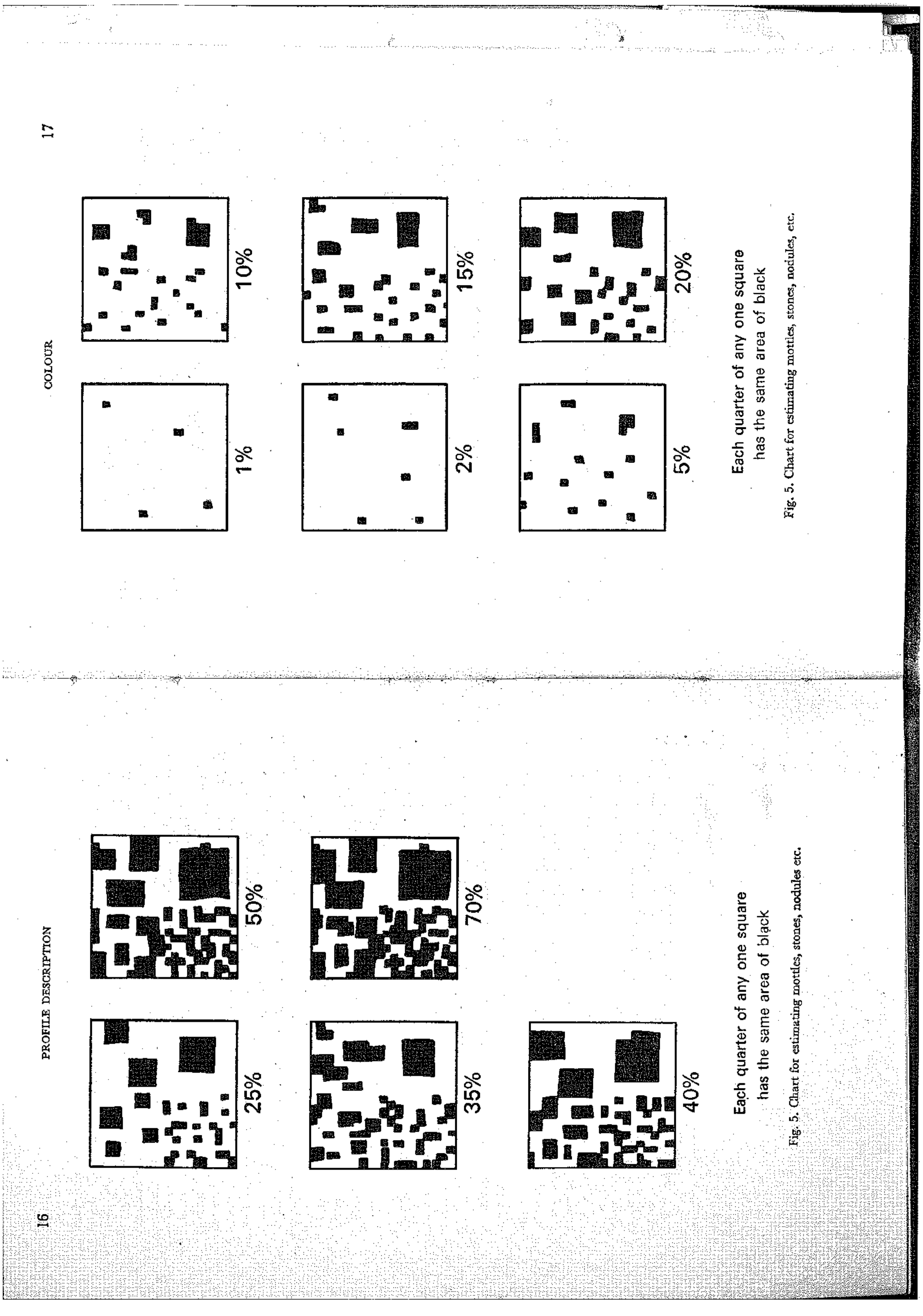
ANNEX 1. DIAGRAMS FOR ASSESSMENT OF SOIL STONE CONTENT (FROM SOIL SURVEY FIELD HANDBOOK)



16 PROFILE DESCRIPTION

Each quarter of any one square has the same area of black

Fig. 5. Chart for estimating mottles, stones, nodules etc.

COLOUR 17

Each quarter of any one square has the same area of black

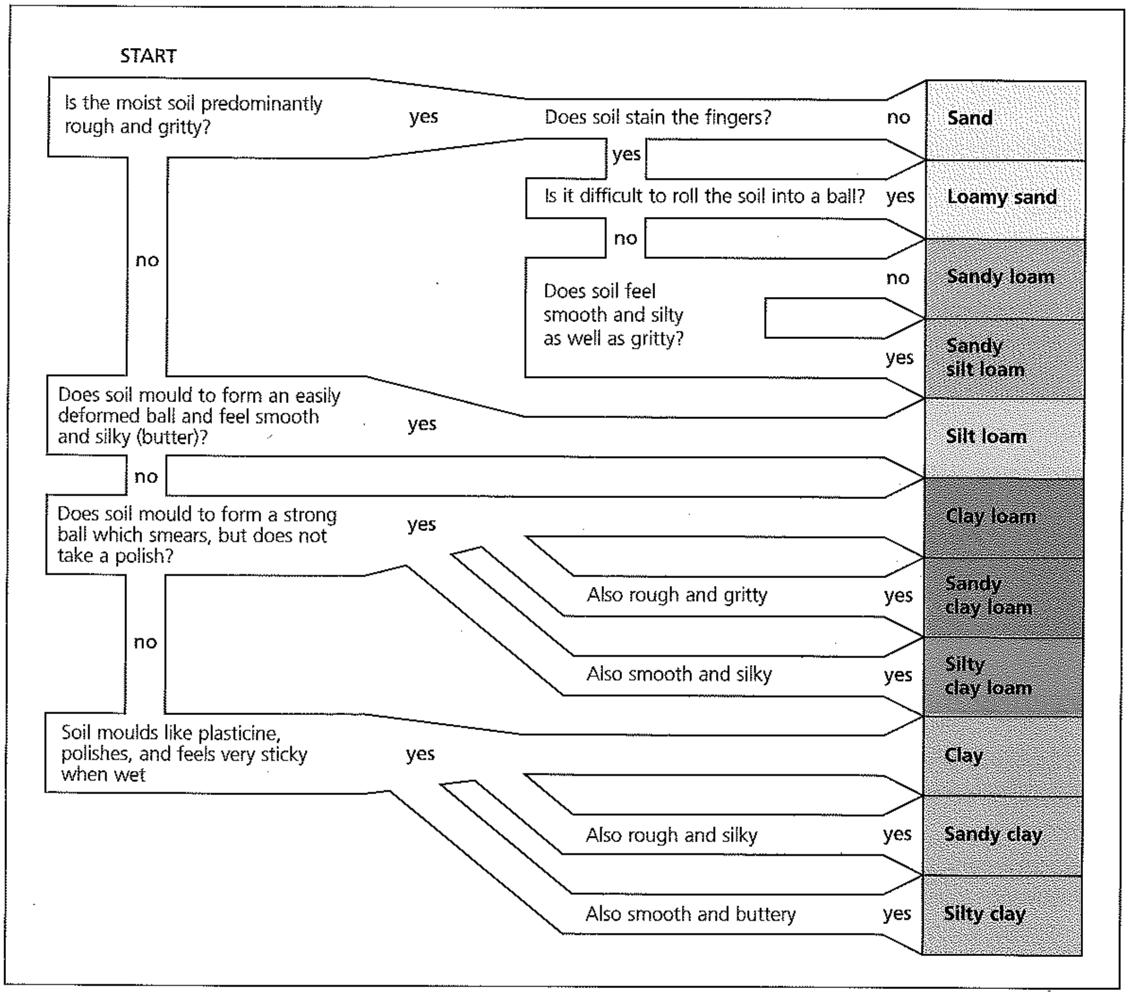
Fig. 5. Chart for estimating mottles, stones, nodules, etc.

