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Review of evidence on the principles of crop nutrient management and nutrition for cereals and oilseeds

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Abstract

The Crop Nutrient Management Partnership 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 (8th edition). The specific objectives of this work package included; i) Critically review the current version of RB209 to identify areas for revision; ii) Revise RB209 sections 3 and 4 and relevant appendices; iii) Evaluate new information for updating RB209 and distil into RB209 ready guidance; iv) Identify gaps in knowledge & future research required. This review focuses on nitrogen and sulphur fertiliser, with phosphorus, potassium, magnesium and micronutrients covered in the review of principles section.

For winter wheat, nitrogen response data was collected totalling around 700 UK N responses, dating from 1981 to 2015. The data were analysed to assess the effects of soil type, SNS and yield potential on nitrogen requirement. Following comparison of a number of approaches for calculating N requirement, it is proposed that an adjustment for predicted yield is included in the nitrogen guidance for winter wheat. The nitrogen recommendations based on SNS Index and soil type should be increased or reduced by 20 kg N/ha per t/ha yield expected above or below a reference yield of 8 t/ha. Inclusion of this yield adjustment brings the RB209 nitrogen advice in line with principles used in the N max limits under the Nitrate Pollution Prevention Regulations.

For winter barley and spring barley the same relationship was found between yield potential and nitrogen requirement. Consequently, the same yield adjustment of 20 kg N/ha per t/ha is proposed, but with reference yields of 6.5 t/ha for winter barley and 5.5 t/ha for spring barley. Barley data was analysed to examine the effects of nitrogen supply on grain %N response, to allow more detailed advice on how nitrogen rates should be adjusted to meet grain quality specifications. Changes are also proposed to the nitrogen timings for winter barley, based on recent AHDB and commercially funded research.

Less nitrogen response data was available for winter triticale, oats and rye, and spring cereals other than barley. For triticale, recent work suggests that nitrogen requirements are similar to those for wheat, so it is proposed that triticale should use the wheat recommendation table. For oats, increases are proposed to the recommended nitrogen rates, although more work is needed to adequately define suitable nitrogen rates and timings. No changes are proposed for winter rye or any spring cereals other than barley, due to lack of data.

Nitrogen fertiliser timings for winter oilseed rape are recommended to change to reflect a 'canopy management' approach, where nitrogen is delayed for crops with large canopies following winter and a proportion of the nitrogen for crops with high yield potential is delayed until yellow bud or early flowering.

New evidence for the response of winter oilseed rape to sulphur (S) was reviewed which showed no justification for altering the current recommended rates of 50 to 75 kg SO_3/ha. There was limited new work looking at S response in cereals and no evidence to change the current (8th edition) RB209 recommended rate of 25-50 kg/ha SO_3; this should be extended to all winter and spring sown cereal crops. However, not all cereal crops will respond to S, and we recommend using the risk matrix published in AHDB Cereals & Oilseeds Information Sheet 28 to assess the likelihood of S deficiency in a revised RB209. There is no evidence to justify changing the current (8th edition) RB209 guidance to apply S in early spring before the start of stem extension. New guidance is provided on sunflower nitrogen requirements.

High priority knowledge gaps include; N management to achieve grain protein targets of high yielding milling varieties and spring barley; optimum N rates for winter and spring oats and spring wheat; and N management for crops used for anaerobic digestion. Medium priority knowledge gaps include whether autumn N is required for crops established with minimal tillage or direct drilling techniques in the presence of straw.

1. Introduction

For winter wheat, N requirements had been extensively researched prior to publication of the 8th edition of RB209, and more recent research had not shown the need for significant changes to the basic rates recommended. However, with increasing yields, there was a need for consideration of expected yield in the calculation of N requirement, since economically optimal N rate had been shown to rise with yield potential. By contrast, there had been little change in winter barley N recommendations in the last 30 years, so the findings of ongoing AHDB Cereals & Oilseeds project 216-0006, which included both a review of existing data and additional experimentation, was key to improving previous advice. Winter triticale N recommendations were also in need of revision, following extensive research into the yields and N requirements of triticale since 2009. Winter oilseed rape N requirements and optimum timings had been investigated by a number of projects which completed close to, or soon after, the date of the previous RB209 revision. Much of this information had therefore not been incorporated into RB209. Relatively little UK research had addressed the N requirements of spring crops, e.g. optimum N timing for spring barley.

