June 2016

Research Review No. 3110149017

Review of guidance on the principles of crop nutrient management and fertiliser use

Susie Roques[1], Stuart Knight[2], Nathan Morris[2], Ron Stobart[2], Pete Berry[3], John Williams[1] and Paul Newell Price[4]

[1]ADAS Boxworth, Battlegate Road, Boxworth, Cambridgeshire, UK, CB23 4NN

[2]NIAB, Huntingdon Road, Cambridge, UK, CB3 0LE

[3]ADAS High Mowthorpe, Duggleby, Malton, North Yorkshire, UK, YO17 8BP

[4]ADAS Gleadthorpe, Meden Vale, Mansfield, Nottinghamshire, UK, NG20 9PD

This review was produced as part of the final report of an 8.5 month project (3110149017) which started in September 2015. The work was funded by AHDB under a contract for £98,669. There were six work packages. This report reviews findings from WP1 – Principles of nutrient management.

CONTENTS

Abstract

The Crop Nutrient Management Partnership (CNMP) was set up by AHDB to review and revise the “Fertiliser Manual (RB209)” and produce a new “Nutrient management Guide (RB209)” for release in May 2017. The main aim of the overall project was to review research since 2009 on crop nutrition for the main arable and grassland crops of England, Wales and Northern Ireland (N.I.) and based on the findings, to revise and amalgamate sections to inform revisions of RB209. The specific objectives of this report were to review research since 2009 and current industry practice on factors affecting nutrient management and propose revisions that are relevant to the principles of nutrient management. Existing recommendations have been summarised and evidence from AHDB, Defra and other relevant projects carried out since 2009 reviewed. Opinions relevant to the WP1 received from eight organisations were also summarised.

The estimation of soil nitrogen supply (SNS) using the ‘Measurement Method’ was re-assessed to take account of recent research on the efficiency with which soil mineral nitrogen (N) is taken up by crops and the amount of N mineralised from soils according to their organic matter content. There was insufficient evidence to justify significant changes to the methodology, but clarification is provided on when to use the approach and how to estimate the amount of N likely to be mineralised from soil organic matter. Findings summarised in AHDB Cereals Topic Sheet 115 have been incorporated. Clearer guidance is also provided on the SNS following the destruction of well-established cover crops. Research on the use of starter fertiliser on cover crops was limited in quantity. Evidence to date does not show consistent benefits from its use.

Recent research on the efficiency of crop N uptake from different types of N fertiliser is reviewed and advice revised. The use of nitrification inhibitors is also discussed. Advice on sulphur (S) is revised to take account of continuing declines in S deposition and recent work on S balances in different crops, based on British Survey of Fertiliser Practice data. In the absence of S response data for grassland and vegetables, sulphur recommendations are based on findings from experiments carried out mainly on cereals and oilseed rape. It is proposed that S fertiliser is applied at rates currently advised in RB209 to most crops and grassland in high risk situations, defined by soil type (lower clay/organic matter content) and rainfall (wetter areas).

Recent research indicates that it may be possible to sustain crop productivity at lower phosphate reserves than currently advised. However, the research is limited in quantity and more work is needed to confirm initial findings. It is therefore proposed that phosphate and potash recommendations are retained with new advice provided on adjusting application rates to allow users to build up P and K reserves more rapidly, where appropriate; and greater clarity on adjusting application rates for targeted yield. Magnesium and micronutrient recommendations are

revised based on the findings from a recent review of non-NPKS nutrient requirements and AHDB Topic Sheet IS25.

1. Introduction

Application of nutrients, especially nitrogen (N), contributes towards sustainable and profitable production of crop and livestock products. Integrated nutrient management is increasingly important for all sectors of agriculture to improve farm profitability. Encouraging sustainable food production and ensuring the resilience of farming systems in the face of market, regulatory and environmental pressures are also important AHDB objectives to secure agricultural production across all sectors into the future.

Under-application of nutrients can result in reduced crop and livestock production. Equally, over-application results in increased costs, reduced crop yield (and quality) and a waste of valuable nutrients.

The production of a new guide providing practical, robust and clear information on nutrient management for optimal economic production and minimal pollution will help increase awareness and uptake of good nutrient management, leading to increased nutrient use efficiency, more efficient food production and improved farm profitability. Enhancing fertiliser nutrient use efficiency is vital to the sustainability of UK agriculture, especially given that the value of the nutrients applied to land in manufactured fertilisers and organic materials amounts to around £1.6 billion per annum (Anon, 2015; Defra, 2008; WRAP, 2013, 2014).

Good nutrient management helps achieve improved water quality by limiting losses of phosphorus and nitrogen to ground and surface waters, and improved air quality by reducing ammonia and greenhouse gas emissions; thereby reducing the carbon footprint of UK agriculture. Ensuring soil pH is at target levels, soil nutrient reserves are adequate for optimal crop production, and all major and micro nutrients are supplied to meet crop requirements (both in terms of quantity and timing of supply) is crucial for optimal nutrient use efficiency.

1.1. Aims and objectives

The main aim of the project was to review research since 2009 on crop nutrition for the main arable and grassland crops of England, Wales and Northern Ireland (N.I.) and based on the findings, and where appropriate, to revise and amalgamate sections in the “Fertiliser Manual (RB209)” to produce new, clear, standalone and scientifically robust recommendations. The main objectives were to:

- Evaluate and review Defra and AHDB (and where applicable other UK) research undertaken since 2009 on the principles of crop nutrient management and crop nutrition.

- Identify where changes to recommendations can be made.
- Present changes in a format suitable for a future RB209 revision.
- Identify knowledge gaps and priorities for future research

The specific objective of this review of the principles of nutrient management (WP1) was to:

- Review research and current industry practice on factors affecting nutrient management since the 8th edition of RB209.

Revisions of section 1 in the “Fertiliser Manual (RB209)” are provided in an Appendix. Both the introduction and the principles of good nutrient management and fertiliser use have been shortened in length while retaining all the key information required by users to manage nutrient inputs effectively to optimise economic crop production and maximise nutrient use efficiency.

1.2. Methodology

RB209 (8th edition) recommendations were summarised and evidence from AHDB, Defra and other relevant projects carried out since 2009 reviewed. Letters and emails were sent to agronomists, contacts in fertiliser companies, breeders and other industry experts (see Appendix I for full list) for their opinions about RB209 (8th edition) in terms of areas where:

- advice is vague or insufficient;
- relevance is limited due to changes in crop areas or industry practice;
- current practice is substantially different from RB209 guidance; and
- recent research may allow improvement on existing advice.

Colleagues were consulted within ADAS and NIAB; and the opinions of the AHDB Technical Working Groups (TWG’s and Crop Nutrient Management Partnership (CNMP) Steering Group were recorded. Industry contacts were also invited to submit data for use in the review. A total of 25 organisations relevant to this work package were contacted; other organisations were contacted as part of the consultation process for other work packages. Opinions relevant to the WP1 review were provided by eight organisations.

2. Consultation on RB209 (8th edition)

2.1. General

As in the earlier (2006) consultation, most respondents were broadly positive about the existing RB209, but strongly welcomed the review and revision process.

Several sources suggested that the scope and confidence of recommendations, particularly for N, should be clearer. There is no indication in RB209 (8th edition) of the size of the evidence base for different recommendations, or the level of accuracy. For example, nitrogen recommendations are given to the nearest 10 kg/ha, but earlier studies have indicated that economic optimum can be up to 40-50 kg/ha from the RB209 recommendation. Similar feedback – that all recommendations should be more transparent and include mention of the evidence base – was also given in the 2006 consultation.

K+S suggested that RB209 should include a fuller introduction, including the principles of soil science and their relevance to fertiliser use, requirements and losses. Specific areas he suggested should be covered were soil structure, drainage, organic matter and pH.

At the Arable Technical Working Group (TWG) meeting on 25th April 2016 it was stated that greater importance should be given to crop rotations; and the concept of planning rotations to build up soil fertility. It was felt that the section on 'Integrated plant nutrient management' on p.17 of the 8th edition could be expanded.

At the CNMP Steering Group meeting on 28th April 2016 it was felt that revised text should highlight the fact that the "Nutrient Management Guide (RB209)" provides guidance based on best available evidence. It was also suggested that a better description of the relationship between nitrogen and sulphur requirements should be provided.

Some respondents questioned whether precision farming needed specific coverage, with one organisation adding that precision farming can and should use the same principles from RB209 as more conventional farming. Precision farming technologies enable some crop nutrient requirements, such as crop N requirement, to be estimated more accurately, but there is no need for different guidance.

2.2. Phosphorus and potassium

K+S suggested that P and K should be addressed separately within RB209 as they are different in many ways. Since the comments of many respondents were related to both, they will be addressed together here.

BSFP data (Anon, 2015) shows that average phosphate applications in 2009-14 were lower than the RB209 (8th edition) recommendations to replace offtake. For cereals, RB209 (8th edition) recommended applications of 45-60 kg/ha to replace offtake when straw is incorporated, or 50-65 kg/ha if straw is removed, and for winter oilseed rape the recommended maintenance application was 50 kg/ha. Actual applications to all tillage crops averaged 29 kg/ha in the 2010-14 period, despite straw being removed from >70% cereal crops. However, these lower applications may have been because many soils contain high levels of P, so it was not necessary to fully replace offtake: NRM data indicates that 30% of arable soils tested were at the recommended Index of 2, 49% were > Index 2 and 21% were < Index 2. The mean P level in arable soils tested by NRM was 30 mg/l, which was above the target range of 16-25 mg/l. Despite applications being below recommended maintenance rates, there appeared to be a slight trend for increasing soil P in arable soils tested by NRM over the last 20 years (1996-2015).

Similarly for potash, BSFP data (Anon, 2015) indicates that average applications were lower than recommended. RB209 (8th edition) recommended that cereals need 35-45 kg/ha to replace offtake if straw is returned, or 70-105 kg/ha if straw is removed, and winter oilseed rape needs 40 kg/ha. Although straw was removed from >70% cereal crops, the average application to all tillage crops in the 2010-14 period was only 39 kg/ha. This could not be easily explained by excess K levels in UK soils, as NRM data provides the following summary: 35% soils were at the target Index of 2-, 33% were > index 2- and 32% were < Index 2-. Mean soil K in NRM tests was 170 mg/l, which was within the target range of 121-180 mg/l. Despite applications being below recommended maintenance rates, there appeared to be a slight trend for increasing soil K in arable soils tested by NRM over the last 20 years (1996-2015).

In contrast to the data, which suggested that farmers were applying less P and K than recommended, several respondents stated that RB209 (8th edition) recommendations were too low. Specifically, the PDA said that the build values for bringing soil P and K up to target Indices were too low, such that recommended applications would take 10-15 years to raise soil Index by 1. Additionally two respondents queried whether K application rates should match plant uptake rates as these are often much greater then net offtake. However, a number of agronomists agreed that P and K recommendations in RB209 (8th edition) were about right, and approved of their flexibility to take yield into account.

One stakeholder requested clarification as to whether P and K applications should be calculated based on the crop that is being grown, or the crop that was grown the previous season. This confusion arises from the mention in some places in RB209 (8th edition) of estimated yield (implying consideration of the current crop), but in other places of achieved yield (implying previous crop).

There is a clear need to confirm that the advice is intended to refer to the current crop, and so rates should be based on expected or targeted yield.

One organisation requested clearer guidance on the role of leaf tissue analysis in determining K applications, and K+S requested coverage of the effects of P and K status on N uptake and assimilation.

At the CNMP Steering Group meeting on 28th April 2016, it was suggested that information on patchy diagnostic tissue sampling/testing in good and bad parts of a crop could be a useful addition to account for different nutrients and situations when tissue analysis is useful.

2.3. Magnesium

The British Survey of Fertiliser Practice does not collect data on Mg applications. NRM data shows that 43% of arable soils tested by NRM were at the target Index of 2, 37% were > Index 2 and 20% were < Index 2, with no long term trend for change in mean soil Mg. Mean arable soil Mg in NRM tests was 110 mg/l, slightly above the target range of 51-100 mg/l.

One organisation disputed the claim in RB209 (8th edition) that Mg applications to potatoes or beet will be sufficient for other crops in the rotation, based on calculations using typical rotations and offtake values. NIAB requested clearer guidance on Mg, since RB209 (8th edition) stated that yield responses to Mg were rare, and most soils were at or above the target Mg Index, but tissue analyses were often reported by labs as indicating Mg deficiency in crops.

At the Arable TWG meeting on 25th April, some attendees felt that the sentence on Mg and K interactions on page 42 of the 8th edition was confusing and should be revised, as it did not clearly explain the relationship between soil extractable Mg and K and the implications for potash deficiency. If RB209 guidelines are followed and K Index is maintained at target levels, potash deficiency is unlikely. However, it is not certain whether this is the case irrespective of the Mg Index. On balance, to avoid confusion the sentence in question has been removed.

2.4. Micronutrients

The paucity of information about micronutrients was raised by individuals from four separate organisations. Particular uncertainties mentioned were the role of leaf tissue analysis, the use of foliar micronutrient products, and phosphite.

At the Arable TWG meeting on 25th April 2016 the application of boron to cereal crops and the reference to toxicity in AHDB Cereals & Oilseeds Information Sheet 25 were discussed. It was agreed that the statement implying that boron is always toxic to cereals should be clarified.

2.5. Other

Existing guidance on estimation of soil N supply, and its effects on N recommendations, were questioned by one organisation. It was pointed out that AHDB Cereals & Oilseeds reports RR58 and PR490 showed that measurement of soil mineral N is less useful than suggested in the 8th edition of RB209, and the 100% recovery of soil mineral N was also queried.

Sources in NIAB requested more guidance on cover crops (including establishment) and their effects on the N requirements of the following crop.

3. Evaluation of new information and updates to RB209 guidance

3.1. Lime recommendations

3.1.1. RB029 (8th edition) advice

The 8th edition provided optimum soil pH values for different cropping and grassland scenarios and lime recommendations based on topsoil texture, initial soil pH and land use (Arable/Grass). There was also information on the key properties that determine the value of liming materials and advice on lime application.

3.1.2. Comments from Consultation

There were no comments on the lime recommendations from the consultation and no new information arising from the ‘principles’ review. However, the RB209 TWG felt that inclusion of the liming factor in the RB209 lime recommendations table would aid the clarity and precision of the recommendations. Consideration should also be given to the inclusion of advice on the use of seashell sand and its impact on soil pH.

3.2. Soil nitrogen supply

3.2.1. RB029 (8th edition) advice

Soil nitrogen supply (SNS) is an important source of ‘free’ nitrogen (N) for crop growth, It consists of N deposited from the atmosphere, the residual mineral N not used by previous crops and N mineralised from crop residues, soil organic matter (SOM) and from organic manures applied in previous years; soil mineral N (SMN – the amount of N in the soil at the time of testing) is distinct from N that is subsequently mineralised from organic matter in warm and moist soil conditions. It is important that SNS is taken into account as part of good nutrient management.

In RB209 (8th edition) Section 1 (Principles), the coverage of SNS can be summarised as follows:

- SMN and mineralised N were identified as contributing to the SNS;
- SNS was identified as a factor influencing decisions about N use / crop requirement;
- SNS was defined and differentiated from SMN;
- Calculation of SNS was explained;
- Key factors influencing SNS were listed;
- Post-harvest mineral N residues and the use of cover crops to reduce nitrate leaching losses was described;
- Importance of excess winter rainfall was explained;
- Release of N from mineralised organic matter was explained;
- SNS Index System was introduced;
- Field assessment method (FAM) was outlined;
- SNS measurement method was outlined;
- Efficiency of N uptake was described, including assumption of 100% for SMN.

In Section 3 (Using the recommendation tables), the field assessment method (FAM) was described in detail using the following steps:

1. Identify soil type
2. Identify previous crop
3. Select excess winter rainfall
4. Identify provisional SNS Index
5. Adjust for certain conditions

The SNS measurement method was also described in detail:

1. Measure SMN
2. Estimate N already in crop
3. Adjust for net mineralisable N
4. Identify SNS Index

In Section 4 (Arable and forage crops), a checklist for decision making included instruction to identify SNS of the field by carrying out SMN analysis or by using FAM (based on previous cropping, previous fertiliser and manure use, soil type and excess winter rainfall), and a recommendation to sample and analyse for SMN where N residues were expected to be moderate or high (e.g. following regular manure use, the incorporation of leafy crop residues, high rates of N fertiliser, limited yield of the previous crop or a dry winter).

In Section 5 (Vegetables and bulbs), N residues following vegetable crops were explained, and assessment of SNS for vegetable crops was described (including the importance of rooting depth).

Appendix 1 (Soil types) described soil types and assessment of texture (repeat of information in Section 3).

In Appendix 2 (SMN sampling),

- SNS was defined and differentiated from SMN;
- Calculation of SNS was explained;
- Sampling uncertainties were outlined;
- Targeting fields for sampling was described;
- Soil sampling guidance was provided: time, method and depth of sampling, transport to the laboratory;
- Analysis in the laboratory was outlined;
- Estimating crop nitrogen content was described;
- Estimating mineralisable N from organic matter was described.

3.2.2. Other relevant documents

The NVZ guidance (2013-16) required that four steps were followed when planning nitrogen applications to each crop in each field. Step 1 required calculation of the amount of nitrogen in the soil that is likely to be available for uptake by the crop during the growing season (SNS). Annex 1 permitted assessment of SNS using an Index value (i.e. FAM) and recommended soil sampling and analysis if SNS is uncertain or expected to be high. It was stated that assessment must include an estimate of the amount of mineralisable N from organic matter or residues.

The Nitrogen for winter wheat management guidelines (Sylvester-Bradley *et al*., 2009):

- Provides a chart for estimating SNS based on soil type, overwinter rainfall and previous crop.
    - The light sand soils category in RB209 is split down further
    - SNS Indices in RB209 are replaced with sliding scale of SNS levels from 50 to >200, where:
        - For Low SNS the recommendation is that SMN analysis is seldom worthwhile
        - For Medium SNS the recommendation is to use SMN analysis on a few barometer fields
        - For High SNS the recommendation is that it is worth checking with SMN analysis

- Prioritises sampling on fields with large or uncertain SNS, or with known high SOM (but not peats); previously in grass; or receiving significant organic manure. Also includes fields where effects *e.g.* lodging or unexpectedly high grain protein, have occurred.
- BUT also recommends annual sampling of representative barometer fields to assess year-on-year SNS variation.
- Recommends sampling practice as follows:
  - Sampling times depend on soil type and excess winter rainfall (Nov-Dec suggested for medium and deep clay / silt soils with low excess rainfall, Jan-Feb for most soils with high excess rainfall). This is broadly consistent with RB209 ('early' or 'late' winter or 'early spring');
  - Recommended sampling depth 0-60cm until January, 0-90cm from February. This is consistent with RB209;
  - Sample at least 15 points in each field, 20 or more in variable fields;
  - Keep samples cool and ensure analysis within 48 hours for nitrate and ammonium;
  - Arrange topsoil analysis for total N (%) or organic matter (%) if not already known. This is not included in RB209.
- Assessment of crop N content uses a similar approach to the 8th edition of RB209 (shoots/m^2), but the N content estimates are at the upper end of the ranges given in RB209 (8th edition; assumes spring not autumn assessment).
- States that additional N is likely to be released by mineralisation during the season where topsoil organic matter content exceeds 5% in England and Wales (10% in Scotland / N Ireland):
  - Add 40 kg N/ha for mineralisable N where organic matter is 6-10%. This was different from RB209 (8th edition), which proposed no adjustment for mineralisable N below 10% organic matter
  - Add 100 kg N/ha for mineralisable N where organic matter is 11-15%. This was comparable with RB209 (8th edition), which indicate an extra 60-90 kg N/ha of mineralisable N compared with 3% organic matter soils.
- Calculation of crop N requirement assumes that SMN and mineralisable N are used with 100% efficiency.

SRUC Technical Note 651 (Sinclair & Wale, 2013) estimates N residues from previous crops as follows:

- Nitrogen residues from soil reserves are arranged into six soil types (categories are different from RB209):
  - Shallow soils: all mineral soils which are less than 40 cm deep.
  - Sands soils: which are sand and loamy sand textures to a depth more than 40 cm.
  - Sandy loams: soils which are sandy loam texture to a depth of more than 40 cm.

    - Other mineral soils: soils with less than 15% organic matter that do not fall into the sandy or shallow soil category (i.e. silty and clay soils).
    - Humose soils: soils with 15% to 35% organic matter. These soils are darker in colour, stain the fingers black or grey, and have a silky feel.
    - Peaty soils
- The last crop grown is allocated into one of five Previous Crop Groups, numbered 1 to 5 in ascending order of residual available N in the soil following harvest of the previous crop:
    - Group 1: all winter and spring cereals, linseed, low N vegetable crops
    - Group 2: forage maize, oilseed rape, potatoes, vining peas
    - Group 3: beans (field, broad, vining), combining peas, medium N vegetable crops
    - Group 4: grain lupins, lettuce
    - Group 5: high N vegetable crops
- These groups are more differentiated than those used in the (moderate rainfall) FAM tables in RB209 8th edition) for light, shallow or medium soils (2 or 3 groups only), and are more similar to the RB209 groups for 'deep silty soils' (4 groups).
- Additional guidance:
    - Residues following cereals are generally lower than those following break crops.
    - The management and performance of the previous crop can have a significant effect on the actual level of N residues.
    - Residues are expected to be lower in a high yielding season or where N application has been less than normal, but may be higher than average if the crop has performed badly due to problems such as disease or drought.
    - In Group 5, N residues can be very variable. Analysis of the crop debris for total N and C content along with an estimate of the quantity ploughed down is recommended in order to help predict release of available N for the next crop.

Unlike RB209 (8th edition), SRUC Technical Note 651 makes soil type and rainfall adjustments to the N recommendations rather than the SNS estimate: if more than 450 mm of rain falls between 1 October and 1 March the standard N recommendations are adjusted, individually for each crop, and separate values for sands, sandy loams, shallow soils and all other soils. SMN analysis is not considered.