ANNEX 2. SOIL TEXTURE (TAKEN FROM RB209 P161)

Assessment of Soil Texture

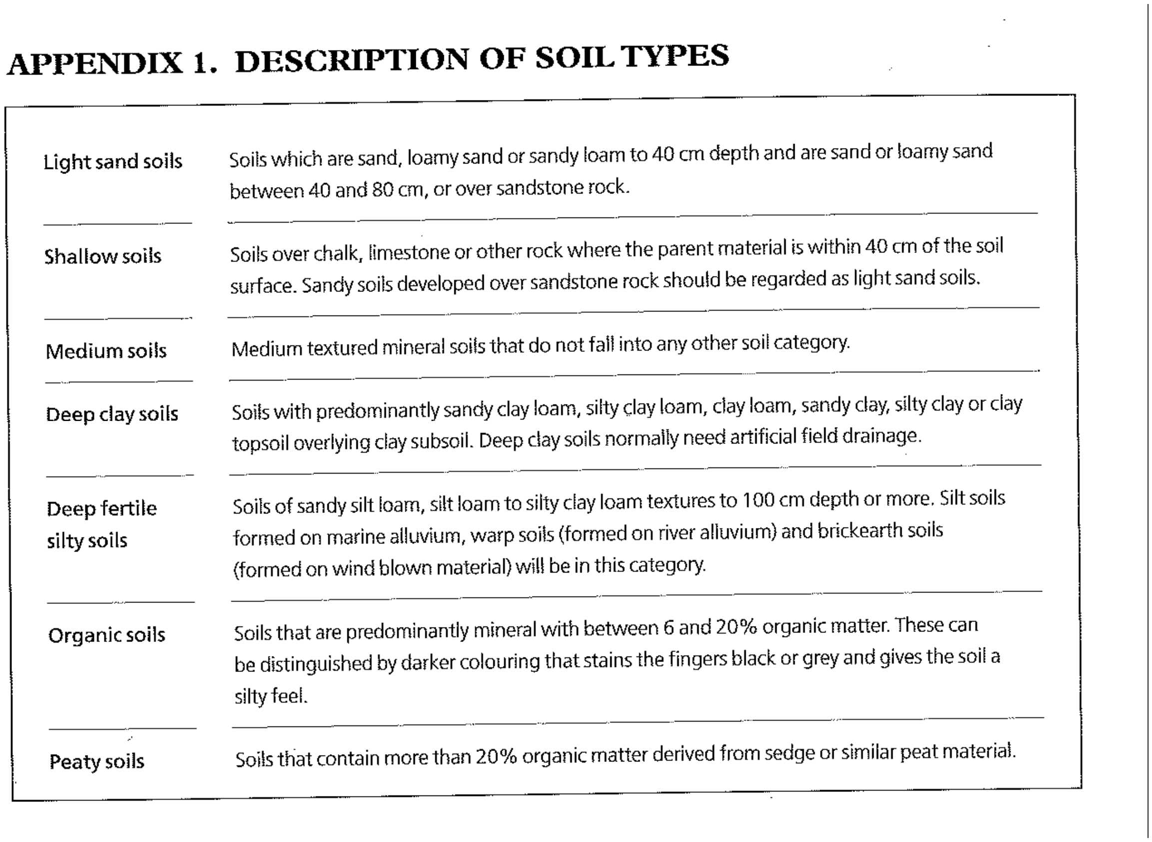
Accurate measurement of soil texture requires laboratory analysis, but for practical purposes texture can be assessed by hand using the following method:

Take about a dessert spoonful of soil. If dry, wet up gradually, kneading thoroughly between finger and thumb until soil crumbs are broken down. Enough moisture is needed to hold the soil together and to show its maximum stickiness. Follow the paths in the diagram to get the texture class.



A texture triangular diagram, defining the particle size distribution for each named texture class, is given in Appendix D of *Controlling Soil Erosion (MAFF PB4093)*.

ANNEX 3. RB209 SOIL TYPE DESCRIPTION (P160)



APPENDIX 1. DESCRIPTION OF SOIL TYPES

Light sand soils	Soils which are sand, loamy sand or sandy loam to 40 cm depth and are sand or loamy sand between 40 and 80 cm, or over sandstone rock.
Shallow soils	Soils over chalk, limestone or other rock where the parent material is within 40 cm of the soil surface. Sandy soils developed over sandstone rock should be regarded as light sand soils.
Medium soils	Medium textured mineral soils that do not fall into any other soil category.
Deep clay soils	Soils with predominantly sandy clay loam, silty clay loam, clay loam, sandy clay, silty clay or clay topsoil overlying clay subsoil. Deep clay soils normally need artificial field drainage.
Deep fertile silty soils	Soils of sandy silt loam, silt loam to silty clay loam textures to 100 cm depth or more. Silt soils formed on marine alluvium, warp soils (formed on river alluvium) and brickearth soils (formed on wind blown material) will be in this category.
Organic soils	Soils that are predominantly mineral with between 6 and 20% organic matter. These can be distinguished by darker colouring that stains the fingers black or grey and gives the soil a silty feel.
Peaty soils	Soils that contain more than 20% organic matter derived from sedge or similar peat material.