Recent research addressing the continuing falls in atmospheric S deposition (Defra SCF0308) and resulting effects on crop S responses (ongoing AHDB Cereals & Oilseeds project 216-0007) indicated a need to update the S recommendations. There had been relatively little recent experimental research into crop requirements for micronutrients, apart from AHDB project 3508 (PR518), but the AHDB Cereals & Oilseeds micronutrient review RR78 drew conclusions from meta-analysis of these and many earlier experiments which will enable some improvements to existing advice.

Estimating the supply of nutrients available in the soil is a perennial challenge for farmers. AHDB Cereals & Oilseeds project 3425 (PR490), which investigated best practice for estimating soil N supply, provided more robust guidance on estimating the soil N supply (e.g. when fields should be measured). AHDB Cereals & Oilseeds Project 3554 (PR529) ‘Identification of critical soil P levels for cereal and oilseed rape on a range of soil types’ and current LINK Project LK09136 and ongoing AHDB Cereals & Oilseeds project 216-0004 have investigated methods of estimating P supply from the soil.

1.1. Aims and objectives

The main aim of this work package was to review research since 2009 on crop nutrition for cereals and oilseeds in England, Wales and Northern Ireland (N.I.) and based on the findings, and where appropriate, to revise and amalgamate the cereals and oilseeds sections in the “Fertiliser Manual (RB209)”. This review focuses on nitrogen and sulphur fertiliser, with phosphorus, potassium, magnesium and micronutrients covered in the review of principles section.

The specific detailed objectives were to:

i. Critically review the current version of RB209 to identify areas for revision.
ii. Revise RB209 sections 3 and 4 and relevant appendices.
iii. Evaluate new information for updating RB209 and distil into RB209 ready guidance.
iv. Identify gaps in knowledge & future research required.

2. Consultation on current RB209

2.1. Approach

The current RB209 was evaluated to determine:

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

To this purpose, letters and emails were sent to agronomists, contacts in fertiliser companies, breeders and other industry experts (see Appendix for full list) for their opinions about these points; colleagues were consulted within ADAS and NIAB; and the opinions of the RB209 review expert 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. Data relevant to the WP4 review was provided by six organisations, and opinions by a further seven organisations.

2.2. General

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

2.3. Nitrogen

Clarity is needed for the scope of the N advice in RB209: whether recommended N rates reflect non-binding advice, statutory maxima, or something in between. The RB209 review Steering Group particularly mentioned the need to signpost users towards N max limits under the Nitrate Pollution Prevention Regulations, as the relationship between RB209 N recommendations and regulation is not currently clear to many, and there is also a lack of guidance on the evidence required to justify use of higher N rates than recommended in RB209, e.g. whether advice from a FACTS qualified advisor is sufficient.

Data from the British Survey of Fertiliser Practice (BSFP) (Anon, 2015) indicated that average N applications were roughly in line with RB209 (8th edition) recommendations. In the five year period between 2009 and 2014, average applications of manufactured N fertiliser were 186 kg/ha for winter wheat, 102 kg/ha for spring barley, 141 kg/ha for winter barley, 191 kg/ha for winter OSR and 129 kg/ha for spring OSR. These rates were all similar to RB209 (8th edition) recommendations for soils at SNS Index 2.

There was consistent feedback from several industry sources and from independent scientists and agronomists, that RB209 N recommendations for cereals are too low. This view was given specifically for feed wheat, milling wheat, barley, oats, triticale, rye and forage maize, as well as generally for all cereals. Senova and others requested separation of the N recommendations for oats, rye and triticale, due to differences in yield, N scavenging and N requirements between these species.