3.2.3. Comments from Consultation

Only one response suggested that (in some years) SNS levels indicated in RB209 (8th edition) are too high, (particularly after high yielding years where lower levels of nitrogen will be left behind).

One response questioned the inclusion of soil mineral nitrogen testing under the heading 'The Basis of Good Practice' and sub-heading 'Reliable Information', pointing to evidence on the uncertainties from Knight (2006) and Kindred *et al*. (2012).

One response to the consultation questioned the RB209 assumption of 100% efficiency of use of SMN, suggesting that a figure of nearer 50% is more appropriate. This is reviewed in more detail in the 'Evidence' section.

The same response questioned the RB209 (8th edition) assumption that mineralised N will compensate for an actual efficiency of use of less than 100% to give the apparent equivalent of 100% efficiency, suggesting instead that the amount of this additional contribution to the soil N supply was better represented as a fixed value independent of the amount of SMN.

It also questioned whether the 100% assumption was in conflict with the statement in RB209 (8th edition) under 'Make an adjustment for net mineralisable nitrogen' that states 'In mineral soils of low to average organic matter content (less than about 10%), the amount of net mineralisable nitrogen will be small and for practical purposes, no adjustment is needed when using the recommendation'.

It was suggested that the implication of all of this would be that the level of adjustment of fertiliser N rate according to SNS in the 8th edition of RB209 (approximately 30 kg N/ha less fertiliser for each additional 20 kg N/ha SNS above Index 0) was too large because it assumed 100% efficiency for SMN and only 60% efficiency for fertiliser N.

One respondent observed that SNS seems strongly linked to soil organic matter (SOM) even over the normal range in arable soils (2-6%), noting that early spring aerial photos often show lusher crops on the soil types of higher organic matter in the field. The respondent proposed that it would be simplest for an amount of mineralised N to be subtracted from the N recommendation rather than adjusting the SNS Index. It was suggested that N recommendations be decreased (or increased) by 10 kg N/ha per 1% SOM above (or below) 4% (based on 0-15 cm soil layer), but with no adjustment in the range 3-5%. This would appear to assume equal efficiency of use of mineralised and fertiliser N. For stony soils the adjustment would be reduced by one third. It was also noted that SOM as measured by the 'Loss on Ignition' method gives results up to 15% higher than the Walkley Black method.

At the Arable TWG meeting on 25th April it was agreed that there should be more information on stony soils in the "Nutrient Management Guide (RB209)" as water availability and fertiliser use efficiencies can be significantly different from stoneless soils. Guidance in the principles section should be signposted from the grass, arable and horticulture sections.

3.2.4. Current Practice

According to the British Survey of Fertiliser Practice (Anon, 2015), 13% of the tillage area was soil tested for nitrogen in 2014, compared to 3% of the grass area. The report did not make clear exactly what test was carried out, but it is assumed to be soil mineral nitrogen (SMN) with or without a test to help estimate mineralisable N.

3.2.5. Review of new information

AHDB Cereals & Oilseeds Project Report 490: Establishing best practice for estimation of Soil N Supply

The main objectives of the project (Kindred *et al.*, 2012) were to:

- Identify key uncertainties in the measurement of SMN and develop recommendations for best practice;
- Compare on-farm strategies for using direct SNS measurements against the FAM in the 8th edition of RB209;
- Evaluate best strategies for different field and farm types.

The project used the amount of N taken up by an unfertilised crop by harvest (termed 'harvested SNS') as the most meaningful metric of soil-derived N (as it affects fertiliser requirements)

Harvested SNS and autumn or spring measured SMN/SNS values were analysed from over 550 cereal experiments, carried out since 1980 over a wide range of soil types, farming systems and locations in the UK. Harvested SNS values ranged from less than 20 to 350 kg N/ha. Most were less than 100 kg N/ha (SNS Index 0, 1 or 2) although 40% of sites had harvested SNS greater than 100 kg N/ha (SNS Index 3 or higher). Similarly, 35% of measured SMN values were above 100 kg N/ha.

The dataset largely supported assumptions in the 8th edition of RB209 on soil type, previous crop, rainfall and organic manure effects:

- High SNS levels were much less common on light and shallow soils than on more retentive soil types (clay and silt soils);
- There were differences in harvested SNS and measured SMN following different crops, tending to be lowest following cereals or sugar beet and higher following oilseed rape or peas and beans;

- A greater proportion of sites had harvested SNS of less than 100 kg N/ha in high rainfall areas (>700 mm annual rainfall or >250 mm excess winter rainfall) than in low or moderate rainfall areas;
- 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 harvested SNS;
- Sites with higher organic matter also tended to give high SNS levels.

The relationship between measured and harvested SNS was examined, noting that both are subject to a number of potential sources of error. Using a broken stick regression model (Figure 1), overall 28% of the variation in harvested SNS was explained by the 'Measurement Method' in autumn or spring, but this ranged from 0% for shallow soils to 32% for silt soils (Table 1).

The slope of the regression line for the overall dataset was 0.52, indicating that increments of measured SNS of 1 kg N/ha equated on average to increments in harvested SNS of 0.52 kg N/ha. The slope ranged from 0.21 for shallow soils to 0.68 for medium soils. As acknowledged in RB209 (8^{th} edition) Section 1, the slope suggests that actual efficiency with which soil N is used may be closer to the 60% currently assumed for fertiliser N than the effective 100% assumed in the calculation of fertiliser N requirement in RB209 (8^{th} edition). The actual efficiency of use of SMN could be nearer 50% if N already in the crop in spring is assumed to be used with 100% efficiency.

The intercept of the regression line for the overall dataset was 55, indicating an expected harvested SNS of 55 kg N/ha where zero SNS was measured in autumn or spring, which to an extent reflects the amount available on average from deposition and mineralisation in the late spring and summer. The intercept ranged from 46 kg N/ha for (lower SOM) sandy soils to 72 kg N/ha for silt soils.

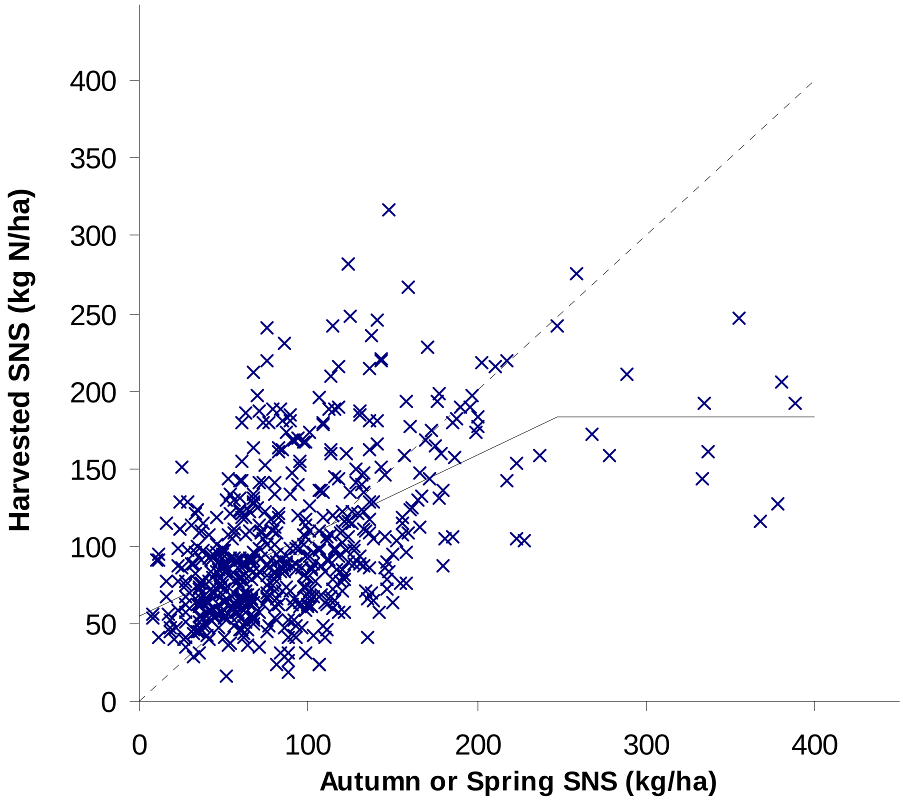

Figure 1. Relationship between measured SNS in autumn or spring and harvested SNS for >550 sites tested since 1980 (Kindred *et al*., 2012).

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 (Kindred *et al*., 2012).

Data group	% variance accounted 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	0.21	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

Harvested SNS and autumn & spring measured SNS values were analysed from 164 cereal sites (mainly winter wheat), in harvest years 2008, 2009 and 2010 over a range of soil types and locations in the UK. Harvested SNS values ranged from less than 20 to 303 kg N/ha. 56% were less than 100 kg N/ha (SNS Index 0, 1 or 2), similar to the previous dataset. In autumn, 62% of sites had measured SNS less than 100 kg N/ha, but in spring 79% of sites had measured SNS less than 100 kg N/ha.

From the 164 cereal sites analysed, it was possible to extract measured (spring, 0-90 cm) and harvested SNS values for 22 specific combinations of rainfall x soil type x previous crop, based on the parameters and groupings used in the 8th edition of RB209, where there are at least two values for that combination, excluding sites with grass or manure history (Table 2). All sites included had less than 5.5% SOM, so no additional adjustment for mineralisable N was made to the measured SNS values.

Table 2. Mean measured and harvested SNS values and corresponding SNS Indices from Project 3425 dataset, for rainfall, soil type and previous crop combinations with at least two values (no grass or manure history) (Kindred *et al*., 2012).

Rainfall category	Soil type group	Previous crop group	Number of sites included	Measured SNS (kg N/ha)	Measured SNS (Index)	Harvested SNS (kg N/ha)	Harvested SNS (Index)	RB209 FAM SNS (Index)
Low	Medium	Cereals	3	69	1	65	1	1
		OSR	3	58	0	78	1	2
		Beans	3	63	1	132	4	2
	Deep Clay	Cereals	3	72	1	50	0	2
		OSR	4	60	0	78	1	3
	Deep Silt	OSR	3	50	0	111	3	3
		High Veg	4	115	3	158	4	4
Moderate	Medium	Cereals	2	36	0	57	0	1
		OSR	8	54	0	83	2	2
		Beans	3	47	0	101	3	2
	Deep Clay	OSR	2	79	1	115	3	2
		Beans	2	53	0	104	3	2
		Peas	2	52	0	72	1	2
	Deep Silt	Cereals	2	140*	4*	135*	4*	1
High	Shallow	OSR	3	60	0	72	1	1
	Medium	Cereals	12	50	0	85	2	1
	Medium	OSR	6	77	1	99	2	1
	Deep Clay	OSR	2	65	1	81	2	1
	Deep Silt	Cereals	2	63	1	65	1	1
	Deep Silt	OSR	3	68	1	81	2	2
	Deep Silt	Peas	3	63	1	108	3	2
	Deep Silt	High Veg	4	162	5	232	5	3

* Note mean comprises one site at Index 1 and one site at Index 5

Key

(green)	Measured or Harvested SNS Index less than RB209 8th Edition FAM
(amber)	Measured or Harvested SNS Index equal to RB209 8th Edition FAM

	Measured or Harvested SNS Index more than RB209 8th Edition FAM

Overall, the dataset largely supported assumptions in RB209 (8th edition) on soil type, previous crop, rainfall and manure effects. High levels of harvested SNS (>160 kg N/ha) were seen most commonly on clay and silt soils in low or moderate rainfall areas. Very high levels of harvested SNS were never seen on light or shallow soils, or in high rainfall areas. However, for the rainfall x soil type x previous crop combinations analysed here, there are indications that measured SNS values were often lower than indicated by RB209 8th edition FAM, whereas harvested SNS values were often higher, especially with moderate or high rainfall.

The relationship between measured SNS in autumn or spring and harvested SNS was examined using a broken stick regression model. 45% of the variation in harvested SNS was explained by measured SNS in autumn (ranging from 0 for shallow soils and light sands to 58% for clay soils), and 49% by measured SNS in spring (ranging from 0 for shallow soils to 62% for clay soils; Table 3). The % variation explained was therefore higher than for the previous dataset. FAM explained 31% of variation in harvested SNS (Table 3). Stepwise multiple regression analysis showed that the biggest improvements to the relationship of autumn or spring measured SNS with harvested SNS came from knowledge of soil type group and previous crop.

The slope of the regression line for the overall dataset was 0.5 for autumn SNS and 0.85 for spring SNS, indicating that increments of measured SNS of 1 kg N/ha equated on average to increments in harvested SNS of 0.5 kg N/ha and 0.85 kg N/ha for autumn and spring SNS respectively. The slopes ranged from 0.84 for light sands to 1.04 for clay soils for SNS measured in spring, and were much closer to the slope of 1.0 that an efficiency of use of 100% might imply.

The intercept of the regression line for the overall dataset was 52 for autumn measured SNS and 44 for spring measured SNS. However, the intercepts ranged from 31 kg N/ha for clay soils to 86 kg N/ha for light sands for autumn SNS, and from 33 kg N/ha for clay soils to 57 kg N/ha for silt soils for spring SNS. Overall the intercepts were comparable with those observed for the previous dataset.

Table 3. Statistical results of broken stick regression analysis between measured SNS in autumn (Aut) and spring (Spr) or FAM, and harvested SNS, for 164 experimental sites in UK between harvest years 2008 and 2010 for different sub-groups of data (Kindred *et al*., 2012).

Group	No. of sites	% variance explained			Intercept			Slope		
		Aut	Spr	FAM	Aut	Spr	FAM	Aut	Spr	FAM
All	164	45	49	31	52	44	-22	0.50	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	3.50	0.84	0.44
Low rainfall areas	44	39	35	27	46	50	-16	0.69	0.86	1.30
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	1.00
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 & Beans	35	26	26	29	71	31	-141	0.38	1.34	2.70
Field veg	12	58	70	25	60	44	-103	0.71	1.05	2.10
Grass or manure	57	39	47	13	68	54	-50	0.39	0.78	1.65
No grass or manure	107	42	48	39	43	39	-35	0.57	0.87	1.48

Kindred *et al*. (2012) identified key uncertainties in the measurement of SMN and provided recommendations for best practice:

- Spring SMN measures explained slightly more of the variation in harvested SNS than autumn.
- In autumn, sampling 0-60 cm was as effective as sampling 0-90 cm, but in spring sampling to 90 cm was best.
- Adjustments for N deposition and crop recovery of SNS improved accuracy and economic performance of SMN predictions.
- Mineralisation measures using SOM%, total soil N% or 'additionally available N' (AAN, offered commercially by CF Fertilisers) 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.
- For oilseed rape, crop N and SMN can be considered to be equivalent in SNS predictions.

- Although a crop N content of 50 kg N/ha per unit of Green Area Index (GAI) is appropriate for crops with a GAI < 2.0, larger canopies may contain closer to 40 kg N/ha per unit of GAI.

In the comparison of on-farm strategies for using direct SNS measurements with FAM,

- SNS prediction proved worthwhile, whether by FAM or SMN measurement, when compared to a simplistic assumption of a fixed value (100 kg N/ha).
- 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.

The best strategies for different field and farm types were:

- 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.

It was concluded that SMN measurement may help to improve N management on farm in two ways

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.

Based on Project Report 490, AHDB Cereals & OilseedsTopic Sheet 115 (2012) provided new information on Estimating Soil Nitrogen Supply (SNS) as follows:

- In most continuous arable fields not receiving organic manures, SNS is likely to be small or moderate (below 120 kg N/ha) and can be estimated most cost-effectively by the FAM. Careful identification of soil type and organic matter content is very important to get an accurate FAM estimate.
- Measuring SMN becomes progressively more worthwhile on a field-by-field basis as predicted SNS increases beyond 120 kg N/ha.
- Measuring SMN is also useful where SNS is uncertain, for example:
    - Fields in which organic manures have been regularly used
    - Where grass has been ploughed out, although the FAM should be used in the first season
    - Following a vegetable crop that has left N-rich residues

- SMN measurements are most useful on silt and clay soils in low rainfall areas. They are less worthwhile on light and shallow soils and should not be used on peat soils.
- For spring sampling, an assessment of the amount of N that is likely to be released following mineralisation should be made. Mineralisation tends to be greater where SOM is high or where there is a history of organic manures or grass. In these situations, a measurement of Additionally Available N gives the most useful prediction of mineralisation.
- As a crude guide, around 10 kg N/ha more SNS may be expected for each 1% increase in SOM above 4% in England and Wales or above 10% in Scotland and Northern Ireland. Where SOM is less than this, mineralisation has generally been ignored until now. However, evidence (Kindred *et al*., 2012) suggests that, at least after cold winters, an estimate of around 20 kg/ha may be appropriate.
- Large SMN measurements can over-estimate SNS and small SMN measurements can under-estimate SNS. Uptake of soil N by crops is rarely less than 50 kg N/ha, so SNS estimates less than this should be treated as 50 kg N/ha and no less. Unless high SNS results (>160 kg N/ha) are confidently expected, they should also be treated with caution.

AHDB Horticulture Project FV 345b

Rahn (2012) considered the specific implications of AHDB Cereals & Oilseeds Project 3425 for Field Vegetables. It was identified that:

- The contribution to following crops from vegetable crop residues must be carefully determined as in some cases the SNS Index can be much lower than expected (or predicted by the FAM).
- Fields in intensively cropped Brassica rotations are likely to have high or uncertain amounts of N residues.
- Careful interpretation of mineral N is needed for shallow rooted vegetable crops.
- Only the SMN present within the rooting depth of the crop should be used to determine SNS Index.
- For growing field vegetables SMN samples should be taken as close as possible to planting date, after N has mineralised from previous crop residues.

AHDB Cereals & Oilseeds Project Report 485: Cost-effective sampling strategies for soil management

For soil N, Marchant *et al*. (2012) concluded that rational sampling effort varies according to the expected SNS in the field, and the field size. Bulked samples of 10-15 soil cores were considered to be adequate for most fields. Therefore where SMN is measured it was recommended that a bulked sample should be formed from 10-15 cores that are located on a ‘W’. Including more than 10 cores in the bulked sample is warranted when fields are larger than 20 ha or if SNS is expected to be high (>160 kg N/ha). More than 20 cores would be justified for a highly variable field in excess of 50 ha.

It was concluded that the greatest financial benefit from sampling occurs when SNS is around 175 kg N/ha since at these concentrations the yield is most sensitive to sampling errors and erroneous decisions, and that there is a smaller benefit when the expected SMN is much higher or much lower since in these circumstances it is clear that either a small or large amount of N fertiliser should be added. Alternative methods of estimating SNS such as FAM were not considered.

AHDB Cereals & Oilseeds Project Report 484: The relationship between soil mineral nitrogen, applied nitrogen and yields in Scottish soils

Around 27 fields were soil sampled to measure SMN each year from 2007-2009, covering most of the main arable area of Scotland (Gilchrist *et al*., 2012). The same fields were tested in February before applications of nitrogen and then post-harvest. There were large season to season variations. The influence of previous cropping was investigated, with oilseed rape crops leaving slightly higher soil nitrogen residues compared to cereals or potatoes. Soil type had some influence on available nitrogen, soils with higher clay content tending to have lower values than more sandy soils. This was explained as being possibly due to greater mineralisation of organic nitrogen in the lighter textured soils due to more rapid drying and warming in the spring.

39 replicated nitrogen dose response trials on winter and spring barley, and winter wheat were carried out in Scotland over three seasons (harvest years 2007-2009). The majority of trials were highly responsive to applied nitrogen and nitrogen optima exceeded the relevant maximum allowance for nitrogen under Scottish NVZ guidelines (N max) in 27 of the trials. All trials were also sampled for SMN, both before nitrogen was applied and for all nitrogen treatments post-harvest. As a predictor of likely crop response to nitrogen the early soil samples did not generally provide a good guide. The exceptions were the soil samples with the highest and lowest soil nitrogen levels (92 kg N/ha and 16 kg N/ha), which subsequently resulted in the most unresponsive and responsive trials to applied nitrogen respectively.

Other Published Papers and Reports

Oliver & Dawson (2014) examined spatial variation in SMN measurements in order to determine how many sub-samples are required to make up a bulked sample for analysis to remove local variation over a given area, and also to guide sampling intensity on a grid for mapping. Overall, four to nine samples were optimal for bulking. The recommended grid intervals for two of the three fields considered were similar, but for the other it was twice as large. These intervals reflected the considerable differences in the scales of spatial variation among the fields.

Blake-Kalff & Blake (2014) examined the development of the determination of additionally available N (AAN), as an indicator of the amount of N that will become available from mineralisation under UK field conditions between the time of SMN sampling and harvest. They found that inclusion of AAN improved the prediction of SNS or fertiliser N requirement when measured against N offtake at harvest, such that for all soil types SNS explained about 62% of the variation in crop N uptake. AAN was closely related to SOM and its C:N ratio. Soils containing greater than 5% SOM showed the most consistent increases in AAN resulting in fertiliser savings of >20 kg N/ha. For soils containing about 10% SOM, AAN was on average 60 kg N/ha. Whilst winter rainfall greatly influences SMN in spring, the inclusion of both AAN and spring crop N uptake indicated that temperature had a greater influence on N availability throughout the growing season.

Orson (2010) examined the impact of SMN (measured in spring) on the optimum economic applied N dose for yield (N_{opt}) of feed winter wheat in 54 NIAB TAG experiments from 1997-2009. 19 of the responses were from six sites where the response to more than one cultivar was tested. All of the sites were on long-term arable soils where no organic manure had been applied for at least three years. They were located on a range of mineral soils, with the exception of sands, and with a maximum of 4% SOM. Previous cropping included cereals, oilseed rape, pulses and sugar beet. The average N_{opt} was 241 kg N/ha and 75% of the sites had an optimum within 50 kg N/ha of this figure. N_{opt} was not related to previous crop, nor was it affected by the level of SMN.