ANNEX 4. DETERMINATION OF GROWHOW ADDITIONALLY AVAILABLE N (AAN)

AAN is a component of the GrowHow N-Min test. It may be regarded as an estimate of mineralisation between soil sampling in spring and harvest, but when SMN is not measured to 90cm it also includes an estimate of SMN in the unsampled depths to 90 cm. Thus there are different estimates of AAN depending on the depth of SMN sampling. The GrowHow method tested in this Project determined SMN to 60 cm so, in this case, AAN_{60} acted as a predictor of both mineralisation and any SMN in the 60-90 cm soil layer. Because AAN is calibrated on data from past seasons its use entails an assumption that conditions influencing mineralisation between sampling and harvest are similar throughout regions of the UK and between years.

Development of the test has involved long term monitoring of fields across the UK with varying crop rotations and a wide range of soil organic matter levels. Sites were targeted that yield at least 8 t/ha. Soils are sampled to 0-30 or 0-60 cm (depending on the depth of SOM) and these samples are incubated anaerobically for 7 days. Most of the fields receive fertiliser N, but soil-N plus fertiliser-N is kept marginally less than expected crop N uptake. Thus the method assumes no surplus unused N. By relating the extent to which crop N uptake exceeds N supply (soil-N plus fertiliser-N) to incubated N (Potentially Mineralisable N; PMN) an estimate of the proportion of PMN that becomes AAN can be made; the relationship is significant although with much variation (Figure A4.1).

The relationship between SOM and AAN for this current HGCA SNS project data (circles) and GrowHow data (crosses) is shown in Figure A4.2. The variation is partly explained by the wide range of C:N ratios of SOM between the experimental sites. Nonetheless a generalised assessment of AAN could be made from this relationship and an estimate of SOM and then could be used as an adjustment for the standard SNS 0-90 cm method.

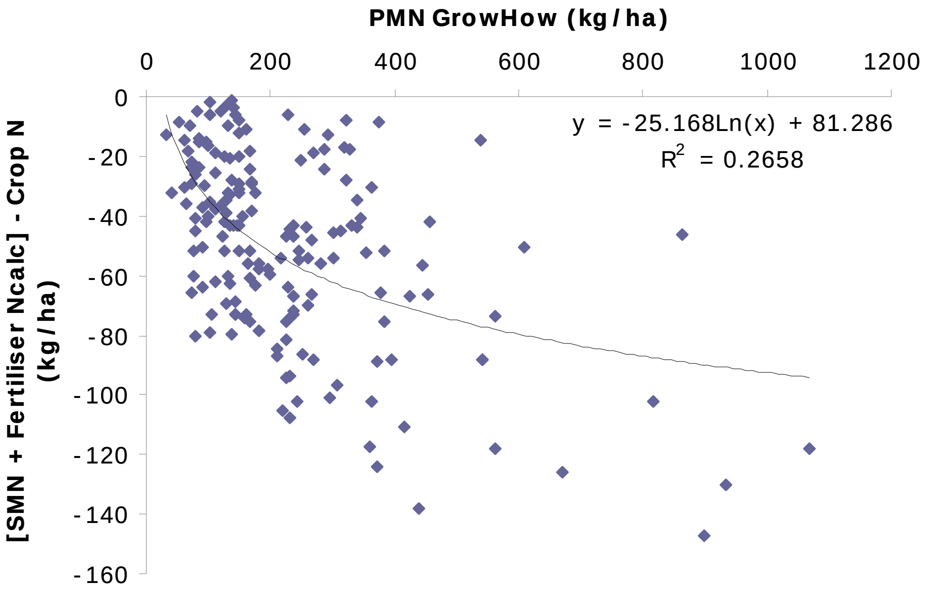


Fig A4.1. Determination of the PMN/AAN ratio for the adjustment of post sampling mineralisation for 0-90 cm soils.

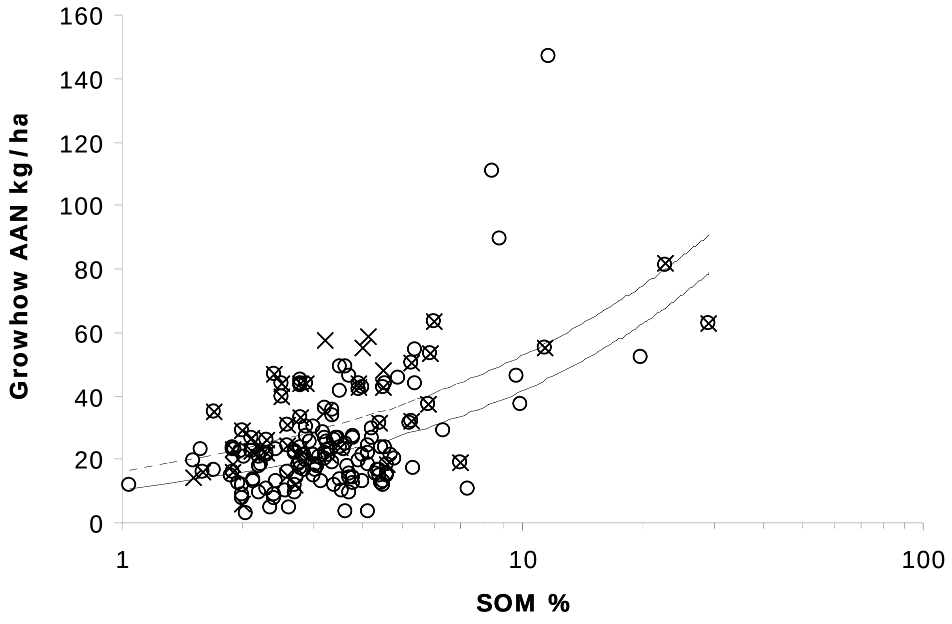


Fig A4.2. Relationship between SOM and Growhow AAN for this current HGCA SNS project data (circles; dashed line) and GrowHow data (crosses; dotted line).