For oats, one respondent advised that more N response work was needed to establish improved recommendations, since in many N response experiments the treatment rates had not been high enough to allow determination of the maximum yield or the economically optimum N rate. There were conflicting views on varietal difference in oats response to N, with one respondent claiming differences between dwarf and conventional varieties, but another respondent stating that varietal differences are usually small.

For wheat, the need for N recommendations to take yield potential into account was mentioned by a number of respondents.

One independent consultant proposed that barley N recommendations should also allow for yield potential: two tables were suggested for different yield potentials, each separated into three categories for crops aiming for about 1.5% grain N (true malting), <1.8% N (lager) or maximum yield (feed/seed).

There were calls from one organisation to increase the recommended extra N for milling wheat from the 8th edition advice of 60 kg/ha, since higher yielding milling varieties such as Skyfall may need more than 100 kg/ha N to boost protein, on top of the N required to realise potential yield. BSFP data suggested that farmers were applying less additional N to milling wheat than was recommended in the 8th edition of RB209: the difference between mean N applications to milling and non-milling wheats was only 32 kg/ha.

There were concerns about the value of grain % N values to evaluate the accuracy of N applications, and it was pointed out that farmers are likely to find % protein figures more helpful than % N.

Autumn N for cereals was highlighted as there may be justification for recommending autumn N for direct drilled crops where straw has not been removed. This was thought particularly important on lighter soils, to retain tillers.

There was relatively little feedback on the RB209 N recommendations for oilseed rape. A number of independent agronomists contacted by ADAS agreed that the (8th edition) N recommendations for oilseed rape were about right. One suggested that the winter OSR recommendations should be more clearly based on “canopy management” principles, and that more clarity was needed in the spring OSR guidance.

One respondent suggested that foliar N applications applied to crops with full canopies should not count towards N max limits, or should count to a lesser extent, since rapid absorption by the crop prevents most environmental losses.

2.4. Sulphur

BSFP data suggested that rates of sulphur applied were similar to those recommended in the 8th edition of RB209. For oilseed rape, the “Fertiliser Manual (RB209)” recommended 50-75 kg SO_3/ha if deficiency was suspected; in practice, 84% of OSR crops received an application, averaging 71 kg SO_3 /ha. For cereals the manual recommended 25-50 kg SO_3 /ha if deficiency was suspected; in practice, 50% of crops were treated with an average of 50 kg/ha.

Several respondents mentioned that the section on S deposition needed updating. The role of gypsum as a source of S was also mentioned. One respondent queried the RB209 (8th edition) claim that when S deficiencies are detected, it is too late in the season to remedy within the current crop; they claimed that this may not be the case for foliar applications of Epsom Salts, which may act fast enough to give a yield response in the existing crop.

3. Revise RB209 sections 3 and 4 and relevant appendices

There was scope to rationalise sections 3 and 4 in the 8th edition of RB209, together with the relevant appendices. In particular, the RB209 Review Steering Group advised that it would be helpful to re-order some of the text and tables so that all the relevant information was closer together in the guide. For example, incorporating Appendix 2 'Sampling for soil mineral nitrogen (SMN)', and guidance on the estimation of crop nitrogen content and mineralisable nitrogen into the main section of the guide was thought to be one potential area for improvement. However, there was a need to balance the potential benefit of bringing related sections together against the downside of making the guide unfamiliar to regular users. The specific revisions to RB209 (8th edition) have therefore provided suggestions for how to combine sections 3, 4 and appendices into one section.

4. Evaluation of new information and updates to RB209 guidance

4.1. Autumn nitrogen

4.1.1. "Fertiliser Manual (RB209)" advice and NVZ guidelines

Section 4 (in the 8th edition) contained the following advice on autumn nitrogen:

- Winter wheat: 'There is no requirement for seedbed nitrogen'
- Winter barley: 'There is no requirement for seedbed nitrogen'
- Winter oats, rye, triticale: seedbed nitrogen is not mentioned, so also implies no requirement
- Winter oilseed rape: 'Autumn nitrogen can be applied to the seedbed or as a top-dressing to encourage autumn growth but research suggests that crops sown after early September are unlikely to respond.' The N recommendation table for winter oilseed rape indicates 30 kg N/ha applied in autumn at SNS Indices of 0, 1 or 2, but no application at SNS Index 3 or above.