The above NIAB TAG dataset and that for wheat in AHDB Cereals & Oilseeds Project Report 438 (Sylvester-Bradley *et al.*, 2008) were used to test alternative methods for determining the optimum applied N dose or feed wheat, including a fixed amount of 240 kg N/ha, the FAM and Measurement Method (both based on the 8th edition of RB209). For the NIAB TAG dataset, notional values had to be used for crop N in spring, and average excess winter rainfall was used for the FAM. It was noted that the two datasets appeared to contain contrasting sites, with many in Sylvester-Bradley *et al.* (2008) having high SMN values in relation to the crops previously grown. The average N_{opt} in this project of 152 kg N/ha contrasted with the 241 kg N/ha in the NIAB TAG dataset.

For the NIAB TAG dataset, using a fixed dose of 240 kg N/ha applied N was as or more reliable in predicting N_{opt} than the other approaches tested. It was proposed that the reason why the fixed dose was more successful than other approaches was because in the NIAB TAG dataset there appeared to be no relationship between SMN measured in the spring (values up to 100 kg N/ha) and N_{opt}. In contrast, using a fixed dose of 240 kg/ha was the most unreliable method of predicting N_{opt} for the Sylvester-Bradley *et al.* (2008) dataset. It was observed previously that many of the sites in that dataset may have experienced high levels of mineralisation (Orson, 2009). It was concluded that, where net mineralisation is low, most likely in long-term arable mineral soils provided organic amendments are not regularly used, a fixed dose of nitrogen may be as or more accurate than using SNS as a guide to N_{opt}.

Orson (2012) tested the recommendations for feed winter wheat contained in RB209 (8^{th} edition), assuming efficiencies of use of SNS of 100%, 50% and 25%. These were compared to applying one fixed amount. Experiments were carried out on commercial fields growing wheat after a range of combinable crops or sugar beet, which had been in arable production for at least an estimated 20 years and with no organic manures or amendments applied. It was concluded that the FAM was more accurate in predicting optima than the 'Measurement Method'. There was a tendency for a more accurate prediction of the optima for individual experiments where 50% efficiency of SNS use was assumed. The Measurement Method tended, on average, to recommend too high a dose of applied nitrogen whilst, again on average, FAM recommended a lower than optimum dose where it assumed that the efficiency of use of SNS was 100%. There was no advantage from adopting the FAM over applying 210 kg N/ha to every crop.

3.2.6. Conclusions: soil nitrogen supply

A number of relatively minor changes are proposed to update best practice for SMN sampling (time, depth number of cores, sample transport, crop N for oilseed rape). These are largely based on the findings of Kindred *et al*. (2012) and Marchant *et al*. (2012), and AHDB Cereals & Oilseeds Topic Sheet 115. Updated guidance on where to use FAM and where to use the 'Measurement Method' is needed, in the light of the conclusions of Kindred *et al*. (2012). The importance of soil type and rainfall in decision making needs greater emphasis. References in RB209 (8^{th} edition) to ‘High SNS’ needs quantifying for arable rotations (it is suggested that this is stated as more than 120 kg N/ha, in line with Topic Sheet 115).

Based on the published evidence, two significant changes were considered:

1. A change to the adjustment made for mineralisable N at higher levels of SOM when using the ‘Measurement Method’. This revised approach would apply only to England and Wales, as Scotland and Northern Ireland are not covered by RB209. There were some inconsistencies between the various references to this in the 8th edition of RB209, and some ambiguity about the size of adjustment to make. However, the main recommendation was for no specific adjustment where the SOM is ‘low to average’ (less than about 10%), but an additional 60-90 kg N/ha of potentially available N above 10% SOM (compared to an equivalent soil at 3% SOM). Following the approach adopted in TS115, an adjustment of 10 kg N/ha of potentially available N per 1% SOM above 4% could have been adopted. This would still equate to an additional 60 kg N/ha of potentially available N at 10% SOM, and is also broadly consistent with Blake-Kalff & Blake (2014).

2. The assumption behind the calculation of SNS within RB209 (8th edition) was that SMN is used with effectively 100% efficiency, with a likely actual efficiency of nearer 60% compensated for by N that becomes available after SMN is measured (largely through mineralisation). This was regardless of the amount of SMN present (assuming total SNS does not exceed crop requirement), and therefore assumed that SMN and mineralisable N are proportionately related. While high SMN levels might to an extent be indicative of high mineralisable N, it is likely that the two will also vary independently. Project Report 490 indicated that compensation may on average equate to 100% apparent efficiency only for SMN levels within a range of about 50-100 kg N/ha, and that actual efficiency and the amount of N that subsequently becomes available varies between situations (including soil types).

Table 4 shows how revised estimates of SNS might look if the following assumptions were made:

- SMN used with 60% efficiency (instead of 100%),
- Crop N content used with 100% efficiency,
- 20 kg N/ha (minimum) from mineralisable N for soils up to 4% SOM (as suggested in TS115, based on Kindred *et al*., 2012),
- 10 kg N/ha additional mineralisable N per 1% SOM above 4% (as suggested in TS115, based on Kindred *et al*., 2012).

SNS = (SMN kg/ha x 0.6) + (Crop N x 1) + (20 kg N/ha) + (10 kg N/ha per 1% SOM above 4%)

If estimates of SNS based on the measured SMN method were modified in this way, there would be no requirement to alter the fertiliser N recommendations in Section 4, which already take into account the efficiency of use of fertiliser N.

It is not evident that it would be appropriate to adjust estimates of SNS using the FAM method in the same way. FAM estimates of SNS may have been determined from harvested SNS values or from N response curves rather than from SMN measurements, and therefore effectively makes no prior assumptions about the efficiency with which SMN present is used.

To an extent, the FAM tables, as they are based partly on previous crop, take some account of higher N mineralisation from the ‘fresh residue’ component of the SOM. Table D (RB209 8th edition p.94) addresses SNS Indices following ploughing out of grass leys. Some guidance is also provided on adjustments to the SNS Index for other conditions (8th edition, Section 3, Field Assessment Method, Step 5, p.95), for example where there has been a history of manure use, or frequent growing of field vegetable crops, both of which could result in higher N mineralisation. So to adjust for SOM as well in the same way as for the Measured SNS could double-count at least some of the mineralised N.

Table 4. RB209 8th editon and potential revised estimates of SNS for different levels of SMN.

SOM	SMN (kg N/ha)	Crop N (kg N/ha)	8th edition mineralisable N estimate	8th edition SNS (kg N/ha)	Revised mineralisable N estimate	Revised SNS (kg N/ha)
4% or less	25	20	0	45	20	55
	50			70		70
	75			95		85
	100			120		100
	125			145		115
	150			170		130
	175			195		145
6%	25	20	0	45	40	75
	50			70		90
	75			95		105
	100			120		120
	125			145		135
	150			170		150
	175			195		165
10%	25	20	60-90	105-135	80	115
	50			130-160		130
	75			155-185		145
	100			180-210		160
	125			205-235		175
	150			230-260		190
	175			255-285		205

For organic soils (defined as between 10% and 20% organic matter), the SNS values indicated within the 8th edition FAM tables span Indices 3-6 and refer the user to 'page 86' (the section on identifying soil type), which does not help with determining the most appropriate SNS Index. Using the adjustment above of 10 kg N/ha per 1% OM above 4% would add 60-150 kg N/ha to the SNS estimate for organic soils. This would typically equate to an increase of between 2 and 4 Index levels compared to a mineral soil, depending on the previous crop, which would in turn suggest SNS Indices in the range 3-6, as indicated in the 8th edition of RB209.

Whilst the publications reviewed suggest that a case could be made for the above changes to the Measurement Method, the evidence that this would substantially improve either the estimate of SNS, and/or the accuracy of subsequent fertiliser N recommendations, is not strong. Although the justification for change is probably greater for the mineralisable N adjustment, introducing that change alone without altering the assumption of SMN use efficiency risks double-counting to an (unknown) extent the contribution of soil N where high levels of SOM are contributing to a high level of measured SMN.

A definitive answer on the potential improvement to the accuracy of fertiliser N recommendations from a more adaptable approach to calculating measured SNS is needed, but this is not provided by the evidence reviewed here. Therefore this should be treated as an ongoing knowledge gap.

Suggested revisions to the text of RB209 are as follows:

The Basis of Good Practice (p.3)

1. Change the heading 'Reliable Information' to '**Relevant Information**'
2. Change 'Soil analysis for SMN' to '**An assessment of Soil Nitrogen Supply**'

Section 1: Principles

3. Guidance on stone content and rooting depth (p.19) should be signposted from the grass, arable and horticulture sections.

4. To improve clarity, amend the definition of SNS (p.26 and elsewhere in the document). Re-order the text as follows:
   "The Soil Nitrogen Supply (SNS) is the amount of nitrogen (kg N/ha) **available for uptake from the soil by the crop throughout its entire life, taking account of nitrogen losses, but excluding nitrogen applied for the crop in manufactured fertilisers or manures."**

5. To avoid misinterpretation (potential rooting depths are much greater than those from which the roots of an average crop will be accessing N), amend the definition of SMN as follows:
   "Soil Mineral Nitrogen (kg N/ha) is the nitrate-N plus ammonium-N content of the soil within the **normal maximum** rooting depth of the crop, allowing for nitrogen losses."

6. Under the heading 'The Field Assessment Method' (p.29), change the wording of paragraph 3 as follows:
   "This method **usually** provides a satisfactory assessment of the SNS in typical arable rotations but the Measurement Method may give a better result where the SNS **is uncertain or could be above 120 kg N/ha."**

7. Under the heading "The Measurement Method" (p.29), change the wording of paragraphs 1 and 2
   "This method should be targeted to fields where the supply of plant-available nitrogen in the soil could be unusually large **(for example above 120 kg N/ha in arable rotations),** and particularly where organic manures have been used regularly in recent years.

"In these situations, direct measurement and estimation of the key components of SNS (SMN, total crop nitrogen content and mineralisable nitrogen) will **more often** result in the best assessment of the amount of soil nitrogen available for a crop and lead to a more accurate decision about how much additional nitrogen to apply"

8. Above the heading 'Nitrogen Uptake Efficiency by Crops' (p.30), change the wording of the next to last paragraph, to reflect recent AHDB Cereals & Oilseeds publications and project reports.

   "It is much more difficult to obtain a reliable estimate of the nitrogen that will be made available from mineralisation of organic matter. However on many mineral soils **with 4% or less soil organic matter,** this will be relatively small and no further adjustment is needed."

9. Under the heading 'Nitrogen Uptake Efficiency by Crops (p.30)' change the wording of paragraphs 2 and 3 to reflect recent reports and papers:

   "Provided that the total soil nitrogen supply does not exceed demand, **where the amount of SMN present within normal rooting depth is in the range 50-100 kg N/ha, on average,** crops will take up an amount of nitrogen from the soil that is roughly equivalent i.e. SMN is used with apparently 100% efficiency.

   "The actual efficiency with which SMN is recovered is likely to be less than 100% (and might typically be closer to 60%). **This should to a greater or lesser extent** be compensated for by additional soil nitrogen that becomes available for uptake during the growing season, mainly through mineralisation of crop residues and soil organic matter. **However, for individual situations both actual efficiency of SMN use and the supply of mineralised N are likely to vary.**

   "SNS estimates of less than 50 kg N/ha should be treated as 50 and no less. Unless high SNS results (>160 kg N/ha) are confidently expected due to the regular addition of organic manures or crop residues, they should be treated with caution."

Section 3: Using the Recommendation Tables

10. Under the heading 'The Measurement Method' (8th edition, p.95), change paragraph 1 as follows:

    "This method is most appropriate where the SNS is likely to be large (above 120 kg N/ha in arable rotations) or is uncertain (see page 29 and Appendix 2). This includes fields with a history of organic manure application and vegetable rotations where the timing of residue incorporation can strongly affect SMN for the following crop. Nitrogen residues can also be large following outdoor pigs. **The SNS Index can be identified using the results of direct measurement of SMN to 90 cm depth in spring, 60 cm depth in autumn / early winter or to maximum rooting depth in shallow soils over rock.** The crop nitrogen content (at the time of soil sampling) and an estimate of net mineralisable nitrogen must be added to the SMN result when calculating the SNS. The Measurement Method is not recommended for peat soils where net mineralisation can be very large and uncertain and the measured SMN may be a relatively small component of SNS. For these soils, the Field Assessment Method or local experience will be better guides to SNS. **SNS is likely to be low on light sand and shallow soils that have not received regular additions of organic manure or crop residues, particularly in moderate to high rainfall areas, and under this scenario prediction of SNS using the Field Assessment Method is advised**.

11. Under the heading 'Step 1 Measure SMN' (8th edition, p.96), change paragraph 1 based on Project Reports 485 and 490:

    "Sampling the soil to 90cm depth is difficult to do manually. **A minimum of 10-15 soil cores per field (based on 10 ha) will be needed to obtain a representative sample. 15-20 soil cores are needed for larger fields (10-20 ha) or where SMN may be high or very variable. Information** on sampling and analysis for SMN is in Appendix 2. Note samples should not be frozen but cooled and maintained at less than 5°C, **and analysed within three days of sampling."**

12. Under the heading 'Step 2 Estimate nitrogen already in the crop' (8th edition, p.97), change the Oilseed Rape section based on Project Report 490

    "Large oilseed rape canopies can contain substantial amounts of nitrogen by the spring (in excess of 100 kg N/ha). Research has shown that even for large canopies all of the N in the crop can be treated as contributing to the SNS.

    "In oilseed rape, the crop contains around 50 kg N/ha for every unit of Green Area Index (GAI). **For larger canopies (GAI of 2 or more) the crop may contain closer to 40 kg N/ha per unit of GAI.**

    "Alternatively, the nitrogen content of an average density crop can be assessed by measuring the average crop height. **This may not be appropriate for semi-dwarf varieties and should not be used on crops that have been flattened by snow.**

    Crop height (cm)   Crop nitrogen content (kg N/ha)

10	35-45
15	55-65
20	75-85”

13. Under the heading ‘Make an adjustment for net mineralisable nitrogen’ (8th edition, p.97), change paragraphs 1 and 3 based on recent AHDB Cereals & Oilseeds publications and reports):

“Nitrogen mineralised from soil organic matter and crop debris after soil sampling is a potentially important source of nitrogen for crop uptake. However, in mineral soils of low to average organic matter content **(4% or less),** the amount of net mineralisable nitrogen will be **relatively** small and for practical purposes, no **further** adjustment is needed when using the recommendations in this Manual.”

“An adjustment may be needed where soil organic matter content is above average or where there has been a history of regular manure applications. Adjustments can be made on the basis of a measurement of the topsoil organic matter content, or data from a laboratory anaerobic incubation or from agronomic factors using a computer model. As a guide where measurement is not done, **for every 1% organic matter above 4%, a topsoil may release an additional 10 kg N/ha. Therefore a soil that has a topsoil organic matter content of 10% may release around 60 kg/ha more potentially available nitrogen than an equivalent soil with 3% organic matter content.** However, some soils with an organic matter content of **above 4%** may release little nitrogen and local knowledge must be used in estimating mineralisable nitrogen. **Therefore it is not possible to specify a routine amount by which to adjust SNS based on soil organic matter level.**”

Section 4: Arable and Forage Crops

14. Under the heading ‘Checklist for decision making’ (8th edition, p.104), amend item 4

“Identify the Soil Nitrogen Supply (SNS) Index of the field, **either by using the Field Assessment Method based on previous cropping, previous fertiliser and manure use, soil type and winter rainfall (see page 86) or by carrying out analysis for SMN (the Measurement Method) (see page 95).** Sampling and analysis for SMN is recommended where nitrogen residues are expected to be **high (SNS of more than 120 kg N/ha for arable rotations), or are uncertain. This may apply following previous manure use or crops receiving high rates of nitrogen fertiliser, or following a dry winter, especially on deep clay and deep silty soils.”**

Appendix 1: Soil Types

15. Remove the ‘Soil Types’ table (8th edition, p.219) as this repeats the table in Section 3

Appendix 2: SMN Sampling

16. Under main 'Appendix 2' heading (8th edition, p.221), amend paragraph 1

"Direct measurement or estimation of the components of Soil Nitrogen Supply (SNS) **can provide** a more reliable basis for nitrogen decisions in some situations."

17. Under the main 'Appendix 2' heading (8th edition, p.221), amend the definition of SMN in the box as follows:

"Soil Mineral Nitrogen (kg N/ha) is the nitrate-N plus ammonium-N content of the soil within the **normal maximum** rooting depth of the crop, allowing for nitrogen losses."

18. Under the heading 'Targeting fields for sampling' (8th edition, p.221-222), amend the fourth bullet point:

"Where there have been problems such as regular lodging of cereals, very high grain protein or nitrogen contents, or previous crop failure (for example due to drought or disease)."

19. Under the heading 'Targeting fields for sampling' (8th edition, p.222), amend the last paragraph:

"The amount of SMN is likely to be larger on nitrate 'retentive' **clay or silty soils** than on nitrate 'leaky' sandy or shallow soils. **As SMN levels are usually low and more predictable on sandy or shallow soils, direct measurement is less likely to be worthwhile."**

20. Under the heading 'Time of sampling' (8th edition, p.222), amend the paragraph:

"In most situations, sampling **in late** winter or early spring before nitrogen fertiliser is applied, is preferable especially in high rainfall areas or on shallow or light sand soils. On soils less prone to leaching, sampling in **autumn or early winter is equally effective.** Avoid sampling within 2- 3 months after application of nitrogen fertiliser or organic manures."

21. Under the heading 'Method of Sampling' (8th edition, p.222), amend paragraph 1:

"Samples must be taken to be representative of the area sampled. **A minimum of 10-15 soil cores should be taken per field (based on a 10 ha field) and bulked to form a representative sample. If the bulk sample is too big, sub-sample by taking many small representative portions for sending to the laboratory; but do not stir the sample excessively.** Areas of land known to differ in some important respects (e.g. soil type, previous cropping, application of manures or nitrogen fertiliser) should be sampled separately. **In larger fields (10-20 ha), increase the number of cores to 15-20 unless the soil type is not uniform, in which case more than one sample should be taken.** This can be done by dividing the field into smaller blocks from each of which 10-15 soil cores are taken."

22. Under the heading 'Transport to the laboratory' (8th edition, p.223), amend the paragraph: "Soil mineral nitrogen concentrations can change during storage of samples. After sampling, soils should not be frozen but be kept refrigerated at less than 5ºC 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**, and within three days of sampling**."

23. Under the headings 'Estimating the crop nitrogen content' (8th edition, p.222) and 'Estimating the nitrogen that will be released from mineralisation' (8th edition, p.223), remove these sections (as repeated elsewhere) and replace with:
"Add an estimate of crop nitrogen content and, where appropriate, mineralisable nitrogen in order to calculate the SNS, as described in section 3 Measurement Method Steps 2 and 3"

3.3. Cover crops

This section covers crop nutrition for and nitrogen supply following cover crops. The literature frequently refers to 'cover crops', 'catch crops' and 'green manures' and there are subtle differences in terms of the objectives associated with each term. For example, 'cover crop' refers to a crop grown to provide soil cover and protection from erosive wind and rainfall; 'catch crop' refers to a crop principally grown to take up nitrogen and reduce nitrate leaching losses over winter; and 'green manure' refers to a crop mainly grown to maintain or enhance SOM. However, cover crops can be grown for multiple objectives. In the following text 'cover crops' will be used as a generic term unless specific differences are pertinent to the literature cited. The majority of the information refers to short duration cover crops established in early autumn and destroyed in winter or spring.

3.3.1. RB209 (8th edition) advice and NVZ guidelines

The "Fertiliser Manual (RB209)" noted that (p.27) "Following destruction of the cover crop, this nitrogen [captured] will be gradually mineralised over many years. However, the amount becoming available for uptake by the next crop is relatively small and difficult to predict. Where cover crops have been used regularly, soil analysis can be a useful technique to help estimate the overall supply of soil mineral nitrogen."

In terms of crop nutrition for cover crops, N application to cover crops is not mentioned in either the manual or the NVZ guidelines. There is no specific N max limit specified for cover crops and they are not listed in the crops to which N max limits apply (although many common components / species used as cover crops and in cover crop mixes are listed).

The closed periods for spreading manufactured fertiliser restrict opportunities to apply manufactured fertiliser to autumn sown cover crops, although a proportion of cover crops are established before the autumn closed period for tillage land. Closed periods for spreading high readily available N (RAN) organic manure to tillage land prevents their use on autumn sown cover crops on shallow and sandy soils, but not for other soils.

EFA guidance advocates specific cover crops components and denotes different residence times for ‘cover crops’ and ‘catch crops’, but does not advocate specific fertiliser requirements / use.

3.3.2. Cover crop establishment

The national acreage of cover crops is not recorded, but the area has increased in recent years. In 2010, a one-off Defra Farm Practice Survey (FPS) found that 81,000 ha (c. 7% of the spring crop area) was cover cropped in 2009/10; the area is likely to have increased since this time due to commercial and legislative (e.g. EFA) drivers.

With regard to starter fertiliser use on cover crops; recent research within the Wensum Demonstration Test Catchment project (Lovett *et al*., 2015) indicated a 15% increase in the canopy size for an autumn sown brassica cover crop from the application of 30 kg N/ha starter fertiliser, but also noted that this had no associated impact on root growth (a small numerical decrease in root growth of around 5% was noted). Recent data from analogous studies in 2016 in the Wensum DTC have suggested similar findings (pers. comm. Lovett, 2016). Wider farm-based cover crop research by Stobart *et al*. (2015) compared 20-40 kg N/ha starter fertiliser over a range of 15 cover crop approaches (single species and mixtures) across two sites, and reported a *c*. 15% increase in cover crop biomass (and an associated mean doubling of autumn weed populations). However, the research indicated that establishment date had a greater impact on early season cover crop growth than starter fertiliser and suggested that interactions between sowing date, cover crop type and starter fertiliser use should be examined further. These findings on cover crop establishment are in keeping with earlier UK data, such as that of Richards *et al.* (1996), who concluded from UK studies, that sowing date had a greater bearing on cover crop growth than early season N availability.