ANNEX 5. DETAILED RESULTS FROM MANIPULATING CANOPY SIZE IN OILSEED RAPE

Autumn

Table A5.1. Autumn SMN (kg/ha), crop N (kg/ha) and total SNS (kg/ha) for small and large crops from individual sites over three years.

Year	Site ID	SMN (kg/ha)		Crop N (kg/ha)		Total SNS (kg/ha)	
		Small	Large	Small	Large	Small	Large
2007/08	8A-R001/2	47	49	22	25	69	75
2007/08	8A-R003/4	72	25	9	76	81	101
2007/08	8A-R005/6	82	60	17	41	99	101
2007/08	8A-R007/8	68	37	46	76	113	113
2007/08	8A-R09/10	37	37	24	44	61	82
2007/08	8T-R011/12	39	18	14	70	53	88
2007/08	8T-R015/16	80	44	11	62	91	105
2007/08	8T-R017/18	100	54	2	45	103	99
2007/08	8T-R019/20	74	73	15	68	89	140
	Mean	**67**	**44**	**18**	**56**	**84**	**100**
2008/09	9A-R021/22	106	46	6	50	113	96
2008/09	9A-R023/24	28	39	38	63	67	101
2008/09	9A-R025/26	20	22	16	16	36	38
2008/09	9A-R027/28	20	17	5	11	25	28
2008/09	9A-R029/30	34	25	9	13	43	38
2008/09	9T-R031/32	22	23	23	34	44	57
2008/09	9T-R033/34	69	67	5	20	74	86
2008/09	9T-R035/36	49	36	3	10	51	46
2008/09	9T-R037/38	55	38	1	19	56	56
2008/09	9T-R039/40	73	85	3	13	76	99
	Mean	**48**	**40**	**11**	**25**	**59**	**65**
2009/10	10A-RO41/42						
2009/10	10A-RO43/44	27	21	33	85	60	106
2009/10	Extra						
2009/10	10A-RO47/48	91	70	6	10	98	80
2009/10	10A-RO49/50	44	35	60	94	104	129
2009/10	10T-RO51/52	68	45	11	30	79	75
2009/10	10T-RO53/54	38	52	23	20	61	72
2009/10	10T-RO57/58	89	50	3	56	92	106
2009/10	10T-RO59/60	91	98	2	31	93	129
2009/10	10T-RO61/62	36	46	86	124	123	169
	Mean	**60**	**52**	**28**	**56**	**89**	**108**
Overall Mean		**57**	**44**	**19**	**46**	**76**	**90**

In 2007/08, the autumn SMN for the small treatment was 67 kg/ha, ranging from 37–100 kg/ha, compared to the significantly (*P*<0.05) smaller mean of 44 kg/ha which ranged from 18–73 kg/ha for the large treatment. Mean crop N for the small treatment in autumn 2007/08 was 18 kg/ha, ranging from 2–46 kg/ha, compared to a significantly (*P*<0.001) larger mean of 56 kg/ha for the large treatment, which had a range of 25–76 kg/ha. There was no significant difference between the mean total SNS in autumn 2007/08 for small and large treatments, each having respective means of 84 and 100 kg/ha, and ranges of 53–113 kg/ha and 75–140 kg/ha.

In 2008/9, the mean SMN, crop N and total SNS values were less than those recorded in 2007/08. The mean SMN for small and large treatments in autumn 2008/09 were not significantly (*P*>0.05) different from each other, with the mean autumn SMN for the small treatment being 48 kg/ha, ranging from 20–106 kg/ha while the mean SMN for the large treatment was 40 kg/ha and ranged from 17–85 kg/ha. In the autumn of 2008/09 the mean crop N of the small treatment was not found to be significantly (*P*>0.05) smaller at 11 kg/ha (1–38 kg/ha range) than the mean large crop N of 25 kg/ha with a range of 10–63 kg/ha. Additionally, the mean total SNS in autumn 2008/09 for both crop sizes were not significantly (*P*>0.05) different, small crops had a mean total SNS of 59 kg/ha, and a 25–113 kg/ha range, while the mean total SNS in autumn 2008/09 for large crops was 65 kg/ha and ranged from 28–101 kg/ha.

In 2009/10, the mean autumn SMN, crop N and total SNS were generally greater than those measured in autumn 2008/09 and generally similar to the measurements in autumn 2007/08. As with previous years, the mean autumn SNSs for both treatments in 2009/10 were not significantly (*P*>0.05) different from each other; the mean autumn SNS for the small treatment was 60 kg/ha with a range of 27–91 kg/ha, and the mean SMN for the large treatment was 52 kg/ha with a range of 21–98 kg/ha. The mean crop N for the small treatment in autumn 2009/10 was 28 kg/ha and ranged from 2–86 kg/ha which was significantly less (*P*<0.001) than for the large treatment at 56 kg/ha with a range of 10–124 kg/ha. The mean total SNS in autumn 2009/10 for small crops was 89 kg/ha and ranged from between 60 kg/ha and 123 kg/ha while the mean large crop total SNS was greater, although not significantly (*P*>0.05) so, at108 kg/ha and ranged from between 72 kg/ha and 169 kg/ha.

Spring

Table A5.2. Spring SMN (kg/ha), crop N (Kg/ha) and total SNS (kg/ha) for small and large crops from individual sites over three years.