Information in the 8th edition was consistent with Nitrate Vulnerable Zone (NVZ) guidance (2013-16). These permitted a maximum autumn application of 30 kg N/ha for winter oilseed rape (allowed as an exemption to the closed period for manufactured nitrogen fertiliser), subject to a total maximum application of 250 kg N/ha (before any adjustment for yield adjustment) which included any nitrogen applied in autumn.

Autumn N on cereal crops was not specifically mentioned in the Nitrate Pollution Prevention Regulations (2015), but was effectively ruled out within NVZs due to the closed period for spreading manufactured fertiliser on tillage land starting on the 1st September.

4.1.2. Comments from Consultation

Autumn N for cereals was identified by several respondents, specifically that there may be justification for recommending autumn N for direct drilled crops where straw has not been removed. This was thought to be particularly important on lighter soils in order to help retain tillers.

No concerns were raised with current guidance on autumn N for oilseed rape.

4.1.3. Current Practice

The British Survey of Fertiliser Practice (Anon, 2015) analyses the month during which fertiliser applications are made, enabling the extent to which autumn N is actually applied to cereals and oilseed rape to be estimated. It should be noted that the BSFP definition of autumn or winter application is from August to January inclusive, whereas the closed period for manufactured fertilisers within NVZs is from 1 September to 15 January.

Averaged over the last 5 years in the survey (2010-2014) 2% of the winter wheat area and 5% of the winter barley area in Great Britain received nitrogen fertiliser in the autumn or winter period. This was slightly lower than the previous 5 year period (3% and 6% respectively) and continued the downward trend recorded over the last 30 years.

Averaged over the last 5 years (2010-2014) 32% of the winter oilseed rape area received nitrogen fertiliser in the same period. This was similar to the average for the previous 5 years, although lower than the 5 year period (2000-2004) prior to that, which was 39%.

The average application rate to winter oilseed rape was 29 kg N/ha, with little annual fluctuation. This was less than the average application rates for 2000-2004 (42 kg N/ha) and 2005-2009 (36 kg N/ha), and consistent with the 30 kg N/ha indicated for autumn use in RB209 (8^{th} edition) and NVZ guidance, although BSFP data includes applications in August and the second half of January, which could be outside the closed period.

4.1.4. Review of new information

A Google search did not reveal any recent, relevant published papers or other literature or data on the response or value of autumn applied N fertiliser for cereals crops. In addition, no new data was offered to this review.

Wade *et al*. (2006) examined the effects of 30-40 kg N/ha applied between drilling and emergence for winter wheat established using disc-based reduced tillage followed by a cultivator drill (not direct drilling or very minimal tillage therefore) at three sites over three seasons following winter or spring beans, winter oilseed rape or winter oats. Seedbed nitrogen increased average established plant populations for wheat by between 3% and 13%, and crop biomass in March by between 9% and 30%, depending on location / soil type. An autumn application of nitrogen after reduced tillage gave a yield benefit of about 0.13 t/ha although this was only significant on one occasion and ranged from 0 to 0.3 t/ha over the three sites.

Ongoing AHDB Cereals & Oilseeds project 216-0006 is testing the effect of 30 kg N/ha applied to early autumn-sown winter barley at drilling or a few days after (Pete Berry, pers. comm.). Autumn treatment was compared with three differently timed spring strategies, all of which applied the same amount of N in total. So far, four out of six experiments have been completed. No yield or grain quality (%N) benefits have been observed from the application of autumn N when compared to the same amount of N applied in the spring. However, in all cases straw from the previous crop was removed and three out of four experiments were established after ploughing.