3.3.3. SNS from cover crops

Previous UK work, such as that of Doring *et al*. (2013), has shown that cover crop type, growth, environmental conditions and location all have a bearing on N uptake and release and that the amounts and timing of release can be highly variable. More recent UK research addressing cover crop performance and the yield response in following crops (e.g. Shah *et al.* 2015; Stobart & Morris, 2014), has tended not to separate N release and other potential drivers (e.g. changes to soil structure) when considering yield response mechanisms. However, research by Silgram *et al*. (2015) examined N release specifically and suggested that a potato crop, following a cover crop, typically recovers 15 to 50 kg N/ha from cover crop residues, but also noted that the amounts and timing of release were variable as was the net economic impact of the cover crop on the following crop. Timing of N release would influence N utilisation by the following crop and whether this would impact on yield. Mineralisation from cover crops is driven to a large extent by key thresholds for C:N (for N release) and C:P for phosphate (P) release (Justes *et al.* 2009, Noack *et al.* 2012; Wendling *et al.* 2015). The actual ratios at the time of cover crop incorporation will vary with cover crop type and scenario (e.g. management and location) and are difficult to predict. However, collectively research suggests that in some situations nutrient release could be meaningful for following crops and as such SMN analysis, in keeping with RB209 (8^{th} edition) guidance, may be useful.

3.3.4. Conclusions: cover crops

Establishment date has a greater impact on cover crop growth than early season N availability. Starter nitrogen fertiliser research is currently very limited in quantity. However, the evidence to date does not suggest clear, consistent benefits.

The recent findings on nitrogen release from cover crops indicate that this is likely to be variable and this is in keeping with earlier information and existing guidance in RB209. Further detailed research to understand and predict the wider nutrient release from cover crops used in a range of farming and use scenarios is required to develop improved best practice guidance. However, it would be worth noting in RB209 that the amount released is both subject to variation and can sometimes be appreciable (i.e. not always ‘small’ as noted in the current text). Given that in some scenarios meaningful amounts of N could be available to the following crop, as noted in the 8^{th} edition of RB209, soil testing would be prudent for these scenarios. It is also worth noting, as discussed at the Arable TWG meeting on 25^{th} April 2016, that short-season crops may not have time to benefit from any mineralised N from a previous cover crop and this should be taken into account when considering SNS for such crops. At the CNMP Steering Group meeting on 28^{th} April it was stated that more information on the effect of cover crops in different situations could be useful. For example, short-term bio-fumigation crops may not be relevant for capturing and releasing N to the following crop. It was also suggested that description of different cover crop types, namely; fertility building, soil structure improvers and forage cover crops could be helpful.

We propose the following amendments to the RB209 (8th edition) text:

Section 1 (8th edition, p.22, new sentence to insert): "**Research on the use of starter nitrogen fertiliser on cover crops is limited. Evidence to date does not show consistent benefits from its use**."

Section 1 (8th edition, p.27): "Well-established cover crops, such as mustard, forage rape or *Phacelia*, sown after harvest can take up significant amounts of soil mineral nitrogen and reduce the risk of nitrate leaching over winter. Generally, the earlier the cover crop can be established, the more mineral nitrogen will be taken up. **Early destruction of a well-established cover crop by the end of February can release useful quantities of N for the following spring crop; sufficient to increase the SNS Index by up to two levels. However, when cover crops are destroyed in March or later, the amount and timing of N release is difficult to predict, with factors such as a high C:N ratios likely to delay mineralisation. The timing and duration of nutrient uptake in the following crop is also a factor, such that short-season crops may not have time to benefit from any mineralised N from a previous cover crop.**"

3.4. Nitrogen fertiliser type

3.4.1. RB209 (8th edition) advice

The proportions of N and other nutrients in various fertilisers were listed in Section 3 (8th edition, p.102) and Appendix 7 (8th edition, p.234), but the relative performances of N fertilisers were addressed only in Section1 (8th edition, p.48), as follows:

"Ammonium nitrate (33.5-34.5% N); ammonium sulphate (21% N, 60% SO3), calcium ammonium nitrate or CAN (26-28% N): The nitrate-N is immediately available for crop uptake, the ammonium-N can be taken up directly but is quickly converted to nitrate by soil microbes.

"Urea (46% N): Before uptake by plants, urea-N must first be converted to ammonium-N by the enzyme urease that occurs in all soils. This process usually occurs quickly and does not significantly delay the availability of the nitrogen for crop uptake. Typically, around 20% of the nitrogen content of applied urea may be lost to the atmosphere as ammonia. As a result less nitrogen is available for crop use and emissions may lead to impacts on biodiversity and human health. Losses are more closely related to soil moisture and weather conditions than to soil type, and may be minimised if urea is applied shortly before rain is expected, and/or is shallowly cultivated into the soil. Urea is a low-density material which, in prilled form, can be less easy to spread accurately over wide bout widths when using spinning disc equipment.

"Liquid nitrogen (18-30% N): Liquid nitrogen fertilisers are solutions of urea and ammonium nitrate. The nitrogen is in forms that are quickly available for crop uptake. Solutions based on urea alone will contain no more than 18% N because at low ambient temperatures urea crystallises out of solution."

The lower efficiency of urea relative to AN was therefore mentioned, but there was a lack of guidance as to how this should be reflected in choice of N product and consequent effects on N application rates.

3.4.2. Review of new information

The two main types of straight N fertiliser are ammonium nitrate (AN) and urea. A recent analysis (Sylvester-Bradley *et al*., 2012) compared the efficiencies of these N fertilisers using data from 47 N response experiments in harvest years 1982 to 1987 and 2003 to 2005. Only one of these 47 experiments showed a significant effect of fertiliser type on N_{opt}, but a cross-site analysis of all the experiments showed highly significant effects of fertiliser type on N_{opt} and yield at N_{opt}. Across all experiments, the mean N_{opt} for urea was about 14 kg/ha higher than for AN, and the median N_{opt} was 26 kg/ha higher. At fixed N levels, yields were lower with urea than AN, by 0.15 t/ha at 100 kg N/ha and by 0.07 t/ha at 200 kg N/ha. Grain %N levels were also 0.07% lower with urea than with AN applied at 200 kg N/ha, showing lower recovery of urea than AN.

This data was used to compare the economic performance of AN and urea, and a third option of urea treated with the urease inhibitor Agrotain. The lower price of urea, relative to AN, was set against the lower yield achieved at a given N rate; the resulting gross margins of AN and urea were similar (Table 5). Sylvester-Bradley *et al*. (2012) concluded that around 10% more urea-N needed to be applied than AN-N to achieve the same yield, and that AN should be preferred to urea if the urea price (£/kg N) was greater than 85-90% of the AN price. Agrotain resulted in a slightly greater Nopt and greater yield compared with AN. As a result the fitted yield at 200 kg N/ha was very similar to AN, and it was concluded that Agrotain improved the N efficiency of urea to almost the same level as AN.

Table 5. Comparison of the economic performance of various fertiliser types: Ammonium nitrate (AN), urea, and urea treated with a urease inhibitor. It is assumed that N application rates are adjusted to allow for ammonia emissions, giving equivalent agronomic performance. Adapted from (Sylvester-Bradley *et al*., 2012).

	Ammonium nitrate (AN)	Treated urea (assuming performance equivalent to AN)	Treated urea (assuming increased yield and 5% ammonia emissions)	Urea (assuming 10% ammonia emissions)	Urea (assuming 20% ammonia emissions)
N applied (kg/ha)	190	190	202	209	229
Grain yield (t/ha)	8.00	8.00	8.19	8.00	8.00
Margin compared to AN (£/ha)*		+£14	+£34	+£9	-£4
Price (proportion AN-N price) above which AN should be preferred to urea		1.00	1.25	0.91	0.83

* Margin calculated using grain price of £150/t and N:grain price ratio of 5

Comparisons of AN and urea have also been made by NIAB-TAG, who conducted 30 replicated trials on wheat from 2002-2010, some of which compared performance at a single N rate and others across a range of doses (Stuart Knight, pers. comm.). The mean yield advantage of AN over urea was 0.06 t/ha, which is similar to that found by Sylvester-Bradley *et al*. (2012), and there was a mean gross margin advantage to urea of £13/ha. There appeared to be an effect of soil type, with AN out-yielding urea in 13 out of 18 (72%) comparisons on shallow soils over limestone or chalk, but only 26 out of 51 (51%) comparisons on medium or heavy soils.

NIAB-TAG also compared AN and urea in six oilseed rape trials in 2003 and 2004 (Stuart Knight, pers. comm.). There was a mean yield advantage to urea of 0.012 t/ha, although none of the experiments showed a significant difference.

Relatively little data was available about crop performance with UAN (urea ammonium nitrate solution), despite it comprising 8.6% fertiliser use on tillage crops from 2005 to 2014 (by weight), compared with 7.5% for urea (Anon, 2015 and earlier years). Given the relative N contents of these products, this implies that UAN accounts for 45-75% as much N to tillage crops as urea. The NT26 project included eight winter wheat experiments and one winter barley experiment, which compared UAN, with and without Agrotain, against AN, urea and Agrotain treated urea (Dampney *et al*., 2006). Across these trials, the mean N_{opt} (calculated with 6:1 break even ratio) for UAN was 30% higher than for AN, while the N_{opt} for urea was only 19% higher. Addition of Agrotain reduced the mean N_{opt} for UAN to 19% higher than for AN. Yields at the optima were similar, hence if the same N rates were applied with each fertiliser type, yields were 3.9% (0.31 t/ha) lower with urea than AN, and 4.5% (0.39 t/ha) lower with UAN than AN. The lower efficiency achieved with UAN than urea must be due to factors other than ammonia volatilisation, which (based on urea content) would put UAN midway between AN and urea. Possibilities are interception of the liquid fertiliser by the foliage, or crop scorch.

In a series of 15 trials by Hydro Agri, mean yields with urea and UAN were only 0.1 t/ha (1.2%) and 0.07 t/ha (0.8%) lower than with AN, respectively (Bhogal *et al*., 2003). This dataset puts UAN between AN and urea for efficiency, as would be expected from its composition.

3.4.3. Nitrification inhibitors

Nitrification inhibitors are described on p.137 in the “Fertiliser Manual (RB209)”:

“These products slow the conversion of ammonium-N to nitrate-N. They are available in manufactured solid and liquid fertilisers and can be added to liquid fertilisers prior to application or sprayed onto soil prior to spreading solid fertilisers. Nitrification inhibitors can delay release of nitrate following fertiliser application which can reduce nitrate leaching and nitrous oxide emissions”.

Recent Defra funded work (Misselbrook *et al*., 2014)) reported that the Nitrification Inhibitor dicyandiamide (DCD) was effective at reducing nitrous oxide emissions following nitrogen fertiliser applications with mean reduction efficiencies of 39% for ammonium nitrate and 69% for urea. However, there was no effect of nitrification inhibitor use on crop yields or N offtakes.

3.4.4. Conclusions: nitrogen fertiliser type

We propose the following amendments to the Section 1 text in RB209 (8th edition):

“Ammonium nitrate (33.5-34.5% N); ammonium sulphate (21% N, 60% SO_3), calcium ammonium nitrate or CAN (26-28% N): The nitrate-N is immediately available for crop uptake, the ammonium-N can be taken up directly but is quickly converted to nitrate by soil microbes.

“Urea (46% N): Before uptake by plants, urea-N must first be converted to ammonium-N by the enzyme urease that occurs in all soils. This process usually occurs quickly and does not significantly delay the availability of the nitrogen for crop uptake. **However,** the nitrogen content of applied urea lost to the atmosphere as ammonia **varies widely depending on soil moisture and weather conditions and is typically 10 to 30%.** As a result less nitrogen is available for crop use and emissions may lead to impacts on biodiversity and human health. Losses may be minimised if urea is applied shortly before rain is expected, and/or is shallowly cultivated into the soil**.** Urea is a low-density material which, in prilled form, can be less easy to spread accurately over wide bout widths when using spinning disc equipment. **Recommended N rates are based on the main N source being ammonium nitrate, ammonium sulphate or calcium ammonium nitrate. If untreated urea is to be used, recommended rates may need to be increased to allow for losses as ammonia. It is unlikely that this adjustment will be necessary if urea is treated with a urease inhibitor.**

“Liquid nitrogen (18-30% N): Liquid nitrogen fertilisers are solutions of urea and ammonium nitrate. The nitrogen is in forms that are quickly available for crop uptake. Solutions based on urea alone will contain no more than 18% N because at low ambient temperatures urea crystallises out of solution.”

3.5. Crop sulphur requirements

3.5.1. RB209 (8th edition) advice

Advice was provided on plant requirements for sulphur (S) and comments made about declines in both atmospheric deposition and the use of sulphur-containing fertilisers, two formerly important sources of sulphur. The need to monitor crops for signs of S deficiency, particularly oilseed rape and grass grown for silage, was emphasised. High risk situations for S deficiency were discussed, such as lighter soils and high rainfall areas.

Diagnostic methods for identifying S deficiency were outlined, including leaf analysis in cereals, oilseed rape and grass, and soil analysis to identify severely deficient soils: “Procedures for plant sampling and interpretation of analytical results are given with each crop recommendation table”.

AHDB Cereals & Oilseeds Information Sheet 28 (2014) – Sulphur for cereals and oilseed rape

Information Sheet 28 was based on research conducted since 1999; most recently AHDB Cereals & Oilseeds Project Report 522 (“Quantifying the sulphur supply from farm manures to winter wheat crops (2013) and Project Report 525 (“Effect of sulphur fertilisation on the acrylamide-forming potential of wheat (2014). In addition to the AHDB Cereals & Oilseeds projects, it covered declining S deposition; S for breadmaking and malting quality; minimising green seeds in oilseed rape; factors that increase the risk of S deficiency; diagnosing S deficiency; treating deficiencies; and recommended forms, and timings and rates of S fertiliser for cereals and oilseeds.

3.5.2. Current practice

According to the British Survey of Fertiliser Practice (Anon, 2015), around 50% of tillage land (compared with 3-6% of the cereal crops and 8% of the oilseed rape area in 1993) and 11% of grassland received manufactured S fertiliser; and 23 and 37% respectively of tillage land and grassland received livestock manures in 2014. Webb *et al*. (2015) estimated that at least 30% of crops and 55% of grassland did not receive S as either manufactured fertiliser or organic manure.

The mean overall application rate of manufactured S fertiliser in 2010-14 was 27 kg SO_3/ha on tillage land and 2 kg SO_3/ha on grassland, while the average field rate (the application rate on fields receiving manufactured S fertiliser) was 60 and 33 kg SO_3/ha respectively (Anon, 2015).

For winter cereals and oilseeds, the average overall application of S fertilizer was less than the amounts recommended in RB209. However, S balances calculated by Webb *et al*. (2015) indicated that where manufactured S fertiliser or livestock manures were applied, cereals and oilseeds were being given enough S to meet RB209 recommendations. Amounts of S fertiliser applied to grassland were also less than that recommended in RB209 (8th edition). Indeed, for silage grass cut 3 times, even the average rate of manufactured S fertiliser application combined with manure application was inadequate to meet the RB209 (8th edition) recommendation of 40 kg SO_3/ha per cut.

3.5.3. Review of new information

Sulphur deposition ranged from around 8 to 20 kg SO_3/ha and was expected to decline further by 2020 to around 5 to 10 kg SO_3/ha. However, Webb *et al*. (2015) concluded that the continued decline in S deposition was unlikely to have major impacts on arable production systems, since:

- Most crops generally only respond to small amounts of S applied, usually no more than 25 kg SO_3/ha S (Cussans, 2007).
- Sulphur deposition represents a small proportion of crop S requirements; and explains a very small proportion of the variance in S responses to fertilizer; the largest factors are soil type and overwinter leaching.

Consequently, RB209 8th edition recommendations appear sufficient to meet the yield requirements of those crops for which S is recommended. However, there may be unreported adverse impacts on crop quality, e.g. crude protein levels in milling wheat and grass .For grassland, Webb *et al*. (2015) also concluded that “there is evidence that for grass swards cut more than once, the amount of S currently being applied is insufficient to provide optimum yield. In addition S deficiency on grass-clover swards has a greater adverse impact on clover growth than on grass growth leading to clover being replaced by grass. This will have the added impact of increasing N fertiliser requirements on such swards".

Diagnosing S deficiency

Maximum N:S ratios in soils have been cited as indicators of potential S deficiency. However, Grant *et al*. (2012) concluded that optimum yields can be obtained without balancing N:S ratios as long as both nutrients are supplied in adequate amounts. Scherer (2001) found that soil analysis approaches were not a reliable predictor of S deficiency due to seasonal effects on the availability of S to plants and the leaching of sulphate. Tissue analysis is a better predictor of S deficiency than soil analysis with the malate:sulphate test the most reliable method (AHDB Cereals & Oilseeds, 2014; Information Sheet 28).

3.5.4. Conclusions: sulphur recommendations

Information on S deposition should be updated to take account of continuing declines. Webb *et al*. (2015) recommended "updating deposition maps to show availability of S deposited at relevant times rather than the annual deposition map from 2006 currently used". However, this would increase the length of the sulphur section and perhaps give too much emphasis to S deposition given the small quantities involved. No map is provided in RB209 for N deposition. The following change to the opening paragraphs is proposed:

"Sulphur is an important plant nutrient **because when S is deficient other nutrients may not be fully utilised and crop yield can be reduced. Plants** need about the same amount of sulphur as of phosphorus. In the past, large amounts of sulphur were released into the atmosphere from industrial processes and this sulphur was deposited on land. However, atmospheric deposition has declined greatly in recent **decades, and the majority of crops in all regions of the UK can no longer be expected to obtain much of their S requirements from S deposition**".

Table 6. S deficiency risk categories.

	Winter rainfall (Nov-Feb)		
Soil type	Low (<175 mm)	Medium (175-375 mm)	High (>375 mm)
Light sand and Shallow	High		
Medium	Low	High	
Deep clayey, Deep silty, Organic and Peat	Low		Intermediate

It is proposed that information from AHDB Cereals & Oilseeds Information Sheet 28 is integrated into RB209, including the S deficiency risk factors proposed by Cussans *et al*. (2007):

“**On mineral, S should be applied to all winter oilseed rape crops and to all cereal, grass, grain legume, brassica vegetable and sugar beet crops grown in high risk S deficiency situations (Table 6). Responses may be reduced where there have been regular applications of organic manures.**
Reference to soil analysis for predicting S deficiency can be removed.

3.6. Crop phosphate requirements

3.6.1. RB209 (8th edition) advice

Section 1 included background to phosphate for field crops (RB209 8th edition, p.33-42). This included advice on general approach, soil sampling and analysis and soil Indices. Advice on building up or running down soil Indices was given on p.39:

“To raise the level of a soil at Index 0 or 1 to Index 2 requires the application of more fertiliser than that needed for the maintenance dressing… Large amounts of phosphate may be required to raise the crop-available phosphate in the soil by one Index, and it is difficult to give accurate amounts. However, as an example, to increase soil phosphate by 10 mg P/litre may need 400 kg P_2O_5/ha as a phosphate fertiliser (i.e. 850 kg/ha of triple superphosphate).”

A table was given (RB209 8th edition, p.39), showing that to raise P Index from 0 or 1 would require 60 or 30 kg/ha P_2O_5 respectively, applied on an annual basis (in addition to the maintenance dressing). This “should result in the soil Index increasing by one level over 10-15 years where arable crops… are grown.”

On p.40 it was stated that “At Index 0 or 1 a crop response to applied phosphate is possible, but the yield is likely to be less than that on a soil at the target Index”.

Section 4 gave specific advice for cereals on p.113-114, which began:
“The amounts of phosphate and potash shown at the target Index, P Index 2 and K Index 2-, are needed to replace the offtake in the yield of grain shown and maintain the soil at the target Index.”

Similar advice for oilseed rape and linseed was given on p.118.

Many of the field experiments upon which RB209 phosphate recommendations are based were carried out on a limited range of soil types, mostly silty clay loam and sandy clay loam soils, whereas cereals and oilseeds are grown on a wider range of soil textures and depths. For a given Olsen P value, the crop availability of P per unit volume of soil should be the same regardless of the crop and soil type (except perhaps on acid soils or for permanent grassland). Critical P values can vary between sites and years depending on weather and soil factors, such as topsoil parent material, texture, structure, moisture, bulk density, porosity, stone content, organic matter content and on subsoil P availability. Critical P values will also depend on the crop grown, on root growth or architecture and the rate of P uptake needed for maximum yield. The recommendations in the 8th edition of RB209 were for all soil types and made no adjustments for different soil types. Critical P levels have not been determined sufficiently widely to allow conclusions to be drawn with any confidence on the main causes of variation.

3.6.2. Comments from Consultation

Where soil P levels are below target Indices it was suggested that using current recommendations to build-up levels of P perpetuates deficiencies for a long time (10-15 years). Therefore, a faster build rate, especially where manures are available was recommended. The current build-up values in RB209 (+60 and +30 for Index 0 and 1 respectively) originate from the original approach to P and K fertilisation, which related the whole fertiliser cost to the cost of growing each crop (relative to returns from yields). However, each individual crop should not be expected to carry the costs of improving the asset value of agricultural land and of the farm business. Managing soil P and K reserves relates to asset value and risk management. The risk of crop yield reductions are much higher at lower P and K Indices even when soil organic matter levels are high and soils are well-structured, due to the effects of weather and field conditions from year to year, e.g. waterlogging.

Clarification was requested as to whether P applications should be calculated based on the crop that is being grown, or the crop that was grown the previous season. This confusion arises from the mention in some places in RB209 (8th edition) of estimated yield (implying consideration of the current crop), but in other places there is mention of achieved yield (implying previous crop). The authors of the 8th edition advised that the guidance is intended to refer to the current crop, and so rates should be based on expected or targeted yield; this should be made clearer within the revised text.

There was a clear demand for sunflower phosphate recommendations to be added to RB209.