Year	Site ID	SMN (Kg/ha)		Crop N (Kg/ha)		Total SNS (Kg/ha)	
		Small Crop	Large Crop	Small Crop	Large Crop	Small Crop	Large Crop
2007/08	8A-R001/2	44	84	40	53	84	136
2007/08	8A-R003/4	60	41	40	105	100	146
2007/08	8A-R005/6	49	64	22	62	71	126
2007/08	8A-R007/8	56	49	71	125	127	173
2007/08	8A-R09/10	37	38	39	81	76	119
2007/08	8T-R011/12	45	27	29	59	74	86
2007/08	8T-R015/16	55	57	24	89	80	146
2007/08	8T-R017/18	79	21	9	68	88	90
2007/08	8T-R019/20	49	43	57	49	106	92
	Mean	**53**	**47**	**37**	**77**	**90**	**124**
2008/09	9A-R021/22	77	58	13	44	90	103
2008/09	9A-R023/24	13	22	48	91	61	113
2008/09	9A-R025/26	15	15	25	24	40	39
2008/09	9A-R027/28	25	21	11	19	37	40
2008/09	9A-R029/30	12	15	41	43	53	58
2008/09	9T-R031/32	27	20	49	51	76	71
2008/09	9T-R033/34						
2008/09	9T-R035/36	40	41	4	26	43	67
2008/09	9T-R037/38	47	41	3	27	50	68
2008/09	9T-R039/40	34	27	9	23	43	50
	Mean	**32**	**29**	**23**	**39**	**55**	**68**
2009/10	10A-RO41/42	24	28	57	58	81	86
2009/10	10A-RO43/44	29	32	42	71	71	104
2009/10	Extra	23	28	29	40	52	69
2009/10	10A-RO47/48	21	17	15	46	36	63
2009/10	10A-RO49/50	41	28	42	71	83	99
2009/10	10T-RO51/52	21	19	13	24	34	43
2009/10	10T-RO53/54	32	31	31	37	63	68
2009/10	10T-RO57/58	90	31	3	58	93	89
2009/10	10T-RO59/60	33	30	2	52	35	82
2009/10	10T-RO61/62	32	25	55	48	87	73
	Mean	**35**	**27**	**29**	**51**	**64**	**77**
Overall Mean		**40**	**34**	**29**	**55**	**69**	**89**

In 2007/08, the mean SMN for both treatments were not significantly (*P*>0.05) different, the small treatment had a mean SMN of 53 kg/ha with a range of 37–79 kg/ha while the large treatment had a mean of 47 and ranged from 21–84 kg/ha. The mean spring crop N for the small treatment in 2007/08 was 37 kg/ha with a range of 9 to 71 kg/ha, while the mean spring crop N for the large treatment was significantly (*P*<0.001) larger at 77 kg/ha and ranged from 49–125 kg/ha. The spring 2007/08 mean total SNS for the small treatment was significantly (*P*<0.01) less than that for the large treatment with respective means of 90 and 124 kg/ha and ranges of 71–127 kg/ha and 86–173 kg/ha.

In spring 2008/09 the mean SMN, mean crop N and mean total SNS were less than in 2007/09. The mean SMN for the small treatment was 32 kg/ha (range of 12–77 kg/ha) while the mean SMN for the large treatment was slightly, but significantly (*P*>0.05) less at 29 kg/ha, with a 15–38 kg/ha range. The mean spring crop N was 23 kg/ha for the small treatment, ranging from 3–49 kg/ha, while the mean spring crop N for the large treatment was larger, although not significantly so (*P*>0.05), at 39 kg/ha and ranged from 19–91 kg/ha. The mean spring total SNS in 2008/09 for both treatments were not significantly (*P*>0.05) different from each other. The mean spring total SNS for the small treatment was 55 kg/ha (37–90 kg/ha range) and the mean total SNS for the large treatment was 68 kg/ha with a 39–113 kg/ha range.

In 2009/10, the mean SMN, mean crop N and mean total SNS were similar to those found in 2008/09 and lower than those found in 2007/08. The 2009/10 spring mean SMN for small and large crops were not significantly different (*P*>0.05), small crops had a mean spring SMN of 35 kg/ha with a 21–90 kg/ha range, while large crops had a mean spring SMN of 27 kg/ha, with 17–32 kg/ha range. The spring 2009/10 mean small crop N was 29 kg/ha and ranged from 2–57 kg/ha, which was not significantly (*P*>0.05) lower than the mean spring large crop N of 51 kg/ha and ranged from 24–71 kg/ha. The 2009/10 spring mean total SNS for small and large crops were not significantly (*P*>0.05) different, small crops had a mean of 64 kg/ha (34 – 93 kg/ha range) and large crops had a mean of 77 kg/ha with a 43–104 kg/ha range.

Harvested SNS

Table A5.3. Harvested SNS (kg/ha) with treatments intended to give small and large crops at individual sites over the three years.

Year	Site ID	Crop N (kg/ha) Small Crop	Large Crop
2007/08	8A-R001/2	95	52
2007/08	8A-R003/4	75	157
2007/08	8A-R005/6	79	73
2007/08	8A-R007/8	110	137
2007/08	8A-R09/10	87	88
2007/08	8T-R011/12	84	110
2007/08	8T-R015/16	169	166
2007/08	8T-R017/18	123	145
2007/08	8T-R019/20	206	220
	Mean	**114**	**128**
2008/09	9A-R021/22	104	221
2008/09	9A-R023/24	95	108
2008/09	9A-R025/26	91	46
2008/09	9A-R027/28	60	59
2008/09	9A-R029/30	95	84
2008/09	9T-R031/32	120	113
2008/09	9T-R033/34		
2008/09	9T-R035/36	161	142
2008/09	9T-R037/38	111	92
2008/09	9T-R039/40	152	80
	Mean	**110**	**105**
2009/10	10A-RO41/42	64	81
2009/10	10A-RO43/44	51	82
2009/10	Extra	90	135
2009/10	10A-RO47/48	52	96
2009/10	10A-RO49/50	207	172
2009/10	10T-RO51/52	34	50
2009/10	10T-RO53/54	34	103
2009/10	10T-RO57/58	137	257
2009/10	10T-RO59/60	38	115
2009/10	10T-RO61/62	115	72
	Mean	**82**	**116**
Overall Mean		**101**	**116**

The mean harvested SNS for the small treatment in 2007/08 was 114 kg/ha and ranged from 75 to 206 kg/ha, while the mean harvested SNS for the large treatment was 128 kg/ha and ranged from 52 to 220 kg/ha. In summer 2008/09 the mean crop N for the small treatment was 110 kg/ha (60–161 kg/ha range) and the mean crop N for the large treatment was 105 kg/ha, with a 46–221 kg/ha range.

In 2009/10 the mean harvested SNS for the small treatment was 82 kg/ha and ranged between 34 and 207 kg/ha while the mean for the large treatment in 2009/10 was 116 and ranged between 50 and 257 kg/ha.