Older published studies supported information in the 8th edition of RB209. For example:

- Vaidyanathan & Turley (1992) found no unique yield benefit from 40 kg N/ha when applied in the autumn where straw was chopped and shallow-incorporated that could not be achieved with adequate N applied in the spring. Only 1% to 9% of the N applied in the autumn was recovered by the crop by early spring.
- An AHDB review of a large number of experiments (Prew *et al*., 1988) found that 40 kg N/ha applied in autumn was on average uneconomic regardless of method of straw disposal, when compared to applying the N in spring.
- In Scotland, SRUC Technical Note TN651 (Sinclair & Wale, 2013) advises that autumn N is not generally recommended, as profitable responses are not normally attained, but that there is a possible N requirement in some winter barley that has been direct drilled, established following minimum cultivation, or established after ploughing down large quantities of straw e.g. after carrots.

4.1.5. Conclusions: autumn N recommendations

There was insufficient new evidence to support a change to the statements in the 8th edition of RB209. However, the evidence that autumn N is not required for winter cereals was largely based on experiments undertaken between 10 and 30 years ago, or that had not been established by direct drilling in the presence of chopped straw. Since those earlier experiments, cereal yields have increased, quantities of straw produced have also increased and cultivation practices and drilling techniques have changed. Therefore extrapolating from that evidence to the current cropping context is questionable. As no recent, relevant data exist, this is a knowledge gap that should be addressed through an examination of responses in winter wheat (and potentially barley) to autumn N in direct-drilled or (very) minimal tillage situations, where straw is incorporated.

4.2. Winter wheat N requirement

4.2.1. "Fertiliser Manual (RB209)" advice and NVZ guidance

In RB209 (8th edition) Section 4 (p.105-106), a table was presented of N recommendations for autumn and early winter sown wheat. The recommended N rate depended on the SNS Index and the soil type, with the maximum recommendation being 280 kg N/ha.

It was stated that "the main causes of yield variation between fields (soil type, rotational position, sowing date or variety) are not associated with variations in the economic rate of nitrogen fertiliser." Instead, growers are advised to use grain %N as a retrospective test of N strategy, with consistently low grain %N indicating insufficient N applications, and vice versa.

The N max limit for winter wheat in NVZs is 220 kg N/ha, with an extra 20 kg N/ha permitted on shallow soils, an extra 20 kg N/ha for each t/ha increase in expected yield over 8 t/ha, and an extra 40 kg N/ha for milling wheat (Nitrate Pollution Prevention Regulations 2015). N max limits were mentioned only on p.50-51 of RB209 (8th edition) Section 1.

4.2.2. Review methodology

To evaluate N requirement for winter wheat, and the effects on N requirement of factors including soil nitrogen supply (SNS), soil type, yield potential and rotational position, a database of N response experiments was collated. The database included over 1200 N response curves from experiments conducted in harvest years 1981 to 2015, most of which were conducted in the UK by ADAS, Scottish Agronomy and fertiliser companies, and the remainder of which were from Denmark (Table 1). All experiments included from five to seven N rates (including nil N), to allow the fitting of linear plus exponential response curves. Data on harvest year, location of experiment, soil type, variety, rotational position and soil test results were included in the database where available.

The Danish data were used only in the initial analysis of the effects of yield potential on N requirement; the data were found to give a slightly different pattern from UK results and were therefore not used in further analyses. All conclusions were therefore based on UK data.

For each site, linear plus exponential curves (George, 1984) were fitted in a stepwise process involving the following steps: (i) fitting a common curve to all varieties or treatments at the site, (ii) fitting parallel curves for each variety by allowing only the constant parameter to vary, (iii) fitting non-parallel curves for each variety by allowing all linear parameters to vary, and (iv) fitting separate curves for each variety by allowing all parameters to vary. The sums of squares explained at each stage was calculated, and a test was made of the improvement in fit over the previous model. If there was no significant improvement between two stages, then the previous model was taken as the best description of the data.