3.6.3. Current practice

BSFP data (Anon, 2015) show that average phosphate applications in 2009-14 were lower than the RB209 (8th edition) recommendations to replace offtake. For example for cereals, RB209 (8th edition) recommended applications of 45-60 kg/ha P_2O_5 (depending on grain yield) to replace offtake when straw is incorporated, or 50-65 kg/ha P_2O_5 if straw is removed, and for winter oilseed rape the recommended maintenance application was 50 kg/ha P_2O_5. Actual applications to all tillage crops averaged 29 kg/ha P_2O_5 over the 2010-14 period; despite straw being removed from >70% cereal crops. However, these lower applications may be because many soils have high levels of P, and many fields receive organic materials which contribute significant amounts of P_2O_5, so it is not necessary to fully replace offtake with fertiliser.

PAAG data indicate that, averaged over the 5 seasons from 2009/10 to 2013/14, only 30% of ‘arable’ soils were at P Index 2. The proportion below Index 2 (i.e. at 1 or 0) appeared to be increasing, with values for the 5 years from 2009/10 to 2013/14 of 17, 18, 23, 28 and 26% respectively. The proportion above Index 2 (i.e. 3 or higher) appeared to be decreasing (54, 52, 48, 43 and 45% respectively). It should be noted that soils treated as arable here may also be growing vegetable crops or potatoes. Mean arable soil P levels decreased only marginally, from 32 mg/kg in 2009/10 to 29 mg/kg in 2013/14.

3.6.4. Review of new information

AHDB Cereals & Oilseeds Research Review 74: Response of cereals to soil and fertiliser phosphorus.

In a recent review, Johnston & Poulton (2011) examined data from three long-term field experiments on contrasting soils, established to provide plots with a wide range of plant available soil phosphorus (Olsen P). The data comprised 102 cereal yield responses to Olsen P, from 1969 to 2008. For each site-season, the authors identified the critical level of Olsen P associated with obtaining 98% of maximum yield.

For all response curves fitted for winter wheat, the average maximum grain yield was 8.03 t/ha. The maximum yield occurred at P Index 0 or 1 on 55% of sites, at P Index 2 on 30% sites, and at P Index 3 on 15% sites (Figure 2). About two-thirds of the results for P Index 2 soils were on soils with 16-20 mg/kg Olsen P. There was a difference between the soil types in the percentage of maximum yields achieved on soils with smaller amounts of Olsen P. On the better structured silty clay loam and the poorer structured sandy clay loam, 87% and 58% of the maximum yields were on soils with 8 to 15 mg/kg Olsen P (P Index 0 and 1), respectively. In some years wheat yielded very well with only 6 to 15 mg/kg Olsen P (P Index 0 and 1), suggesting that seedbeds and soil conditions, especially for root growth and nutrient acquisition, were particularly favourable.

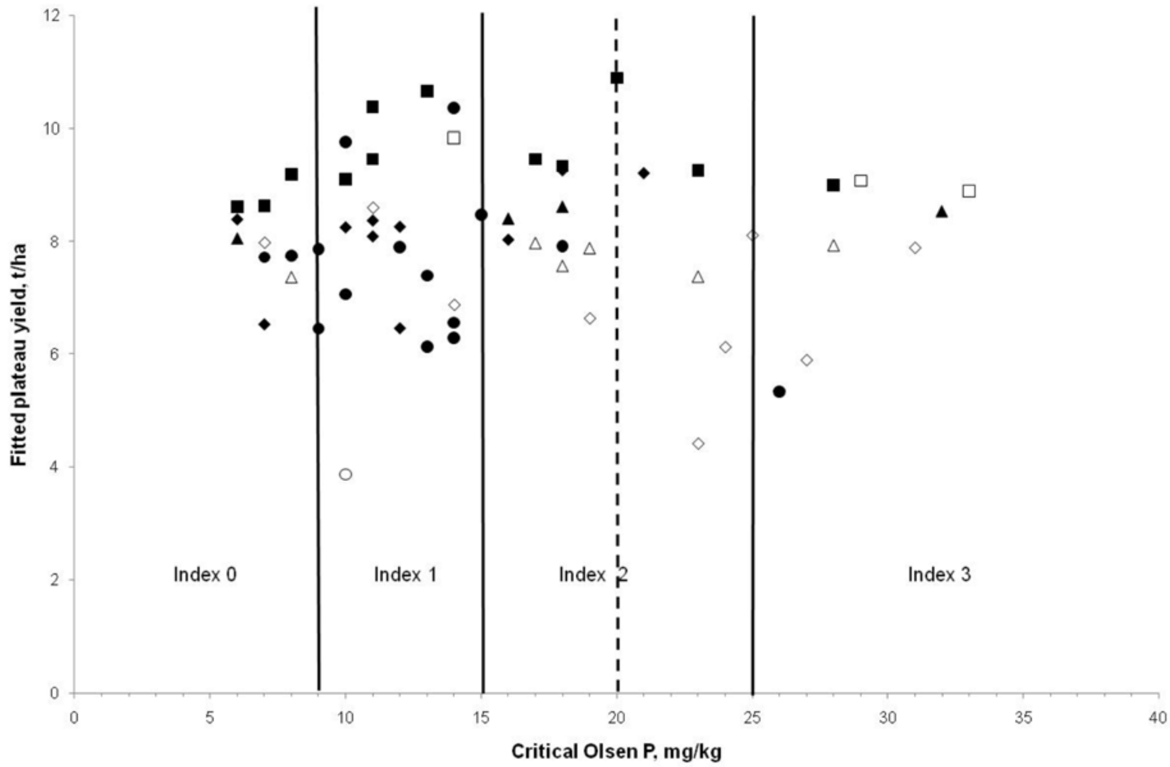

Figure 2. Fitted plateau yields of winter wheat and the critical Olsen P associated with 98% of that yield from three long-term field experiments (1969-2008). Filled symbols denote crops receiving sufficient N to achieve maximum yield; open symbols denote crops receiving insufficient N.

For spring barley, on the better structured silty clay loam, all 7 of the maximum yields were determined at P Index 1 or the lower half of P Index 2. For the other 35 maximum yields, 42% of these were on soils with a poorer soil structure with 21-35 mg/kg Olsen P (mid-point P Index 2 to mid-point P Index 3).

The year to year variability in the critical Olsen P within this dataset reflects differences in soil conditions and highlights the importance of improving soil structure, to facilitate nutrient uptake by roots and hence achieve maximum yield. The year to year variability in maximum yield was mainly due to weather, especially rainfall and the length of the grain filling period. The review concluded that there would be considerable risk to cereal yields if soils were not maintained at P Index 2. Due to the wide range in Olsen P associated with 98% of the maximum yield on each of the three soil types, it would be very difficult to offer more specific advice on Olsen P for particular soil types.

The phosphorus balance was calculated for these experiments. To build-up Olsen P large amounts of phosphate were required: to increase Olsen P from the mid-point of P Index 1 (12 mg/kg) to the mid-point of Index 2 (20 mg/kg) required 300 to 330 kg/ha P_2O_5 (as 670 to 750 kg/ha triple superphosphate, TSP).

AHDB Cereals & OilseedsProject Report 529: Identification of critical soil P levels for cereal and oilseed rape on a range of soil types.

Within the AHDB Cereals & Oilseeds project , a series of new experiments on six sites with low Olsen P levels were established on soil types including deep clays, loams and shallow soils over limestone or chalk (Knight *et al*., 2014). Varying rates of phosphate fertiliser were applied across all sites to create a range of Olsen P levels from P Index 0 to P Index 3. In each year from 2010 to 2013, measured grain or seed yields were related to Olsen P levels where no further P fertiliser was applied. In 2012 and 2013 sub-plots received fresh P fertiliser prior to cultivation to test the response of the crop to fresh P at each level of Olsen P.

Results over four years generally supported advice in the 8th edition of RB209: that soils growing cereals and oilseed rape should be maintained at P Index 2. For winter wheat, meaningful estimates of the fitted maximum yield and critical Olsen P levels associated with 95% or 98% of maximum yield were obtained for eight of the ten crops. The levels of Olsen P associated with 95% of maximum yield ranged from 8.5 mg/kg (Index 0) to 17.8 mg/kg (Index 2), and for 98% of maximum yield the range was 10.5 mg/kg (Index 1) to 24.4 mg/kg (Index 2) (Table 6). Across the eight wheat crops, average critical P levels were around 12 mg/kg for 95% of maximum yield and 16 mg/kg for 98% of maximum yield, which are between the mid half of P Index 1 and the lower half of P Index 2.

Table 6. Fitted maximum wheat yield and Olsen P to achieve 95% and 98% of maximum yield in field experiments (2011-2013) (Knight *et al*., 2014).

Site	Year	Plot values on which analysis is based	Fitted maximum yield		Olsen P for 95% max yield		Olsen P for 98% max yield		Variance accounted for (%)
			t/ha	s.e.	mg/kg	s.e.	mg/kg	s.e.	
Peldon	2011	Large plots (18)	8.86	0.22	13.8	2.80	18.6	4.47	70
Peldon	2012	Sub plots (36)	12.04	0.19	9.6	1.69	13.3	3.01	53
Peldon	2013	Sub plots (36)	8.67	0.28	9.9	1.56	12.0	2.32	47
Weston	2012	Sub plots (36)	10.50	0.45	8.5	2.92	10.5	4.19	44
Great	2011	Large plots (18)	8.64	0.35	10.2	2.91	13.1	4.73	50
Carlton	2012	Sub plots (36)	8.45	0.34	11.4	3.13	14.6	4.95	41
Caythorpe	2012	Sub plots (36)	4.54	0.47	17.8	4.32	21.9	5.79	59
Cholsey	2013	Sub plots (36)	11.33	0.78	17.1	10.3	24.4	16.37	38

Fresh P fertiliser treatments, at a fixed rate of 200 kg/ha P_2O_5 (435 kg/ha TSP), were applied at all sites in autumn 2011 and 2012. A high rate was used in order to test the assertion that no amount of fresh P fertiliser could give the same yield as that achievable by maintaining soils at Olsen P Index 2. In winter wheat, the mean yield increase with fresh P of about 1.0 t/ha at Index 0 was not sufficient to raise yields to the level achieved with soils maintained at Index 2. The mean increase with fresh P of about 0.5 t/ha at Index 1 was sufficient to raise yields to the level achieved with soils maintained at Index 2.

The overall P balances were reported for each site; the results indicated that there was considerable variation between sites in the amount of P fertiliser applied (calculated for all plots receiving more than 100 kg/ha P fertiliser). The amount of P_2O_5 (net of offtake) required to raise Olsen P from mid Index 0 to 1 or 1 to 2 ranged from 208 kg P_2O_5/ha on a deep clay soil to 632 kg P_2O_5/ha on a calcareous soil over limestone (Table 7).

Wider research by Heming (2007) examined the behaviour of P in a range of English arable soils by plotting the change in resin P in the topsoil at the end of a 3-5 year period, against the P balance over the same period. This showed that applying excess P fertiliser increased the change in resin P in the topsoil and reducing P fertiliser decreased it; typically 3-4 kg P/ha was required for each mg/l Resin P (6-8 kg P/ha for each mg/l of Olsen P). However, it was found on calcareous and red soil that when P fertiliser was applied in accordance to offtake, Resin P in the topsoil fell by 4 mg/l/yr (2 mg/l Olsen P/yr). To prevent this occurring, an extra 3 to 10 kg/ha P (7 to 23 kg/ha P_2O_5) per year of fertiliser was required.

Table 7. Amount of P or P_2O_5 required (net of offtake) to raise Olsen P by 1 mg/kg or 1 Index over three seasons (2010-2012).

Site	Soil texture	To raise Olsen P by 1 mg/kg		To raise Olsen P from mid Index 0 to 1 or 1 to 2		To raise Olsen P from mid Index 2 to 3	
		kg P/ha	kg P_2O_5/ha	kg P/ha	kg P_2O_5/ha	kg P/ha	kg P_2O_5/ha
Peldon	Deep clay	11.4	26.0	91	208	170	390
Great Carlton	Fine loam	21.3	48.8	170	390	319	731
Caythorpe	Sandy loam	29.4	67.4	235	539	441	1011
Cirencester	Silty clay loam over limestone	34.5	79.0	276	632	517	1185
Cholsey	Silt loam over chalk	32.3	73.9	258	591	484	1109

On a calcareous soil over limestone, the project proved that applying and incorporating a large dose of TSP fertiliser was much less effective at achieving a sustained increase in Olsen P above Index 1. This site had extractable calcium levels above 4,500 mg/l and average pH values above 7.5. This may have contributed to reduced P availability. Research in areas with calcareous soils has shown that the availability of P to plants for uptake is impaired due to the formation of poorly soluble calcium phosphate minerals.

The key points from AHDB Cereals & Oilseeds Project Report 529 (Knight *et al*., 2014) were:

- Results over four cropping years generally supported current advice to maintain soils at P Index 2.
- At Index 0, even a large application (200 kg/ha P_2O_5) of fresh P fertiliser did not raise wheat yields to those achieved at Index 2. However, at P Index 1 a large application of P did increase yields to those achieved at P Index 2.
- The amount of P fertiliser required to increase Olsen P by a given amount varied between sites depending on soil type.
- The shallow limestone soil required three times as much P fertiliser as the heavy clay in order to raise the soil P level by one Index, and at this site it was not possible to consistently maintain the soil at P Index 2 as recommended for arable rotations.

SRUC Technical Note TN668: Managing soil phosphorus

In Scotland, TN668 (Sinclair *et al*., 2015) reported on the classification of phosphorous sorption capacity (PSC) according to soil association by creating a digitised 1:250,000 Soil Map that ranked PSC for non-calcareous soils from low (PSC 1) to high (PSC 3). PSC refers to the differing capacity of soils to bind with applied P making it temporarily unavailable for plant uptake. This new, soil-specific approach takes account of the contrasting capacity of different soil types to regulate P availability for plant uptake. On high PSC soils (PSC 3), higher adjustments (kg/ha P_2O_5/year) are recommended to build-up soil P status and maintain target plant available P.

The P values for the SAC and RB209 analytical methods are shown in Table 8. The new SRUC guidelines recommend that for cereal-based arable rotations and established grass/clover swards the current target soil P status, using the SAC Modified Morgan's method, is lowered to M- (4.5-9.4 mg/l extractable soil P) on PSC 1 and 2 soils but M+ (9.5-13.4 mg/l extractable soil P) on PSC 3 soils. The target recommendations for rotations with potatoes and other P responsive crops remains as M+ for all PSC Indices. The new data on PSC Indices have allowed fine-tuning of these adjustments (Table 9) allowing for a lower adjustment for PSC 1 and 2 soils compared with the current recommendation which is maintained for PSC 3 soils.

Table 8. Classification of soil P analytical results into Status.

SAC status	RB209 Soil Index	Extractable P (mg/l)	
		SAC Modified Morgan's	Olsen P
VL	0	0-1.7	0-9
L	1	1.8-4.4	10-15
M-	2	4.5-9.4	16-20
M+	2	9.5-13.4	21-25
H	3	13.5-30.0	26-45
VH	4	>30.0	>45

Table 9. Effect of P sorption capacity on adjustments (kg P_2O_5/ha/year) to build-up or run-down soil P status.

P sorption capacity	Soil P status				
	Very low (VL)	Low (L)	Mod (M-)	Mod (M+)	High (H)
PSC 1	+40	+20	0	-10	-20
PSC 2	+60	+30	0	-20	-30
PSC 3	+80	+40	+20	0	-40

AHDB Project 216-0004 Cost-effective phosphorus management on UK arable farms (Sustainable-P)

The objectives of the on-going Sustainable-P project are to:

1. Improve understanding of the factors affecting rates of change in soil P status with P additions from both fertiliser and organic P sources;
2. Provide robust evidence on critical levels of soil P for modern combinable crops; and
3. Maximise and determine the value of fresh fertiliser P applications in terms of crop yield and quality under varying levels of soil P fertility.

Extensive farm experience and some recent trial results indicate that soils differ, at least in rates of soil P decline and quantities of P-balance (inputs minus off-takes) required to change soil P levels.

Within this project, a review of a large commercial dataset of soil samples collected using precision nutrient mapping allowed soil nutrient variation to be mapped across fields and whole farms. Preliminary analysis indicated that there was little effect of soil type on P responsiveness ranging from 15-25 kg P_2O_5/ha per mg/l soil Olsen P for shallow soils over chalk or limestone, heavy soils, medium soils and sandy or light soils. There was also no correlation between annual P_2O_5 balance needed to keep the soil P unchanged and soil pH.

LINK Project LK09136 Improving the sustainability of phosphorus use in arable farming

This project has reviewed three key strategies to improve sustainable P use in arable farming, including: (i) minimising crop P requirements, (ii) maximising root recovery of soil P, and (iii) developing targeted fertiliser technologies to improve P recovery (Edwards *et al*., 2015).

Phosphate recommendations in RB209 have largely relied on soil P storage rather than fresh P to optimise crop P supplies. The balance method of assessing efficiency of fertiliser P use appears misleading because it discounts P contributions from non-labile soil sources (Edwards *et al*., 2015). Long term studies indicate that soils release at least 5-9 kg/ha/year P without any fertiliser use, and that net recoveries of conventional fertiliser P are only 10-15%. The philosophy of feeding the soil rather than the crop has therefore been questioned. Current fertiliser P recommendations largely rely on soil P storage rather than fresh P to optimise crop P supplies. It has been suggested that this reliance results in poor capture of freshly-applied P by plant root systems and rapid reversion of plant-available P. Concern has also been raised that the current recommendations assume little or no P loss by fixation or leakage, and that they are managed by P tests with limited repeatability and variable ability to predict crop responses. It has therefore been proposed to investigate future management strategies that could be tailored to specific farm, crop and environmental conditions, including P fertiliser placement; seed P coatings; foliar P applications; and products that modify P availability. However, there is not yet sufficient evidence to fully assess the reliability of these (sometimes novel) P targeting technologies.

The conclusions of this project are still awaiting final publication. However, there appear to be potential opportunities for targeting applications of fresh P fertilisers to meet crop P demand in some situations. Where fresh TSP fertiliser was placed with the seed on sites with a low P Index soil (Index 0 or 1) in harvest years 2011, 2012 and 2014, there were positive responses both in winter and spring barley. A profit figure was calculated based on yield return over fertiliser cost, excluding drill (fertiliser placement costs). The profit ranged from +£11/ha to +£83/ha where TSP fertiliser was placed compared to no P application. In 2013 and 2014, responses in winter wheat were inconclusive across two experiments on variable sites, indicating a positive profit (+£167/ha) in 2013 and a negative profit (-£54/ha) in 2014. In two OSR trials, placed TSP fertiliser showed no yield response and therefore no positive profit from placement.

UK commercial replicated trials (Yara UK)

Commercial trials have also reported yield responses to spring applied (unincorporated) fresh P fertiliser applied as TSP in winter oilseed rape and winter wheat crops. On a mid P Index 2, loam soil over sandstone, the yield response of winter oilseed rape to either 50 kg P_2O_5 /ha or 100 kg P_2O_5/ha, broadcast in the spring, was between 0.3 t/ha and 0.5 t/ha (no *P* statistic provided). In winter wheat, on a calcareous soil with P Indices of 1 (Low) or 3 (High) a significant yield response of 0.5 t/ha was recorded where 92 kg/ha P_2O_5 was applied on the low P Index soil compared to no fresh P fertiliser. No significant response was seen on the High P Index soil.

DC-Agri; field experiments for Quality Digestate and Compost in Agriculture – WP1 report

The DC-*Agri* project investigated the effects of repeat applications (*i.e.* annual applications over a minimum of three years) of compost and digestate in comparison with farmyard manure and livestock slurry on soil and crop quality (Bhogal *et al*., 2016). The aim was to compare the effect of organic material treatments on soil physical and chemical properties with that of a fertiliser only 'control' treatment. Therefore, manufactured fertilisers (N, P_2O_5, K_2O & SO_3) were applied to all treatments (based on MANNER-NPK predictions, "The Fertiliser Manual (RB209)" or SAC Technical Note recommendations) to ensure (as far as was practically possible) that no major nutrient limited plant growth and that crop yields and residue returns were the same on all treatments (i.e. the only difference in organic carbon (matter) inputs would be from the applied organic materials). The phosphate supply from organic materials ranged from 29 kg P_2O_5/ha/yr where food-based digestate was applied, to 159 kg P_2O_5 /ha/yr where FYM was applied.

In 2012, on a calcareous, P Index 2 soil near Devizes (Wiltshire), the use of organic materials increased winter wheat yields (by 5-18%; 0.4-1.4 t/ha; $P<0.01$; Figure 3a) and grain phosphorus concentrations ($P<0.05$; Figure 3b), despite the control receiving a maintenance application of phosphate fertiliser according to RB209 recommendations. As the soil at Devizes was a P-fixing soil (shallow soil over chalk, pH 8), the yield response may have been a result of the additional P supply from organic materials. In 2013, organic materials also increased yields by 9-30% (0.5-2.2 t/ha) relative to the control. The key conclusion from the project was that on P-fixing soils the addition of organic materials provided a ‘nutrient boost’ resulting in a 5-30% increase to crop yields over the ‘control’ treatment.

a) b)

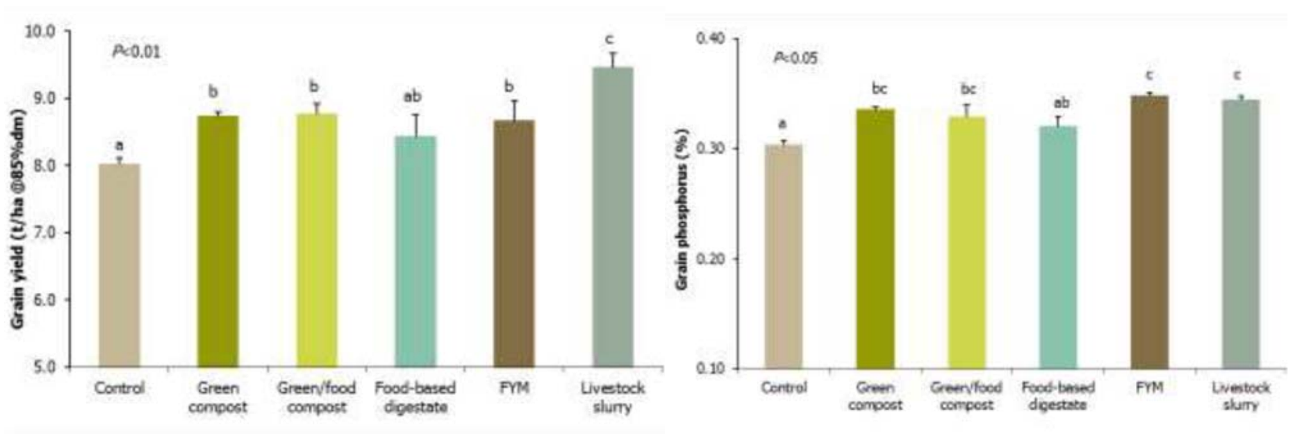

Figure 3. Winter wheat grain yields (a) and phosphorous concentrations (b) at Devizes in 2012 (with standard errors). Bars labelled with different letters indicate significant differences between treatments (*P*<0.05) (Bhogal *et al*., 2016).