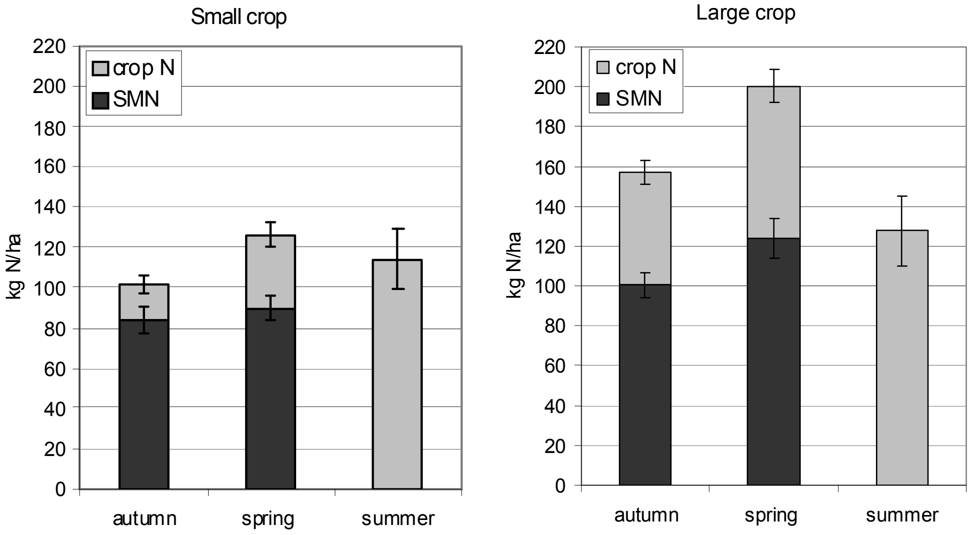


Figure A5.1. Mean SMN (kg/ha) and crop N (kg/ha) in autumn, spring and summer 2007/08 with small and large crop treatments. N=9 ± SEM per treatment.

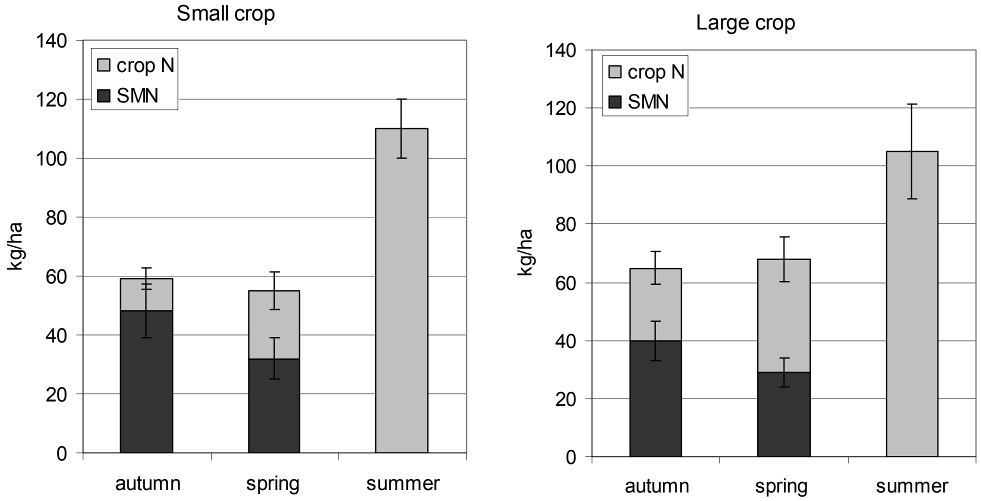


Figure A5.2. Mean SMN (kg/ha) and crop N (kg/ha) in autumn, spring and summer (2008/09) with small and large crop treatments. N=9 ± SEM per treatment.

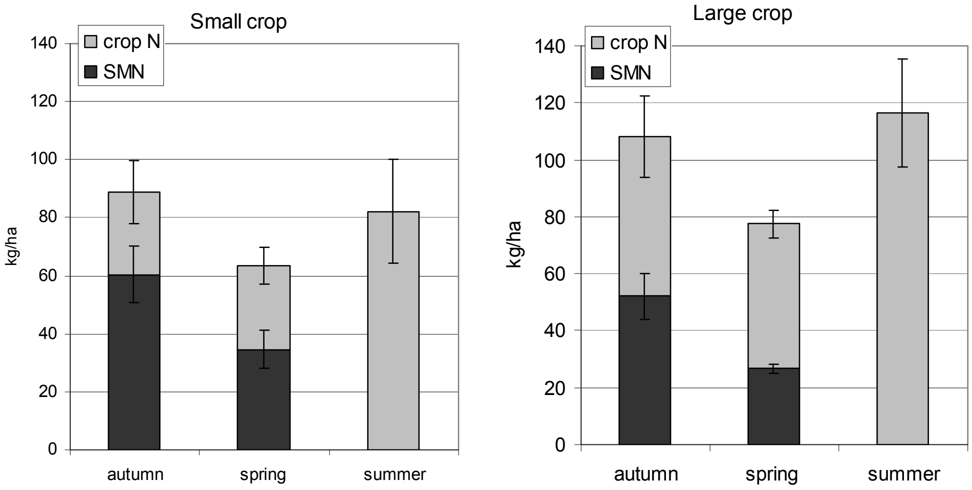


Figure A5.3. Mean SMN (kg/ha) and crop N (kg/ha) in autumn, spring and summer 2009/10 with small and large crop treatments. N=10 ± SEM per treatment.

ANNEX 6: MODELLING IMPLICATIONS FOR SMN SAMPLING STRATEGIES OF SPATIAL VARIATION IN SMN.

By Ben Marchant (Rothamsted Research)

Worked conducted as part of HGCA Project 3189, *Cost effective sampling strategies for soil management,* by B.P. Marchant, A.G Dailey and R.M. Lark of Rothamsted Research.

Modelling SMN

Models of spatial variation of SMN were fitted to datasets from nine fields. All fields were close to Reading or Silsoe / Rothamsted research stations. Data were generally only from 0-30 cm soil depth. Data down to 90 cm were limited. A constant multiplier (fitted to the data) was used to convert from 0-30 cm to 0-90 cm. This was equivalent to assuming that the coefficient of variation (CV) in 0-90 cm layer was equal to the CV of the 0-30 cm layer. There was insufficient evidence make more complicated adjustments. CVs for the datasets ranged between 0.4 and 0.75.