Economically optimal N rates (Nopt) were calculated using a break-even ratio of 5 for the cost of N fertiliser (£ per kg N) and the grain price (£ per kg). The SNS for each site was either taken from measured soil mineral nitrogen (SMN) and crop N data in winter/spring, or from total crop N at harvest in nil N plots; if both measured SNS and total crop N at harvest were available, an average was taken to give site SNS.

Table 1. Data sources for review of winter wheat N requirements.

Project	**Reference**	**Harvest years**	**No. site seasons**	**No. site x season x treatment combinations**
Nitric database	ADAS UK Ltd	1981-1993	229	229
Denmark N		1987-2008	507	507
XAA105	Dampney *et al*., 2006a	2003-2005	9	36
NT26	Dampney *et al*., 2006b	2004-2005	9	43
Optimum N	Sylvester-Bradley *et al*., 2008	2005-2007	32	132
ADAS N x fungicide trials	Commercial in confidence	2006-2011	5	8
Yara trials	Commercial in confidence	2006-2015	28	73
Scottish agronomy trials	Gilchrist *et al*. 2012	2007-2009	7	10
MALNA	Weightman *et al*., 2011a	2007-2009	5	20
ADAS N x Species trials	Kindred *et al*. 2010a	2009-2010	2	14
N timing	Kindred *et al*. 2010b	2009-2010	6	21
Triticale-N	Weightman *et al*., 2011b	2010	2	4
MIN-NO	Sylvester-Bradley *et al*., 2015	2010-2012	6	6
HY-LO	Sylvester-Bradley *et al*., 2016	2011-2012	5	100
Triticale	Innovate UK project 101093; Clarke *et al*. 2016	2011-2014	13	33
ADAS N product trials	Commercial in confidence	2012-2013	2	7
LearN	AHDB Current Project 216-0005	2014-2015	33	33
Agronomics	Innovate UK project 101627	2015	2	7

4.2.3. Effects of SNS and soil type on N requirement

For winter wheat, RB209 (8th edition) recommendations were similar to the economically optimal N rates measured in field experiments, for the 590 UK N response experiments for which soil type was known (Table 2). For light sand soils, mean N_{opt} was 20-50 kg N/ha higher than RB209 (8th edition) recommendations across the SNS range, and for deep silty soils mean N_{opt} was 20-30 kg N/ha higher than RB209 recommendations, particularly at low SNS indices; for other soil types, mean N_{opt} was within 30 kg N/ha of the RB209 recommendation across the SNS range, and in most cases closer (Figure 1).

Table 2. Mean economically optimal N rates (N_{opt}) for winter wheat and RB209 (8th edition) recommended N rates, by soil type and SNS Index, for UK sites at which soil type is known. N_{opt} calculated using a break even ratio of 5. Figures in brackets show number of site x treatment combinations included in mean.

		Mean economically optimal N rate (kg/ha) SNS Index											
Soil group		**0**		**1**		**2**		**3**		**4**		**5**	
Light sand	Mean	202	*(12)*	157	*(8)*	89	*(5)*	85	*(2)*	77	*(3)*	151	*(1)*
	RB209	160		130		100		70		40		0-40	
Shallow	Mean	238	*(34)*	206	*(11)*		*(0)*	194	*(24)*	135	*(5)*	55	*(2)*
	RB209	280		240		210		180		140		80	
Medium	Mean	241	*(30)*	206	*(20)*	171	*(17)*	230	*(4)*	154	*(20)*	37	*(29)*
	RB209	250		220		190		160		120		60	
Deep clay	Mean	213	*(18)*	174	*(62)*	151	*(60)*	164	*(31)*	134	*(38)*	57	*(34)*
	RB209	250		220		190		160		120		60	
Deep silt	Mean	232	*(20)*	238	*(18)*	197	*(64)*	121	*(11)*	98	*(5)*	74	*(2)*
	RB209	220		190		160		130		100		40	