Sunflower P recommendations

There was insufficient data to provide phosphate offtake values for sunflowers. The UK Grower’s Guide (Cook, 2009) provides nutrient recommendations for sunflowers. Maintenance applications of 40-60 kg/ha P_2O_5 should be sufficient for crops grown on soils at target P Indices. Build up rates at P Indices 0 and 1 should be the same as for other crops.

3.6.5. Knowledge gaps

There are insufficient data to support a significant change to phosphate recommendations at this time. However, improving P supply to crops is highlighted as a significant knowledge gap. Responses to fresh P fertiliser (both organic and inorganic forms) need to be assessed at multiple sites (representing a wider range of soil types, including calcareous soils) to quantify the long-term effectiveness, in terms of yield and economics, of maintaining the soil at Index 1 and applying fresh P fertiliser annually to the crop to maintain yield potential.

Examination of soil P responses to overall P balances (based on P added minus total P removed) on differing soil types (including calcareous soils) has shown significant variation and some link with soil types (Heming, 2007). Recent AHDB work on the SOYL database indicates some significant differences between farms. It is therefore suggested that RB209 should provide the option to apply P fertiliser according to the desired period for change in soil P reserves. This can be achieved through 'signposting' towards the Potash Development Association (PDA) PK calculator. The PK calculator includes P and K 'build-up' values for three principal soil types (light, medium and heavy) derived from work carried out at Rothamsted Research (Johnston *et al*., 1999; Blake *et al*., 2003). However, further research is needed on the response of different soil types to P additions; and the ability of different P sources to increase soil P reserves and Olsen P levels.

3.6.6. Conclusions: phosphate recommendations

There is insufficient new evidence to support a substantial change to the current RB209 recommendations. There is some evidence (from Critical P and DC-*Agri* projects) to suggest that the approach to supplying P to crops could be adjusted, particularly on calcareous soils (mainly shallow soils over chalk or limestone with high available calcium) where it is difficult to maintain soil Olsen P at Index 2. In these situations, maintaining soils at P Index 1 and applying fresh P as fertiliser or manure on an annual basis may increase yields compared to those achieved at P Index 2, provided that adequate fresh P is applied. Evidence from the Targeted P-LINK Project (which tested fresh P on Index 1 sites) indicates that such fresh P applications, because they were very poorly recovered (4%), were not economic unless they were placed with the seed, rather than broadcast. Fresh P was economic for potatoes, and response was increased by placement, but was not economic for combinable crops where P fertiliser was broadcast. Recent evidence from the Critical P project suggests that soils at Index 0 are unlikely to give the same yields as at Index 2, even with very large applications of fresh P.

Since there is clear evidence that soil P 'responsiveness' varies between sites, and that this may be soil type dependent (Heming, 2007), revised guidelines could involve a 2 stage process of calculating 'build-up'/'run-down' rate, then offtake, rather than rolling both into single tables as at present (i.e. fertiliser requirement = soil correction ('build-up'/'run 'down rate) + crop offtake – supply by manures). It is currently recommended that to raise the level of a soil at Index 0 requires an additional 60 kg/ha P_2O_5 and at Index 1 an additional 30 kg/ha P_2O_5 in addition to the maintenance dressing. This typically results in the soil Index increasing by one level over 10-15 years. This has been considered by some advisors to be too long and therefore recommendations to increase build-up rates over a shorter time period should be considered.

It was agreed at the Arable TWG on 25th April 2016 that phosphate and potash offtakes should be related to 'targeted yield' rather than 'expected yield' in the new "Nutrient Management Guide (RB209)". In addition, the following proposed text revisions refer specifically to phosphate. They are in addition to the text written for potash:

1. The text under the first table on p.37 (RB209 8th edition) should read:

   "The amount of applied P required (over and above offtake) to raise soil P levels will vary according to soil type.

   "On calcareous soils (with free calcium carbonate) it may not be possible to maintain Olsen P at the target Index due to rapid P reversion processes. In these situations, it may be more appropriate to maintain soils at P Index 1 and apply fresh P fertiliser on an annual basis to increase yields to those achieved at P Index 2.

   "Where crops are grown on soils **at P Index 1, in some circumstances it may be possible to raise yields to the level achieved at Index 2 by applying phosphate fertiliser at higher than recommended rates. However, this is not possible at P Index 0.**

   "Where soil P levels are below the target Index 2, they are most likely to give optimal yields on soils that are well structured and enable good rooting."

2. On p.39 (RB209 8th edition), under the heading "Building up or running down soil Indices", replace the current text and Table with the following:

   ""To raise the level of a soil at Index 0 and 1 to Index 2 requires the application of more fertiliser than that needed for the maintenance dressing. The amount of extra fertiliser to apply **each time is determined by the number of years over which the Index is to be raised (see below). Raising Indices over a shorter period of time minimises the period of yield loss, but in the short term will increase the annual cost.**

“Large amounts of phosphate and potash may be required to raise the crop-available phosphate and potash in the soil by one Index, and it is difficult to give accurate amounts. However, as an example, to increase soil phosphate by 10mg P/litre may need 400 kg P_2O_5/ha as a phosphate fertiliser (i.e. 850 kg/ha of triple superphosphate). To increase soil potash by 50 mg K/litre may need **300-500** kg K_2O/ha as a potash fertiliser (i.e. **500-800** kg/ha of muriate of potash), with more potash required on heavier soils where the clay type can make a difference. **The amount to apply at each dressing is a business decision that depends on how quickly the land manager aims to increase the asset value of the land. Consequently, two sets of build-up application rates are shown in the Table below with the approximate time over which Index 2 can be reached.** These amounts have been calculated using the mid-point values for each **initial** Index (as mg/litre) compared to the mid-point value of the target Index. **The Potash Development Association (PDA) PK calculator provides further options for building-up soil nutrient reserves at varying rates:**

http://www.pda.org.uk/calculator/pkcalculator.html”

Adjusting applications for soil Index

Period over which to adjust soil Index	Current P or K Index					
	0	1	2-	2+	3	4 or higher
	Adjustment to application (kg/ha)					
10-15 years	+60	+30	0	-30	-60	No phosphate or potash required
5-10 years	+100	+50	0			

3. On p.40 (RB209 8th edition), the heading should be revised to “Adjusting the application of P and K according to the soil Index and **targeted** yield”. It is proposed that a different approach be taken to the current tables as follows:

Example: Winter Wheat

Application required to replace offtake						Application to replace offtake (to nearest 5 kg/ha)		
Grain yield (t/ha)	P_2O_5 (kg/ha)	K_2O (kg/ha)	Straw yield (t/ha)	P_2O_5 (kg/ha)	K_2O (kg/ha)	Grain + Straw (grain yield t/ha*)	P_2O_5 (kg/ha)	K_2O (kg/ha)
6	47	34	3	4	29	6	50	65
8	62	45	4	5	38	8	65	85
10	78	56	5	6	48	10	85	105
12	94	67	6	7	57	12	100	125
(per t/ha)	7.8	5.6	(per t/ha)	1.2	9.5	(per t/ha)	8.4	10.4

*Standard recommendations assume straw yield will be 50% of grain yield

4. In Section 3 (RB209 8th edition, p.100-101) a new "Example" for P should read:

"Soil P analysis is 12 mg/litre which is at the low end of P Index 1 (range 10 to 15 mg/litre P – see Appendix 4). Winter wheat is to be grown, targeted grain yield is 8 t/ha and straw will be removed. Previous crop (winter wheat) was 2 t/ha higher yielding than expected (straw removed).

"The table on page 114 shows a recommendation of 95 kg P_2O_5/ha for winter wheat (straw removed) at soil P Index 1. This recommendation is for a soil P analysis value of 13 mg/litre, the mid-point of P Index 1. Because the soil is at the bottom of Index 1, it would be more appropriate to apply 110 kg P_2O_5/ha, a value between that for P Index 0 and 1. Adding 20 kg/ha (2 x 8.4 from Appendix 5) for the under application to the previous crop brings the total to 130 kg P_20_5/ha."

"Alternatively, calculate the required application rates (using offtake values from Appendix 5 and soil Index adjustments from Section 1, page 40) as follows:"

	P_2O_5 (kg/ha)
Offtake in grain (= targeted grain yield x offtake per tonne grain)	62
Offtake in straw (= targeted straw yield x offtake per tonne straw) (assume straw yield is 50% of grain yield if uncertain)	5
Total offtake	67
Build soil index (at Index 0 or 1)*	+45
Run-down soil index (at Index 2+ or 3)	-
Too much P/K applied to previous crop (e.g. yield lower than expected; straw not removed)	-
No, or too little, P/K applied to previous crop (e.g. application 'holiday'; yield higher than expected)	+20
Total application required (rounded to the nearest 5 kg/ha)	130

* Based on build over 10-15 years and current P Index mid-way between 0 and 1.

3.7. Crop potash requirements

3.7.1. RB209 (8th edition) advice

In the introductory "Basis of Good Practice" (RB209 8th edition, p.3):

- Regular soil analysis for pH, P, K and Mg was listed as an example of 'Reliable information'
- Nutrient balances were listed under 'Reliable information'
- Adjusting phosphate and potash for yield levels was listed under 'Correct decisions...'
- Placement of fertilisers for responsive crops was listed under 'Decisions... on fertiliser application...'

In Section 1 (RB209 8th edition, Principles, p.33-42):

- Managing soil supply and maintenance of target Indices were introduced
- Replacement of offtake was outlined
- Importance of soil sampling was identified
- Typical yield responses to soil K were illustrated
- Approach to managing soil K was explained in detail
- Basis of recommendations (as kg K_2O/ha) was stated
- Soil sampling and analysis were described in detail
- Potash releasing clays were explained and differentiated from other clay soils
- Target soil Indices (K Index 2-, 121-180 mg/l) were stated for arable / forage / grassland rotations
- Evidence was presented that, at K Index 0, fresh potash fertiliser may not achieve yields comparable to those achieved at the target Index
- An example of how to calculate applications to maintain the soil Index was given
- Adjustments to build-up or run-down soil Indices were shown:

- 300 kg K_2O/ha to raise soil K by 50 mg/l
- Rationale for raising in smaller increments was given as cost
- For arable / forage / grassland: 60 kg K_2O/ha required over maintenance to raise soil K from (mid) Index 0 to 1; 30 kg K_2O/ha required from (mid) Index 1 to 2, over 10-15 years

- Crop recommendations in RB209 (8th edition) represented the higher of i) rate of nutrient for maximum crop response or ii) rate of nutrient based on maintenance plus amount suggested to raise soil Index
- Advice on how to raise the Index more quickly was given (ensure soil well mixed by cultivation; frequent soil analysis, allowing time after application for equilibrium to be achieved)
- Advice on how to achieve decline in soil Index was given
- Examples of adjusting application for yield and soil Index were presented
- Yield and other impacts of inadequate / excess soil Indices were described
- Advice was given for potash use on sandy / sandy loam soils: maintain soils at *c*. 150 mg/l for sandy loams, but a maximum of 100 mg/l for sands / loamy sands. On sands apply potash every year

In Section 3 (RB209 8th edition, Using the Recommendation Tables, p.99-102):

- Potash recommendations in each crop section were explained:
  - The basis of the recommendations was reiterated
  - Adjusting for the potash balance in previous crops was mentioned
- Example recommendation calculations were presented
- The importance of allowing for potash supplied from organic manures was stated
- The use of a nutrient balance sheet for each field was advocated

In Appendix 3 (RB209 8th edition; Sampling for Soil pH, P, K, Mg and Na; p.225-226):

- The importance of correct sampling procedure was explained. Advice was provided on:
- When to sample:
  - Sample every 4th year given as a general guideline
  - When soil is in settled state, same point in rotation and relative to applications and cultivations
  - After last fertiliser application has been cultivated in, and not within 6 months of application
  - Avoid when soil very dry
- How to take a representative sample:
  - Sample areas of land known to differ separately
  - Exclude atypical areas, headlands, near trees / hedges

  - 25 individual sub-samples is adequate for a uniform area, in a W pattern
- Sampling depth:
  - Uniformity is important especially where crops are established without ploughing
  - Sampling to 15cm was recommended for arable situations
  - No differentiation in sampling depth for different cultivation methods

Appendix 4 (RB209 8th edition, p.227) classified soil P, K and Mg Analysis into Indices. For K this is based on ammonium nitrate extract.

Appendix 5 (RB209 8th edition, Phosphate and Potash in Crop Material, p.228-229) included data on grain / seed only (all cereals, oilseed rape); grain + straw (winter wheat / barley, spring wheat / barley, winter / spring oats); and straw only (winter wheat / barley, spring wheat / barley, oilseed rape). Variation in straw K content, and cause, are included in a footnote.

3.7.2. Other relevant documents

In SRUC Technical Note TN633, Sinclair *et al*. (2013) made the following key points:

- Soil sampling was recommended every 4-5 years.
- Sampling time was stated as not critical for cereals and oilseed rape (but not within 12 weeks of fertiliser application). September to February was advised.
- Sampling whole fields to derive an average figure was discouraged where major soil type variation exists or soil levels are high. GPS sampling was suggested (at up to one sample per hectare).
- Differences in the analysis method between Scotland (Modified Morgan's) and England/Wales were highlighted.
- The target soil status for K for cereals and oilseeds is M- (lower half of moderate, which is 76-140 mg/l using the SAC analysis method but corresponds to 121-180 mg/l for RB209).
- The strategy for cereal and oilseed crops on moderate status soils was equivalent to RB209 (8th edition): maintenance application to balance offtake.
- Leaf analysis for K was identified as a means to check what is in the crop.
- Calculation of nutrient balance was recommended.
- K contents (kg/t of fresh material) were given for grain / seed only, grain / seed plus straw, or straw only for different crops as in RB209 (8th edition) Appendix 5. These were the same as in RB209 (8th edition), except that the K content of oat, rye and triticale straw-only was also specified (same as spring barley / wheat).

PDA (Potash Development Association) Leaflet 24 (2011) contains advice on soil sampling:

- Recommends 25 sub-samples for bulking into a single sample for a uniform field.

- Recommends 16 sub-samples per grid point when grid sampling.
- Recommends waiting at least 8 weeks after fertiliser application before sampling.
- It is stated that to increase plant-available soil K by 50 mg/l requires approximately 300-500 kg/ha K_2O, with less potash required on some heavier soils where the clay type can make a difference.
- Identifies that K may be concentrated in top 5-8 cm under shallow minimal cultivation systems, or with continuous direct drilling a large difference between the top 5 cm and 6-15 cm deep zones.
- Effects of different cultivation systems and their implications for sampling depth.
    - Regular ploughing/cultivation: Nutrients are mixed into a fairly homogeneous soil layer 20-25 cm deep (depending on ploughing depth). Nutrient concentrations in a core taken to 15 cm should be the same as those in the whole mixed layer.
    - Regular minimum cultivation to 5 cm: Applied phosphate and potash will tend to accumulate in this shallow mixed layer leading to stratification of nutrient concentration in the top of the soil profile. Nutrient concentrations in a sample to 15 cm depth will not be equivalent to those in the traditional mixed layer, which is normally to the depth of ploughing. The samples will not be comparable and may over-estimate the supply of phosphate and potash available to the crop. However, there was no available evidence to inform the relationship between sampling depth and crop response to nutrient applications in this situation.
    - Occasional ploughing after several years of minimum cultivation: The soil layer that is mixed by minimum cultivation (and relatively rich in nutrients) will be buried by ploughing to a depth that is not accessed during normal soil sampling. Samples taken after ploughing are likely to underestimate the supply of phosphate and potash available to the crop in these systems. However, there was no experimental evidence to support this view; further work is needed (section 4).

PDA Leaflet 11 (2011) advises on potash for cereals:

- If potash supply is limiting, the uptake and utilisation of nitrogen will be restricted, with impacts on yield, yield response to N and quality (e.g. conversion of N to grain protein).
- Peak potash uptake with cereals occurs around the late flowering stage when there may be more than 300 kg K_2O/ha in a high yielding crop. This is much greater than offtake at harvest
- Where tissue testing is being considered, measurement of tissue water (cell sap) is recommended, as an indicator of whether K concentrations are at or below optimum levels. It is suggested that this is more reliable and meaningful than measurement of K content in the dry matter.

- K content in straw is stated as being much more variable than in grain. It is different for winter wheat/barley, spring wheat/barley and oats, and is affected by growing conditions.
- Winter cereal straw retains less K as there is more time for redistribution out of the upper parts of the plant - typical removal of potash is 9.5 kg K_2O/t fresh straw. Winter barley, being harvested earlier, often retains more K in the straw than wheat.
- Typical removal of potash in spring wheat/barley is around 12.5 kg K_2O/t fresh straw. Winter and spring oats tend to retain much higher levels of K in straw than other cereals - often with values of over 2% K in dry matter.

The PDA has developed a calculator (http://www.pda.org.uk/pda-app/, described in PDA, 2012) for estimating nutrients needed to correct soil deficiency. This is aimed at raising levels more quickly than the 10-15 years assumed in RB209, in order to reduce the period of economic loss. The Calculator has two main functions.

1. It enables a quick calculation of the phosphate and potash offtakes by most UK crops at harvest.
2. If soil Indices are below the target level the second section of the Calculator provides a guide to the quantity of nutrient that is likely to be required to correct the deficiency. This will vary according to the level of deficiency and the soil type. The quantity will usually be more than can reasonably be applied in one season, and the Calculator asks by how much and how quickly you want to correct the deficiency, i.e. over how many years. The desired improvement can be input by Index or more precisely by mg/litre as determined by soil analysis.

The Calculator displays the nutrients required to replace the offtake at harvest, and shows separately the guide quantity of phosphate and or potash needed to correct the deficiency. A maximum of 100 kg P_2O_5/ha per year is recommended for deficiency-correcting applications of phosphate, but no limit is specified for potash. Plough down of large corrective K doses is advised.

Further advice from the PDA was published in Potash News January 2015 (PDA, 2015), regarding the effects of soil texture and pH on potash availability The typical quantity of potash that potash-releasing clay soils can release into available forms for crop uptake each year is given as 50 kg K_2O/ha (a web search of recent publications revealed no data to validate this). K availability increases as the concentration of Ca ions in the soil increases, as the Ca displaces the K from the clay lattice and makes it more available in solution. At pH 6.0 K availability is 100%, 72% at pH 5.5 and 52% at pH 5.0.

In a further PDA publication, Johnston & Milford (2012) examined interactions between K and N. For N to be used efficiently, a crop must have access to, and take up, an adequate amount of potassium from the plant-available (exchangeable K) pool of K in the soil. This is because there is a strong interaction between these two nutrients in crop growth which decreases the crop's response to applied fertiliser N when the exchangeable K content of a soil is below a critical target level. Interactions between N and K on crop growth and yield can be explained by their effects and interactions on the growth processes within the plant at the tissue and individual cell levels.

3.7.3. Comments from Consultation

Several respondents stated RB209 (8th edition) recommended application rates for potash are too low. A 'Farmers Weekly' article (6th December 2013) claimed that UK oilseed rape crops may be suffering from insufficient potash applications, on the basis that although the crop removes less than 50 kg/ha K_2O, it needs 300-400 kg/ha K_2O during the growing season (noting that German farmers typically apply about 140 kg/ha K_2O). However, other agronomists contacted considered that potash recommendations in RB209 are about right, and approved of their flexibility to take yield into account.

One respondent requested clarification as to whether potash applications should be calculated based on the crop that is being grown, or the crop that was grown the previous season. This confusion arises from the mention in some places in RB209 (8th edition) of estimated yield (implying consideration of the current crop), but in other places of achieved yield (implying previous crop). Johnny Johnston (Rothamsted Research) clarified that the advice is intended to refer to the current crop, and so rates should be based on predicted yield, but he agreed that this could be made clearer within the text of RB209 (8th edition). On a related point, one respondent suggested retrospective adjustment of application rates in the current year where yields (and therefore offtakes) in the previous year were higher low lower than predicted.

One respondent noted that straw yields are variable and can be low relative to grain yield (reducing potash offtake), but RB209 (8th edition) recommendations assume a fixed straw:grain yield ratio of about 2:1 (unless straw yields are known in which case offtakes can be calculated separately for grain and straw).

Two respondents argued that the build values for bringing soil K up to target Indices are too low, such that recommended applications would take 10-15 years to raise soil Index by 1. One respondent argued that run-down rates for soils with excess K may be too high, considering that soil sampling often takes place before cultivations and the level of sampling variation likely to exist. It was proposed that RB209 use a two-stage process, calculating build / run-down rate and replacement of offtake separately, rather than rolling into one value as in the current recommendation tables.

One respondent suggested that K Index 3 was too broad and should be split into K Index 3- (241-310 mg/l) and 3+ (311-400 mg/l).

One respondent questioned the focus on maintaining soil Indices, and asked whether there may be yield or quality benefits from potash applications to growing crops, e.g. to improve grain quality in oats.

One respondent requested clarification of the potash fertilisation policy for sandy and sandy loam soils on the basis that current recommendations in RB209 (8^{th} edition) were vague.

One respondent requested clearer guidance on the role of leaf tissue analysis in determining potash applications.

One respondent proposed coverage of the effects of K status of crops on N uptake and assimilation.