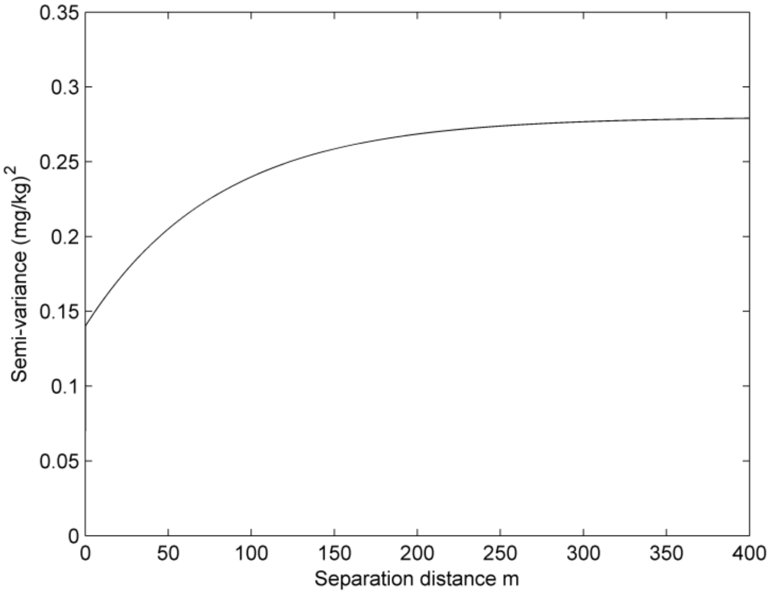


Fig A6.1. Variogram showing spatial correlation up to approximately 200 m.

The fitted model assumed that variation increased linearly with the mean SMN of the field (i.e. error as a % did not vary with mean SMN). The fitted proportionality constant was 0.51. An exponential variogram model was fitted to the remaining variation and this suggested that the effective range of spatial-correlation was approximately 200m and more than 50% of the variation was nugget (not spatially correlated) (Figure A6.1).

Simulating SMN

The fitted SMN model was used to simulate SMN across fields by the LU simulation method[2]. Outlines for fields of size 5, 10, 20, 30, 60 ha were extracted from SOYL datasets. Where barometer fields were used, these were positioned in the south-western corner of the field. All results were based on 5000 simulated realizations. For each realization an underlying mean of the SMN was input to control the variability of SMN and allow exploration of the effectiveness of different sampling schemes for different SMN levels.

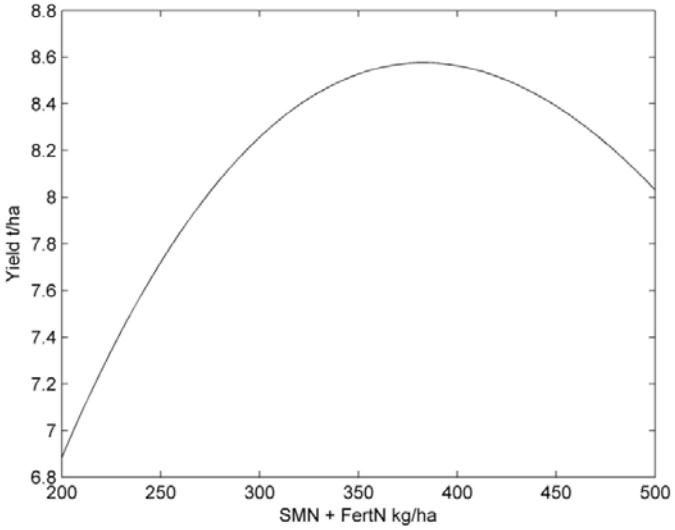


Figure A6.2. Yield response

Sample schemes

Sample schemes were all based on a 'W' design. Tests showed that benefits from optimized designs were small (although optimized designs might be cost effective in other situations). A 'W' transect was drawn across the field (or the barometer field). A number (n) of equally spaced cores were 'extracted' on this transect. These were bulked to form a single field estimate of SMN. Sampling costs were based on discussion with soil sampling companies – £5.33 per core extracted, plus £36 to analyze a bulk sample to 90 cm.

Modelling yield response to N

A single yield response curve was fitted to data from HGCA report (Sylvester-Bradley et al. 2008; Figure A6.2). Optimum yield was 8.6 t/ha.

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[2] Deutsch & Journel 1998. GSLIB Geostatistical Software Library and User's Guide. Oxford University Press.

Estimating N application rate

For each simulated realization, the N application was chosen to maximize profit (value of yield – fertiliser cost) based on the assumption that SMN in the field was equal to the estimate from the bulked sample. The price of wheat was assumed to be £ 100/t, and the break even ratio with fertiliser N = 5, equivalent to ammonium nitrate at £173/tonne.

Simulation tests

(i) No prior (before sampling) knowledge of SMN

For each realization of SMN across the field, a value for the underlying mean SMN was sampled from a uniform distribution between 0 and 300 kg/ha. Field SMN was estimated by sampling, and N application rate was estimated as described above. Then total profit (yield value – fertiliser cost – sampling costs) was calculated, and was averaged over 5000 realizations. Tests were repeated over all field sizes, sampling the whole field or sampling 5 and 10 ha barometer fields with different numbers of cores extracted.

(ii) Uncertain prior (before sampling) knowledge of SMN

Here it was assumed that the farmer had uncertain knowledge of the underlying mean of field SMN content (based on soil type, previous crop, previous applications etc.). Probability distribution functions (pdfs) of this knowledge are shown below. The amount of uncertainty was based on the premise that when SMN is thought to be between 0-50 kg/ha there is a 2% chance that the actual value is greater than 200 kg/ha (Figure A6.3). The same underlying uncertainty was assumed with medium and large expected SMN. Nevertheless, note that uncertainty for medium and large SMN was successively greater than for small SMN because, in the model, the variance of SMN increased with SMN.

In simulation tests the expected SMN was fixed and then underlying SMN was sampled from the corresponding pdf. This was used to simulate SMN across the field and then to proceed as in the 'no prior knowledge' tests above. Total profit was again averaged over 5000 realizations. Tests were repeated for different expected SMNs, different field sizes, both with and without barometer fields. Average profits with sampling were compared with profits when 'before sampling' estimate of SMN was assumed.