There was a clear demand for sunflower potash recommendations to be added to RB209.

3.7.4. Current Practice

According to the British Survey of Fertiliser Practice (Anon, 2015), average potash applications to cereals and oilseed rape were lower than recommended by RB209 (8^{th} edition) in the 2010-14 period.

- Recommendations were that cereals need 35-45 kg K_2O/ha to replace offtake if straw is returned, or 70-105 kg/ha if straw removed, and that winter oilseed rape needs 40 kg/ha.
- Although straw is removed from >70% cereal crops, the average application to tillage crops over the 2010-14 period was only 39 kg K_2O/ha (winter wheat 32, winter barley 44, spring barley 46 and oilseed rape 28).

Average dressing cover (% area treated) over the 2010-14 period for tillage crops was 43% for winter wheat, 60% for winter barley, 71% for spring barley and 41% for oilseed rape. Average field rate (for the area treated) over the 2010-14 period for tillage crops was 74 kg K_2O/ha for winter wheat, 73 kg K_2O/ha for winter barley, 65 kg K_2O/ha for spring barley and 67 kg K_2O/ha for oilseed rape.

PAAG data suggest that, averaged over the 5 seasons from 2009/10 to 2013/14, only 38% of arable soils were above target (K Index 2+ or higher), yet the area of winter wheat and oilseed rape not treated was more than 50%. 31% of arable soils were at target (K Index 2-) and 31% of soils were below target (K Index 1 or 0). Mean soil K level over the 5 year period was 180 mg/l, which was at the top end of the range for K Index 2- of 121-180 mg/l.

3.7.5. Review of new information

New K fertilisers

A Polyhalite K fertiliser (also marketed as ‘PolysulphateTM’) contains 14% K_2O, 48% SO_3, 6% MgO and 17% CaO. It is reported that trials have shown availability of K is similar to standard sources.

Data supplied by K+S were reviewed from one oilseed rape trial comparing K (and S) sources (polyhalite, sulphate of potash and muriate of potash fertilisers), and with target K_2O application rates of 0, 15, 30, 60 and 120 kg/ha. The pre-trial soil K level was 95 mg/l (Index 1). On average, plots receiving muriate of potash had a 0.14 t/ha higher seed yield and 0.1 t/ha higher oil yield than those that were untreated, but there was no dose response. Responses to polyhalite and sulphate of potash are not considered here as application rates of K_2O and SO_3 varied simultaneously with treatment.

AHDB Cereals & Oilseeds Project Report 485: Cost-effective sampling strategies for soil management

A range of alternative sample designs for testing soil P and K levels were evaluated and compared with the conventional ‘W’ pattern recommended in RB209 (Marchant *et al*., 2012). Although they could be reduced with alternative designs, errors from estimating soil-nutrient status with a ‘W’ were not large enough to substantially affect the quality of soil nutrient management. Recommendations were instead limited by other sources of uncertainty in predicting the amount of nutrients the crops will access from the soil. It was concluded that the benefits of using optimized designs do not outweigh the extra complexity that they entail.

Assuming testing every 4 years, a bulked sample every four years of 10 soil cores was sufficient to maintain both soil P and K stocks within a target range (sufficient to ensure that both P and K concentrations would remain within Index 2 for more than 97.5% of years). Field size did not substantially alter this. This is less than half of the number of cores that is currently recommended in RB209. In the scenarios explored in the project, decisions regarding K were found to require less accurate information than P, with potentially fewer than four cores required.

Previous work by Oliver *et al*. (1997) examined the bulking required for within-field mapping of soil P and K rather than the field averages considered in this project. They suggested that for surveys conducted on a grid each observation should consist of 16 bulked cores from within an area of 5 m^2 around the grid node. 16 cores were suggested because on the two fields studied they ensured that the sampling errors in estimating the mean nutrient content of the 5 m^2 were less than 1 and 7 mg/l for P and K respectively. However they did not assess sampling effort relative to the potential implications of the sampling errors for loss of soil nutrient status and decreased profits.

Sunflower K recommendations

There was insufficient data to provide potash offtake values for sunflowers. The UK Grower's Guide (Cook, 2009) states that a relatively high level of potash is required during the growing season, but the majority is returned to the soil at harvest. Maintenance applications of 40-60 kg/ha K_2O should be sufficient for crops grown on soils at target K Indices. Build up rates at K Indices 0 and 1 should be the same as for other crops.

Other Articles

A news article published on the Yara website on 20 September 2015 (http://yara.co.uk/news/211742/increased-yield-from-better-timing-of-p-and-k-applications/) reported benefits of applying small autumn applications of phosphate and potash followed by early spring applied P and K. Oilseed rape showed a 0.6 t/ha yield response over a similar total rate of both nutrients applied all in the autumn; whilst winter wheat showed a yield response of 0.7 t/ha.

Regarding tissue testing for K, Barraclough *et al*. (1997) concluded that for diagnosing winter wheat plant K status, the newest fully expanded leaf blade (leaf 1) should be used. However, critical leaf K concentrations appeared to depend on yield. At growth stages between GS31-39, critical %K in leaf 1 dry matter ranged from 1.9% for crops yielding up to 8.5 t/ha to 2.9% K for a crop yielding 9.5 t/ha. For growth stages between GS31-61, critical K in leaf 1 tissue water ranged from 150 mM for crops yielding up to 8.5 t/ha to 200 mM K for a crop yielding 9.5 t/ha. Both sets of critical values for wheat were supported by a subsequent project (Barraclough *et al*., 2000).

Barraclough *et al*. (1997) observed that total plant nutrient concentrations in shoot dry matter decrease with plant age and are affected by growing conditions and the supply of other nutrients that affect dry matter production. However, Greenwood & Stone (1998) concluded that K concentrations in tissue water fluctuate widely over short periods in a non-systematic manner, making them less useful.

3.7.6. Conclusions: potash

Text in the 8^{th} edition of RB209 should be revised to clarify that the amount of potash that needs to be available to the crop to meet peak uptake of K exceeds the amount that will be removed in grain or grain and straw. The role of tissue testing for K also needs clarifying.

The text should make it clear that fertiliser recommendations are designed to replace offtake (based on estimated yield) by the current crop, not the previous crop, and advise that under- or over-estimates of offtake should be accounted for when determining recommendations for the next crop.

Where straw yield can reliably be estimated, advice should be given to describe separate estimation of K offtake in grain and straw, to take account of variable / proportionately lower straw yields.

The amount of potash required to raise K Index should be presented separately, to enable below-target Indices to be rectified more quickly.

The advice on soil sampling should be amended to give an appropriate number of sub-samples required to create a field average soil sample for K analysis, and to take account of the effect of cultivation system (as described in PDA Leaflet 24). Guidance should also be provided on the use of GPS sampling and the scope to operate at lower Indices with precision sampling.

Key knowledge gaps are:

1. Do the large peak uptakes of potash (300+ kg/ha K_2O) associated with high yield potential crops require higher levels of exchangeable soil K than are indicated from older response trials where yields might typically be more modest.
2. There are no recent published independent data to assess significance of K application timing, and specifically the yield or quality benefits of fresh K application in spring to growing crops.
3. Offtakes of K_2O in rye and triticale straw (including crops harvested whole e.g. for Anaerobic Digestion)?
4. Optimal rates of soil K build-up in below-target soils for different crop rotations, taking account of yield loss, fertiliser costs and soil type / efficiency of use.
5. Better quantification of rates of decline for soil K in absence of applied fertiliser (potash releasing clays compared to other soil types).
6. Should soils under shallow tillage (+/- rotational ploughing) or continuous direct drilling be routinely sampled to 20-25 cm depth rather than 15 cm, to better quantify nutrient availability (and change over time) in the whole topsoil layer?
7. Is tissue testing in spring a useful indicator of the likelihood of a response to a foliar application of K fertiliser?

Suggested revisions to the text (RB209 8th edition) are as follows:

Introduction: The Basis of Good Practice *(*RB209 8th edition, p.*3)*

1. Change the third bullet point under correct decisions from ‘Consider adjusting phosphate and potash for yield level’ to: “**Adjust phosphate and potash for targeted crop yield (including straw where removal is planned)**.”

Section 1: Principles

2. Under the heading “Crop nutrient requirements” (RB209 8th edition, p.16), amend the second paragraph as follows: “The names macro- and micro- nutrients do not refer to relative importance in plant nutrition; a deficiency of any one of these elements can limit growth and result in decreased yield **and less efficient use of other nutrients**. It is therefore important to ensure that there is an optimum supply of all nutrients – if a plant is seriously deficient in, for example, potassium it will not be able to utilise fully any added nitrogen and reach its full potential yield and any unutilised nitrogen may be lost from the field.”

3. Under the same heading, amend the fourth paragraph to: “Achieving the right timing of nutrient application is as important as applying the correct amount. Crop demand varies

throughout the season and is greatest when a crop is growing quickly. Rapid development of leaves and roots during the early stages of plant growth is crucial to reach the optimum yield at harvest, and an adequate supply of all nutrients must be available during this time. **The amount of a nutrient taken up by a crop may exceed the amount that will be removed in the crop at harvest. For example, at its peak a high yielding cereal crop may have taken up the equivalent of 300 kg/ha K_20, but less than half of this amount may be removed in the grain plus straw at harvest.**"

4. On p.34 (RB209 8th edition), change the text in the second paragraph to: "To maintain soils at the correct Index it is usually sufficient to replace the amount of each nutrient **expected to be** removed from the field in the harvested crop. This amount can be calculated from the **targeted yield (including straw where removal is planned)** and an average concentration of the nutrient in the harvested **product(s) as shown in Appendix 5** (see worked example on page ...)."

5. Following the section on "Soil sampling and analysis" on p.35 (RB209 8th edition), insert a brief section headed "Tissue Analysis" as follows:

   "**Tissue analysis can be used to indicate whether or not the P or K concentrations in a plant are at, or below, optimum levels at a particular point in time. It is not useful as a predictor of potential nutrient uptake by a crop, or a crop's nutrient requirement over a season. Tissue analysis is therefore best used to complement, and not replace, soil analysis.**

   "To provide meaningful information, testing should be carried out at a defined growth stage and on a specific part of the plant. For example, for winter wheat, testing is best carried out on the newest fully expanded leaf blade during stem extension (between GS31 and GS39). At such times patchy diagnostic sampling in good and bad parts of a crop can be a useful method to determine whether or not nutrient deficiency is an issue.

   "Laboratories typically analyse plant tissue for P and K by measuring their concentrations in the dry matter. These can vary with season, growth stage, fertiliser application, weather or other factors that affect nutrient uptake and rate of growth. P and K concentrations can also be measured in the leaf tissue water (cell sap) on-farm using appropriate equipment, but these are prone to short term fluctuations and may be less useful."

6. Under the heading “Potash-releasing clay soils” (RB209 8th edition, p.36), change the text in the first paragraph as follows. It may be necessary to split the resulting text into two paragraphs:

   “... Unfortunately no routine soil analysis method is available to estimate the amount or rate of release of this potash. However, the potash that is released goes to the readily crop-available pool measured by soil analysis so that this value does not decline **as** quickly if the amount of potash applied is less than that removed in the harvested crops. Local knowledge and past experience can be useful when assessing the potash release characteristics of clay soils. If the crop-available potash status of a clay soil changes little when the potash balance is consistently negative over a number of years this is a useful indicator that potash is being released from the clay by weathering. **As a rough guide, potash-releasing clay soils might typically release around 50 kg K_2O/ha into available forms for crop uptake each year.**

   “Remember that the annual rate of potash release may not be sufficient to meet the requirement of crops with a large yield potential requiring large amounts of potash. It is essential to monitor crop yields to ensure that the yield potential of the site is being realised and if this is not the case then potash fertilisers should be applied. **Where the soil K level is allowed to fall below the target Index, the quantity of potash required (over and above offtake) to raise the level in the soil may be greater for potash-releasing clays than for other clay soils. This is because part of the potash applied may be used to replace that previously released from the clay minerals.** A rough classification…”

7. Under the heading “Maintaining the soil Index”, change the text in the first paragraph: “The amount of phosphate and potash required for maintenance, in kg P_2O_5/ha and kg K_2O/ha, can be calculated **from the targeted yield** of the crop **that is to be** removed from the field and its nutrient content. Typical values for the content of phosphate and potash in crops are given in Appendix 5. For cereals**, offtake in grain plus straw (where removed) can be determined from an estimate of grain yield alone. Where that applies, recommendations in this manual assume that on average straw yield is 50% of grain yield. However, straw yields can vary substantially and may be higher or lower than 50% of grain yield.”**

8. Revise the heading on p.40 (RB209 8th edition) to “Adjusting the application of P and K according to the soil Index and **targeted** yield” and use a different approach in the tables, as follows:

“Example: Winter Wheat

Application required to replace offtake						Application to replace offtake (to nearest 5 kg/ha)		
Grain yield (t/ha)	P_2O_5 (kg/ha)	K_2O (kg/ha)	Straw yield (t/ha)	P_2O_5 (kg/ha)	K_2O (kg/ha)	Grain + Straw (grain yield t/ha*)	P_2O_5 (kg/ha)	K_2O (kg/ha)
6	47	34	3	4	29	6	50	65
8	62	45	4	5	38	8	65	85
10	78	56	5	6	48	10	85	105
12	94	67	6	7	57	12	100	125
(per t/ha)	7.8	5.6	(per t/ha)	1.2	9.5	(per t/ha)	8.4	10.4

*Standard recommendations assume straw yield will be 50% of grain yield

Adjusting applications for soil Index

Period over which to adjust soil Index	Current P or K Index					
	0	1	2-	2+	3	4 or higher
	Adjustment to application (kg/ha)					
10-15 years	+60	+30	0	-30	-60	No P or K required
5-10 years	+100	+50	0			

9. Under the heading “Potash use in sandy and sandy loam soils” (RB209 8th edition, p.41), change the text to:

“Sandy and sandy loam soils together with other soils containing very little clay, have a limited capacity to hold potash. On such soils it is almost impossible to achieve the **target soil K Indices of 2- (for arable, forage crops and grassland) or 2+ (for vegetables).** For sandy loams it is generally possible to maintain soil at 150 mg K/litre (Index 2-) but for sands and loamy sands, the realistic upper limit is 100 mg K/litre (upper Index 1). Adding potash fertilisers to try to exceed these values will result in movement of potash into the subsoil where it may only be available to deep-rooted crops. On sands, it is preferable to apply and cultivate into the topsoil an amount of potash fertiliser each year that is sufficient to meet the potash requirements of the crop to be grown. **Note that this may be higher than the expected offtake at harvest.**”

10. Under the heading “Finding the phosphate, potash and magnesium recommendations” (RB209 8th edition, p.99-100), revise the text as follows:

“Current phosphate, potash and magnesium recommendations are based on achieving and maintaining target soil Indices for each nutrient in the soil throughout the crop rotation.

Soil analysis should be done every 3-5 years. The use of soil analysis as a basis for making fertiliser decisions is described on page 29 (RB209 8th edition), and the procedure for taking soil samples in Appendix 3.

“The phosphate and potash recommendations shown at Index 2 and 2- respectively are those required to replace the offtake in the yield shown (apart from potatoes where the phosphate recommendation at Index 2 is greater than offtake). The recommendation should be increased or decreased where yields are **expected to be** substantially more or less than this. The amount to apply can be calculated using the targeted yield and values for the offtake of phosphate and potash per tonne of yield given in Appendix 5. The larger recommended applications for soils at Index 0 and 1 will also bring the soil to Index 2 over a number of years.

“Recommendations are appropriate where the phosphate or potash balance for preceding crops have been close to neutral. Adjustments can be made where the balance for the preceding crop was significantly positive or negative. **This might occur where actual yields were substantially different from those expected, or where there was a change of plan on straw removal.** A phosphate or potash ‘holiday’ can result in a need for greater than normally recommended amounts for following crops. Potatoes can leave a positive phosphate balance so that less than the normally recommended amount might be needed by the following crop.

“Other important points to consider when using the recommendation tables are:

- **Recommendations are given as phosphate (P_2O_5), potash (K_2O) and magnesium oxide (MgO). Conversion tables (metric-imperial, oxide-element) are given in Appendix 8.**
- All recommendations are given for the mid-point of each Index. For some crops, there are different recommendations depending on whether the soil is in the lower half (2-) or upper half (2+) of K Index 2.
- Where a soil analysis value (as given by the laboratory) is close to the range of an adjacent Index, the recommendation may be reduced or increased slightly taking account of the recommendation given for the adjacent Index. Small adjustments of less than 10 kg/ha are generally not justified.
- Where more or less phosphate and potash are applied than suggested in the tables adjustments can be made later in the rotation.”

Example 1

Soil analysis shows P Index 2 and K Index 1. The next crop to be grown is spring barley, the targeted grain yield is 6t/ha and the straw will be baled and removed from the field.

The table on page 114 recommends 50 kg P_2O_5/ha and 100 kg K_2O/ha.

Alternatively, calculate the required application rates (using offtake values from Appendix 5 and soil Index adjustments as described in Section 1, page 40) as follows:

	P_2O_5 (kg/ha)	K_2O (kg/ha)
Offtake in grain (= targeted grain yield x offtake per tonne grain)	47	34
Offtake in straw (= targeted straw yield x offtake per tonne straw) (assume straw yield is 50% of grain yield if uncertain)	5	35
Total offtake	52	69
Adjustments		
Build soil Index (at Index 0 or 1)	-	+30
Run-down soil Index (at Index 2+ or 3)	-	-
Too much P/K applied to previous crop (e.g. yield lower than expected; straw not removed)	-	-
No, or too little, P/K applied to previous crop (e.g. application 'holiday'; yield higher than expected)	-	-
Total application required (rounded to the nearest 5 kg/ha)	50	100

Example 2

Soil K analysis is 65 mg/litre which is at the low end of K Index 1 (range 61 and 120 mg/litre K – see Appendix 4). Winter wheat is to be grown, targeted grain yield is 8 t/ha and straw will be removed. ***Previous crop (winter wheat, straw not removed) was 2 t/ha higher yielding than expected.***

The table on page 114 (RB209 8th edition) shows a recommendation of 115 kg K_2O/ha for winter wheat (straw removed) at soil K Index 1. This recommendation is for a soil K analysis value of 90 mg/litre, the mid-point of K Index 1. Because the soil is at the bottom of Index 1, it would be more appropriate to apply 130 kg K_2O/ha, a value between that for K Index 0 and 1. **Adding 20 kg/ha (2 x 10.4 from Appendix 5) for the under application to the previous crop brings the total to 150 kg K_20/ha.**

Alternatively, calculate the required application rates (using offtake values from Appendix 5 and soil Index adjustments from Section 1, page 40) as follows:

	P_2O_5 (kg/ha)	K_2O (kg/ha)
Offtake in grain (= targeted grain yield x offtake per tonne grain)		45
Offtake in straw (= targeted straw yield x offtake per tonne straw) (assume straw yield is 50% of grain yield if uncertain)		38
Total offtake		83
Adjustments		
Build soil Index (at Index 0 or 1)*		+45
Run-down soil Index (at Index 2+ or 3)		-
Too much P/K applied to previous crop (e.g. yield lower than expected; straw not removed)		-
No, or too little, P/K applied to previous crop (e.g. application 'holiday'; yield higher than expected)		+20
Total application required (rounded to the nearest 5 kg/ha)		150

* Based on build over 10-15 years and current K Index mid-way between 0 and 1.

11. In Section 4, under the heading "All Cereals – Phosphate, Potash, Magnesium and Sulphur" (RB209 8th edition, p.113-114), revise the text as follows

"The amounts of phosphate and potash needed to replace offtake and maintain the soil at the target Index (P Index 2 and K Index 2-) are shown in the Table. The upper half of the Table shows the maintenance applications for each cereal when straw is incorporated. The lower half of the Table shows the maintenance applications when straw is removed (and with straw yield assumed to be 50% of grain yield).

"The amounts of phosphate and potash are appropriate to the grain yields shown for each crop in the table. The phosphate and potash recommendations can be adjusted if yields are likely to be larger or smaller than those shown. Where the soil Index is already higher than target, adjustment for larger yield is not necessary.

"To adjust the amounts, multiply the difference in targeted grain yield by the phosphate and potash content per tonne of grain yield using the appropriate value for where straw is either incorporated or removed as given in Appendix 5, and then add to (for larger yields) or subtract from (for smaller yields) the amounts in the Table. For example, at P Index 1, the adjusted phosphate recommendation for wheat with an expected yield of 10 t/ha where straw is incorporated is 90 + (2 x 7.8) = 106 kg/ha.

"Where the weight of straw to be removed can be estimated separately, use the amounts of phosphate and potash per tonne of straw shown in Appendix 5 to

calculate the amounts removed in the straw, and add these to the appropriate amounts for grain yield in order to calculate the overall amounts removed.

“Crops grown on soil at Index 0 and 1 would be expected to respond to the **higher** amounts of phosphate and potash shown in **the Table**. Also over a number of years, these extra amounts of fertiliser will help to raise most soils, except light sands, to Index 2. At Index 3 and above no phosphate and potash need be applied for a few years but check soil analyses regularly.

“At Index 2, phosphate and potash can be applied when convenient during the year but at Index 0 and 1, they should be applied and worked into the seedbed. To avoid damage to germinating seedlings do not combine drill more than 150 kg/ha of nitrogen plus potash on sandy soils.”

(Include existing table on page 114, RB209 8th edition)

Alternatively, calculate the required application rates using expected offtake values from Appendix 5 and soil Index adjustments from Section 1 as described in Section 3.

12. Under the heading “Oilseed rape and Linseed – Phosphate, Potash, Magnesium and Sulphur” (RB209 8th edition, p.118-119), revise the text as follows

“The amounts of phosphate and potash needed to replace offtake for the seed yields shown and maintain the soil at the target Index (P Index 2 and K Index 2-) are shown in the Table. The amounts of phosphate and potash are appropriate for the seed yields shown. The phosphate and potash recommendations can be adjusted if yields are likely to be larger or smaller than those shown in the Table. Where the soil Index is already higher than target, adjustment for larger yield is not necessary. To adjust the amounts, multiply the difference in targeted seed yield by the phosphate and potash content per tonne of seed yield using the appropriate value given in Appendix 5, and then add to (for larger yields) or subtract from (for smaller yields) the amounts in the Table. For example, at P Index 1, the adjusted phosphate recommendation for winter oilseed rape with a targeted yield of 4.5 t/ha is 80 + (1 x 14) = 94 kg/ha.