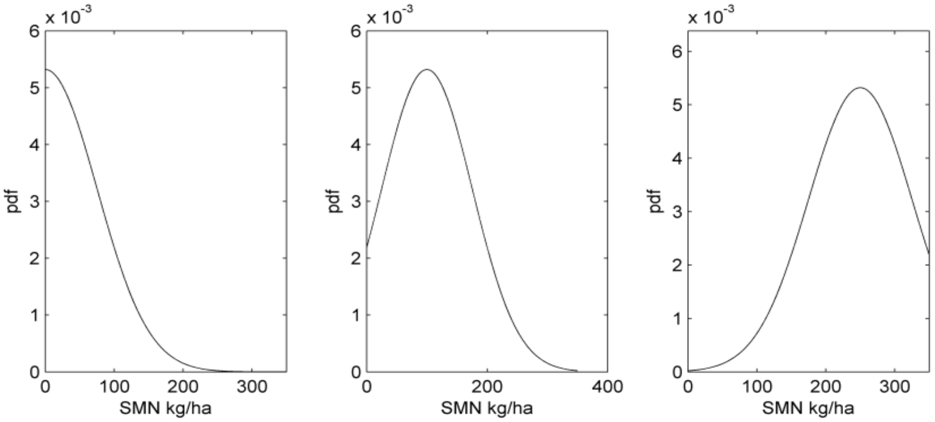

Figure A6.3. Pdfs of prior (before sampling) knowledge of underlying mean SMN.

Results

With the assumptions summarised above, the optimum number of cores required to maximise the economic benefits of sampling (compared to fertilising according to the expected SNS) varied from less than 5 on small (5ha) fields to more than 20 on large (60ha) fields (Figure A6.4), and the optimum number of cores increased as expected SNS increased. The optimum number of cores was reduced by two or three if a 'barometer' portion of the field was sampled only.

The benefits of basing fertiliser N decisions on SMN sampling rather than assuming an 'expected SNS' were largest for an expected SNS of about 175 kg/ha (Figure A6.4). As the level of expected SNS increased beyond 175 kg/ha the benefits of sampling diminished because remaining responses to fertiliser N at these high SNS levels are small. Benefits of sampling obviously increased with larger fields.

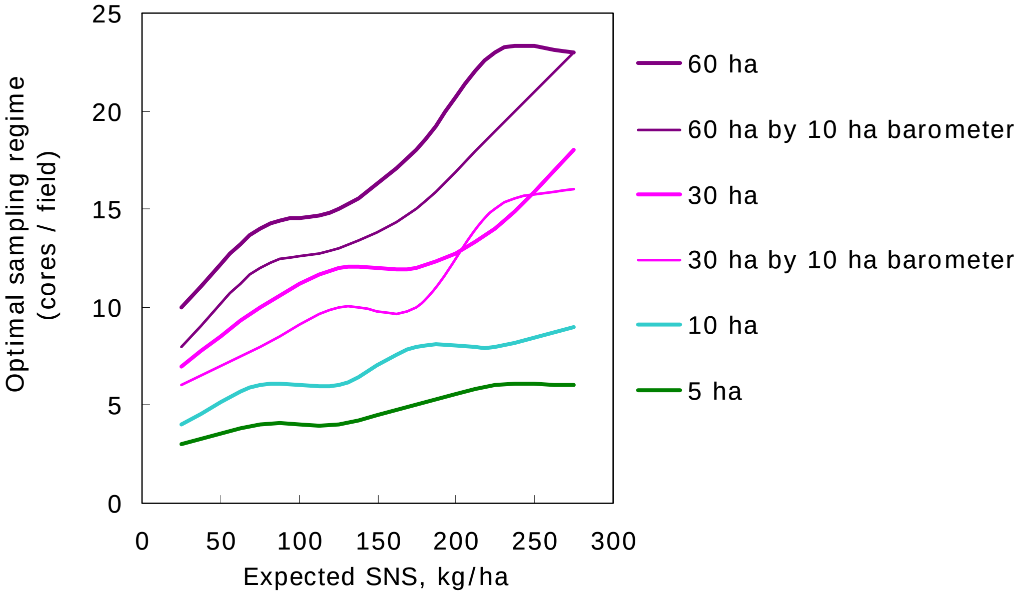

Figure A6.4. Estimated optimal core numbers for sampling SMN, according to different levels of expected SNS, different field sizes, and whether sampling was constrained to 'barometer' fields.

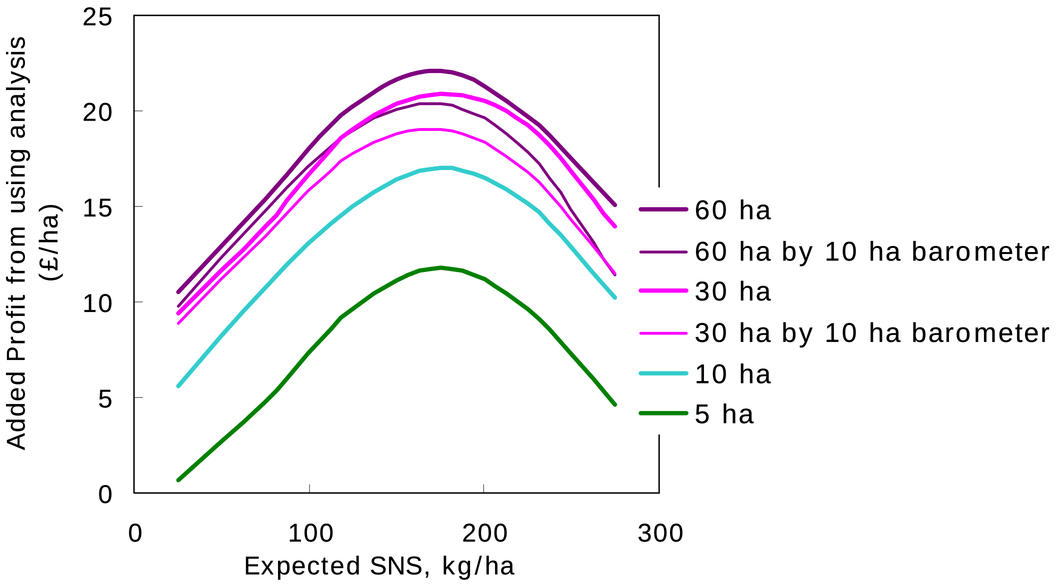

Figure A6.5. Estimated added profit from using SMN analysis to predict harvested SNS (hence profit from N fertiliser use), instead of using ‘expected SNS’, according to different levels of expected SNS, different field sizes, and whether sampling was constrained to ‘barometer’ fields.