“Crops grown on soil at Index 0 and 1 would be expected to respond to the **higher** amounts of phosphate and potash shown in **the Table**. Also over a number of years, these extra amounts of fertiliser will help to raise most soils, except light sands, to Index 2. At Index 3 and above no phosphate and potash need be applied for a few years but check soil analyses regularly.

"At Index 2, phosphate and potash can be applied when convenient during the year but at Index 0 and 1, they should be applied and worked into the seedbed."

(Include existing table on page 118, RB209 8th edition)

"Alternatively, calculate the required application rates using expected offtake values from Appendix 5 and soil Index adjustments from Section 1 as described in Section 3."

13. In Appendix 3, under the heading "Taking a representative sample" (RB209 8th edition, p.225), amend the second paragraph to begin: "A sample of **15** individual sub-samples (cores) will be adequate for a uniform area…"

14. In Appendix 5 (RB209 8th edition, p.228), add a value for potash content of straw for winter or spring oats (based on AHDB Cereals & Oilseeds Information Sheet 05 (2009) Assessing the nutrient content of cereal straw):

Straw	Potash (K_2O) kg/t of fresh material
Winter or spring oats	**16.7**

3.8. Magnesium and micronutrients

3.8.1. RB209 (8th edition) advice

Section 1 (RB209 8th edition, p.33-42) covered the principles of maintaining target soil Indices for P, K and Mg, rather than focusing on the needs of individual crops. There was more detail on P and K than Mg: target soil Indices for P and K but not Mg were tabulated on p.37, and there were example calculations of application rates to maintain, build-up or run-down soil Indices of P and K Indices, but no examples for Mg. The following specific information was given on Mg:

(RB209 8th edition, p.38) "No replacement application is shown for magnesium for a number of reasons. The amounts of magnesium removed in a harvested crop tend to be small, perhaps 10-15 kg MgO/ha and it appears that this amount of magnesium can be released during the weathering of clay minerals in many soils. Consequently the amount of exchangeable magnesium in soil tends to change only slowly. Rather than suggest an annual replacement, it is better to monitor change in exchangeable magnesium and when this declines to Mg Index 1 consider applying magnesium especially to sensitive crops like potatoes, sugar beet and some vegetable crops."

(RB209 8th edition, p.42) "Soil analysis gives the quantity of readily available magnesium in mg Mg/litre of soil, along with an Index (see Appendix 3). The analysis is done on the same soil extract as that used to determine potassium. Potatoes and sugar beet are susceptible to magnesium deficiency and may show yield responses to magnesium fertiliser on soils at Mg Index 0 and 1. Other arable crops may show deficiency symptoms at soil Mg Index 0 but seldom give a yield response to applications of magnesium. Deficiency symptoms often occur early in the growing season when root growth is restricted, for example by soil compaction or excessive soil moisture, but they disappear as the roots grow and thoroughly explore the soil for nutrients. Soil should be sampled and tested regularly, every 3–5 years. For soils at Mg Index 0, 50 to 100 kg MgO/ha can be applied every three or four years.

"Where the Mg Index is low and soil acidity needs to be corrected, applying magnesian limestone may be cost-effective. An application of 5 t/ha of magnesian limestone will add at least 750 kg MgO/ha, and this magnesium will become crop-available over many years. However, if used too frequently, the soil Mg Index can exceed 3. In this situation care should be taken to ensure that there is sufficient available potash in soil to ensure that there is no risk of potash deficiency in the crop being grown."

Micronutrients were covered only in Section 1 (RB209 8th edition, p.45-46). For each micronutrient, information was given on the crops most susceptible to deficiency, deficiency symptoms and (in some cases) soil or tissue test thresholds for treatment.

Magnesium was mentioned in Section 3 (RB209 8th edition, p.99), but the focus was on P and K.

Section 4 (RB209 8th edition, p.113) gave the following advice for all cereals:
"At Mg Index 0, magnesium fertiliser should be applied every 3-4 years at 50 to 100 kg MgO/ha."

Section 4 (p.118) gives the following advice for oilseed rape and linseed:
"At Mg Index 0 and 1, magnesium at 50 to 100 kg MgO/ha should be applied every three or four years."

Appendix 3 (RB209 8th edition, p.225) advised on soil sampling for pH, P, K and Mg; Appendix 4 (p.227) defined the soil Indices for P, K and Mg; and Appendix 5 (p.228) detailed the amounts of phosphate and potash in crop material, to enable calculation of offtake, but did not cover magnesium.

3.8.2. Review of new information

In 2013, ADAS reviewed the non-NPKS nutrient requirements of UK cereals and oilseed rape for AHDB Cereals & Oilseeds (Roques *et al*., 2013). Meta-analyses were carried out on the results of published and unpublished experiments measuring yield responses to boron (B), copper (Cu), manganese (Mn), magnesium (Mg), molybdenum (Mo) and zinc (Zn). The analyses were limited to experiments carried out in the UK or at sites thought to have reasonably similar climates and yield potentials to the UK: northern Europe, Canada and New Zealand. The results of the review were disseminated in the form of an AHDB Cereals & Oilseeds Information Sheet (IS25).

For this review, literature searches were done for experiments carried out since the 2013 review, which could be included in the meta-analyses. The only relevant studies found were five experiments on Mg response funded by Potash Ltd. in 2004 and 2005, and two Swedish experiments on Mn for winter barley (Stoltz & Wallenhammar, 2014). These were added into the meta-analyses for those nutrients, but did not change the results or conclusions drawn.

The UK Grower's Guide (Cook, 2009) states that sunflowers are sensitive to boron deficiency, which can be a particular problem on calcareous or sandy soils. Signs of deficiency occur during flowering and seed maturation, and are indicated by poor seed set, red-brown necrotic patches and abnormal head and neck development.

3.8.3. Conclusions: magnesium

There is an inconsistency between the implication that Mg should be managed in the same way as P and K, by maintaining soil Indices, and the lack of information to enable growers to do this, relative to P and K. The table of phosphate and potash offtake values in Appendix 5 of RB209 (8^{th} edition) could potentially be expanded to cover magnesium, but there is currently insufficient data to enable this change to be made.

Also, it is possible that in-season yield responses to Mg may occur in crops other than potatoes and sugar beet, counter to the RB209 (8^{th} edition) text. However, again there is a lack of data to conclude on this issue, particularly as most of Mg response experiments have used magnesium sulphate and therefore failed to control for sulphur, making it unclear whether any yield responses were due to Mg or S.

We therefore propose no changes to the majority of the text or advice on Mg. However, at the Arable TWG meeting on 25th April, some attendees felt that the sentence on Mg and K interactions on page 42 of the 8th edition was confusing and should be revised, as it did not clearly explain the relationship between soil extractable Mg and K and the implications for potash deficiency. If RB209 guidelines are followed and K Index is maintained at target levels, potash deficiency is unlikely. The sentence will therefore be removed to avoid any further confusion.

3.8.4. Conclusions: micronutrients

The initial text on micronutrient on p.45 (RB209 8th edition) should be edited as follows; additional text has been adapted from AHDB Cereals & Oilseeds Information Sheet 25 (2013):

“Micronutrients or trace elements are those crop nutrients required in small amounts for essential growth processes in plants and animals. Some micronutrients that are essential for animals are not required by plants but the animal usually acquires them via the plant. In practice only a few micronutrients are known to be present in such small amounts in soil in England and Wales that there is a risk of deficiency in plants and animals. Deficiency is most frequently related to soil type, soil pH, soil structural conditions and their effect on root growth, and crop susceptibility. **For continuous arable cropping on mineral soils, the maximum availability of nutrients from the soil is achieved at pH 6.5. To maintain an appropriate pH, test soils every 3–5 years and treat acidic soils with a liming material (see p.19-21).**

“Visual symptoms of a deficiency of a specific micronutrient **are often short-lived and** can be confused with those produced by other growth problems. **Furthermore, by the time symptoms appear it can be too late to correct a deficiency.** Consequently**, decisions about when to apply micronutrients should be informed by crop and soil risk factors (table below), and** visual diagnosis of a micronutrient deficiency should, where **appropriate**, be confirmed by plant and/or soil analysis.

“Soil analysis for micronutrient deficiencies may be done on the same samples taken every 3-5 years for routine analysis of P, K, Mg and pH (see Appendix 3); if a deficiency is suspected, ensure that an analysis package is chosen which includes the micronutrients in question.

“If a deficiency is suspected, tissue analysis in the spring can be a useful diagnostic tool. If tissue analysis indicates a deficiency, soil samples should be taken after harvest, if the nutrient is one for which soil sampling is appropriate, as tissue analysis only provides an indication of the nutrient status of the crop at the time the sample was taken. The soil may contain adequate amounts of the nutrient and the deficiency may simply have been caused by reduced availability, due to adverse weather conditions or inappropriate pH.

“Tissue samples are best taken in spring. Samples should not be collected after fertiliser applications or immediately before a weekend or public holiday. Walk a ‘W’ pattern across the sampling area, stopping at least 25 times to collect the youngest fully-expanded leaf from 2-3 plants. Dry any wet leaves and send to a laboratory immediately.

The text on p.45-46 (RB209 8th edition) under the heading “Deficiencies affecting crop growth” could then be replaced by a table based on that on p.3 of IS25, which gives risk factors and suggested analyses to predict or diagnose deficiency of boron, copper, manganese, molybdenum and zinc. Text will be added to state that “**Deficiency can affect sugar beet, brassica crops, sunflowers and carrots**”. Additional columns may be added to the table to describe visual deficiency symptoms (as given on p.2 of IS25) and treatment advice (p.4 of IS25), or this information may be given as text, as in IS25. Alternatively, such tables could be provided within the crop sections.

Finally, at the Arable TWG meeting on 25th April 2016 it was agreed that the use of the statement in AHDB Cereals & Oilseeds Information Sheet 25 that “boron should not be applied to cereals because it can be toxic” should be clarified.

4. Knowledge gaps

Table 10. Summary of knowledge gaps, and suggestions for work to address these gaps.

Area	Knowledge gaps	Relevant work underway	Future work	Level of priority
Estimation of SNS	Potential improvement in fertiliser N recommendations from more adaptable approach to calculating measured SNS	AHDB Project Report 490 AHDB project 216-0005	'Unifying' analysis needed of relevant recent datasets	Medium (ongoing area of contention)
Efficiency of N fertiliser products	Efficiency of UAN		N efficiency relative to AN & in dry conditions	Medium
Sulphur	Response of grass and grass-clover swards to S application		Assess impacts of S fertiliser application on clover persistence in mixed swards	High
Cover crops	Nutrient release Starter fertiliser		Timing, amount and impact of nutrient release from cover crops. Response to starter fertiliser	Medium
Estimation of SNS	Potential improvement in fertiliser N recommendations from more adaptable approach to calculating measured SNS	AHDB Project Report 490 AHDB project 216-0005	'Unifying' analysis needed of relevant recent datasets	Medium (ongoing area of contention)
Phosphorus and potassium	Relationship between cultivation system and optimal soil sampling depth to predict P and K response		Field experiments under contrasting cultivation systems to investigate the relationship between sampling depth and phosphate and potash recommendations	High
Phosphorus	Responses to fresh P fertiliser to quantify the long-term effectiveness	AHDB critical P project	Responses and effectiveness of annual fresh P applications (both organic and inorganic forms) at Index 1 to maintain yield potential	High
Phosphorus	Overall P balances on differing soil types (including calcareous soils)	AHDB project 216-0007	Examination of soil P responses to overall P balances on range of soils	Medium

Area	Knowledge gaps	Relevant work underway	Future work	Level of priority
Potassium	Levels of exchangeable K required in soil to support peak uptake by high yielding crops		Review existing data Test yield response to soil K in high yielding situations	High (are yields now limited by soil K levels?)
Potassium	Yield and quality benefits of fresh K applied to combinable crops in spring		Evaluate responses at, and below, target soil K levels	High (can soil K level be allowed to decline?)
Potassium	Offtakes of potash in rye and triticale straw		Measure in straw samples under range of conditions	Low (areas still relatively low)
Potassium	Optimal rates of K build-up in below-target soils		Economic analysis of suitable datasets	Medium (30% of soils below target Index)
Potassium	Rates of decline for soil K for different soil types (including potash releasing clays)		Analyse soil K over time for suitable large datasets	High
Magnesium	MgO offtake in crop material In-season yield responses to Mg applications		Yield response experiments using Mg/S products must balance S	Medium
Micronutrients	Improvement of thresholds for Mn to cereals; prediction of B & Mo responses in OSR		Combination of soil & tissue tests.	High

5. References

Anon (2015). The British Survey of Fertiliser Practice: Fertiliser use on farm crops for crop year 2014.

Barraclough, P.B., Bollons, H.M., Chambers, B.J., Hatley, D., Moss, D.P (1997). Plant testing to determine the P and K status of wheat. AHDB Cereals & Oilseeds Project Report No. 137.

Barraclough, P.B., Bollons, H.M., Chambers, B.J., Bhogal, A. & Hatley, D. (2000). Development of on-farm plant tests for phosphate and potassium in wheat. AHDB Cereals & Oilseeds Project Report No. 224.

Bhogal, A., Dampney, P. & Goulding, K. (Editors). (2003). Evaluation of urea-based nitrogen fertilisers. Report for Defra Projects NT2601 and NT2602.

Bhogal, A., Taylor, M., Nicholson, F., Rollett, A., Williams, J., Newell-Price, P., Chambers, B., Litterick, A. & Whittingham, M. (2016). DC-*Agri*; field experiments for quality digestate and compost in agriculture. Work Package 1 report: Effect of repeated digestate and compost applications on soil and crop quality. WRAP.

Blake, L., Johnston, A.E., Poulton, P.R. and Goulding, K.W.T. (2003). Changes in soil phosphorus fractions following positive and negative phosphorus balances for long periods. Plant and Soil 254, 2, 245-261.

Blake-Kalff, M.M.A. & Blake, L. (2014). Assessment and prediction of nitrogen mineralisation and its effect on crop productivity. *Proceedings of the International Fertiliser Society* **754**.

Cook, S.C. (2009). Sunflowers – a growers guide. AHDB Cereals & Oilseeds guide SF6.

Dampney, P., Dyer, C., Goodlass, G. & Chambers, B. (2006). WP1a Crop Responses. Component report for Defra Project NT2605 (CSA 6579).

Defra (2008). The national inventory and map of livestock manure loadings to agricultural land (Manures-GIS).

Edwards, T., Withers, P., Sylvester-Bradley, R. & Jones, D. (2015). Routes to improving the efficiency of phosphorus use in arable crop production. AHDB Cereals & Oilseeds Research Review No. 83.

Gilchrist, A.D., Christie, A.G., Fraser, J. & Inglis, L. (2012). The relationship between soil mineral nitrogen, applied nitrogen and yields in Scottish soils. AHDB Cereals & Oilseeds Project Report No. 484.

Greenwood, D.J. & Stone, D.A. (1998). Prediction and measurement of the decline in the critical-K, the maximum-K and total cation plant concentrations during the growth of field vegetable crops. *Annals of Botany* **82**, 871-881.

Heming, S.D. (2007). Phosphorus balances for arable soils in Southern England. *Soil Use and Management* **23**, 162-170.

Johnston, A.E. & Poulton, P.R. (2011). Response of cereals to soil and fertiliser phosphorus. AHDB Cereals & Oilseeds Research Review No. 74.

Johnston, M.A., Miles, N., Thibaud, G.R. and Hughes, J.C. (1999). Quantities of potassium fertilizer required to raise soil test value. Communications in Soil Science and Plant Analysis 30, 17-18, 2485-2497.

Kindred, D., Knight, S., Berry, P., Sylvester-Bradley, R., Hatley, D., Morris, N., Hoad, S. & White, C. (2012). Establishing best practice for estimation of Soil N Supply. AHDB Cereals & Oilseeds Project Report No. 490.

Knight, S.M. (2006). Soil mineral nitrogen review: Practice and interpretation. AHDB Cereals & Oilseeds Research Review No. 58.

Knight, S., Morris, N., Goulding, K., Johnston, J., Poulton, P. & Philpott, H. (2014). Identification of critical soil phosphate (P) levels for cereal and oilseed rape crops on a range of soil types. AHDB Cereals & Oilseeds Project Report No. 529.

Lovett, A.A., Hiscock, K.M., Outram, F.N., Cooper, R.J., Dugdale, S., Stevenson, J., Sunnenberg, G., Hama-Aziz, Z., Dockerty, T.L., Noble, L., Beamish, J. & Hovesen, P. (2015). Experiments with cover crops and cultivation techniques in the Wensum DTC. Aspects of Applied Biology 129, 85-90.

Marchant, B.P., Dailey, A.G., Lark, R.M. (2012). Cost-effective sampling strategies for soil management. AHDB Cereals & Oilseeds Project Report No. 485.

Misselbrook, T.H., Cardenas, L.M., Camp, V., Thorman, R.E., Williams, J.R., Rollett, A.J. and Chambers, B.J. (2014). An assessment of nitrification inhibitors to reduce nitrous oxide emissions from UK agriculture. Environmental Research Letters **9**: 115006.

Oliver, M.A., Frogbrook, Z.L., Webster, R. & Dawson, C.J. (1997). A rational strategy for determining the number of cores for bulked sampling in soil. In J.V. Stafford (Ed.), Precision agriculture '97. Volume I, spatial variability in soil and crop (pp. 155-162). Oxford: BIOS Scientific Publications,

Oliver, M.A. & Dawson, C.J. (2014). Spatial variation of Soil Mineral Nitrogen as a guide to sampling for site-specific management. *Proceedings of the International Fertiliser Society* **753**.

Orson, J.H. (2009). An assessment of soil mineral nitrogen as a guide to the nitrogen fertiliser rate for winter wheat in England. *Proceedings of the International Fertiliser Society* **661**, 41-48.

Orson, J.H. (2010). Nitrogen recommendations for UK cereal crops: a review. *Aspects of Applied Biology* **105**.

Orson, J.H. (2012). Nitrogen recommendations for UK cereal crops: the role of soil mineral nitrogen. *Aspects of Applied Biology* **117**.

PAAG (Professional Agricultural Analysis Group) 2009/10, 2010/11, 2011/12, 2012/13, 2013/14 Collation of Data from Routine UK Soil Analysis

Rahn, R. (2012). Establishing best practice for determining Soil Nitrogen Supply (HGCA 3425) – Reporting and Technology Transfer (Post Warwick HRI). Final report of AHDB Cereals & Oilseeds project no. FV 345b.

Roques, S., Kendall, S., Smith, K., Newell Price, P. & Berry, P. (2013). A review of the non-NPKS nutrient requirements of UK cereals and oilseed rape. AHDB Cereals & Oilseeds Research Review No. 78.

Sinclair, A. & Wale, S. (2013). Technical Note TN651: Nitrogen recommendations for cereals, oilseed rape and potatoes. SRUC.

Sinclair, A., Shipway, P. & Wale, S. (2013). Technical Note TN633: Phosphorus, potassium, sulphur and magnesium recommendations for cereals, oilseed rape and potatoes. SRUC.

Sinclair, A., Crooks, B., Edwards, T. & Coull, M. (2015). Technical Note TN668: Managing soil phosphorus. SRUC.

Stobart, R. & Morris, N.L. (2014). The impact of cover crops on yield and soils in the New Farming Systems programme. *Aspects of Applied Biology **127***, 223-232.

Stobart, R., Morris, N.L., Fielding, H., Leake, A., Egan, J. & Burkinshaw, R. (2015). Developing the use of cover crops on farm through the Kellogg's OriginsTM grower programme. Aspects of *Applied Biology* **129**, 27-34.

Stoltz, E. & Wallenhammar, A.-C. (2014). Manganese application increases winter hardiness in barley. *Field Crops Research* **164**, 148-153.

Sylvester-Bradley, R., Kindred, D.K., Blake, J., Dyer, C.J. & Sinclair, A.H. (2008). Optimising fertiliser nitrogen for modern wheat and barley crops. AHDB Cereals & Oilseeds Project Report No. 438.

Sylvester-Bradley, R., Dampney, P., Kindred, D., Richards, I., Sinclair, A., White, E., Goulding, K., Whitmore, A. & Philips, H. (2009). Nitrogen for winter wheat – management guidelines. AHDB Cereals & Oilseeds.

Sylvester-Bradley, R., Kindred, D.K., Wynn, S.C., Thorman, R.E. & Smith, K.E (2012). Efficiencies of nitrogen fertilizers for winter cereal production, with implications for greenhouse gas intensities of grain. *Journal of Agricultural Science, Cambridge* **152**, 3-22.

WRAP (2013) *A Survey of the UK organics recycling industry in 2012*. WRAP RAK005-002.

WRAP (2014). *A survey of the UK Anaerobic Digestion industry in 2013*. WRAP.

6. Appendix I: companies invited to submit data and/or opinions to inform the review

ADAS

Agrii

AHDB (RB209 Review Arable TWG and Crop Nutrient Management Partnership Steering Group)

Association of Independent Crop Consultants (AICC; various individual contacts)

CF Fertilisers UK Ltd (formerly GrowHow)

Ecopt Consultancy

Frontier Agriculture Ltd

Harper Adams University

Hutchinsons

Institute of Biological, Environmental and Rural Sciences (IBERS), Aberystwyth University

International Fertilizer Society

The James Hutton Institute

K+S UK & Eire Ltd

Maize Growers Association (MGA)

Micromix Plant Health Ltd

NIAB

NRM Laboratories

OMEX

Potash Development Association (PDA)

Rothamsted Research

Scotland’s Rural College (SRUC)

Senova

SOYL

Teagasc

Vine House Farm

Yara