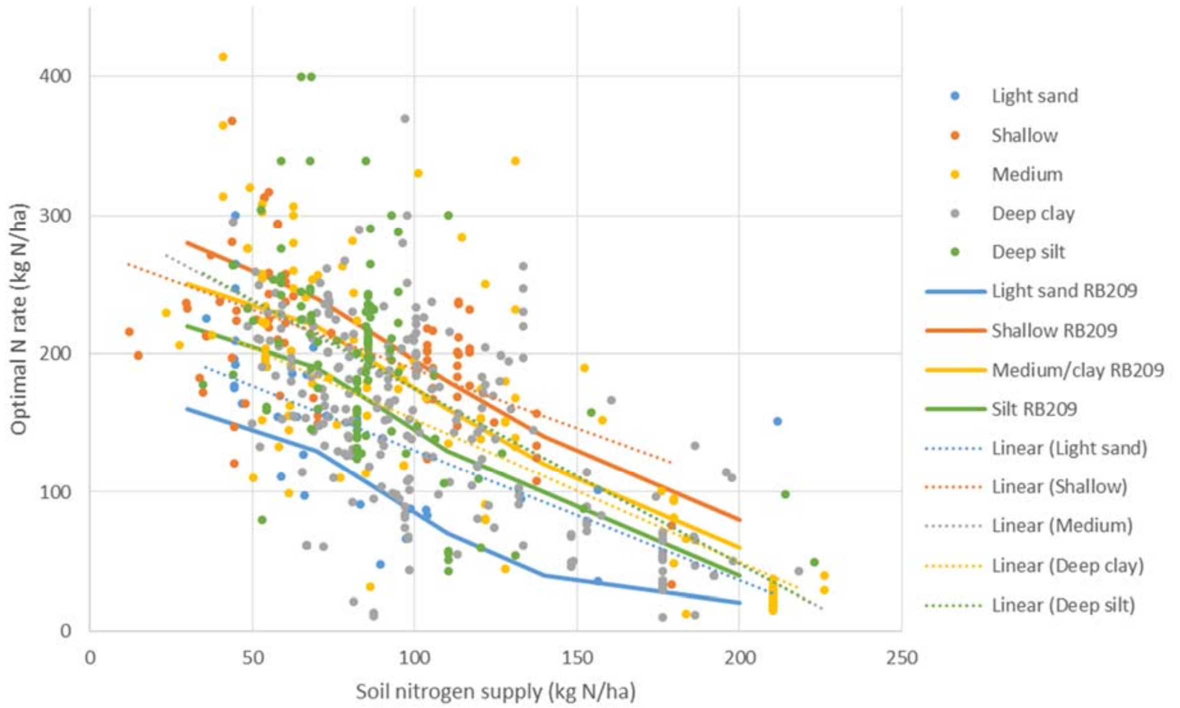

Figure 1. Effects of soil nitrogen supply (SNS) on economically optimal N rate (N_{opt}) of winter wheat, calculated at a break-even ratio of 5. Dotted lines show linear regressions for each soil types; solid lines show RB209 (8th edition) recommendations, plotted at the central value of each SNS Index.

4.2.4. Effect of yield potential on N requirement

Yield at the N_{opt} for each site x treatment combination was plotted against SNS + 0.6 * N_{opt}, to show the effects of potential yield on N requirement. To estimate the amount of N available for crop uptake it was assumed that 100% of SNS was taken up and 60% of fertiliser N was taken up (hence the efficiency factor of 0.6). Data from UK and Danish experiments was plotted separately, in case differences between cropping systems had an effect on the relationship. The results were similar positive correlations for both datasets (Figure 2); there was a small but significant improvement in the variance explained by fitting separate lines for each country (38.2% variance explained) than a single regression line for all the data (35.6% variance explained). The slope of the UK line was 11.1 kg/ha additional N for each t/ha additional yield; if the 60% recovery of fertiliser N is taken into account, this equates to 18.6 kg/ha additional fertiliser N applied for each t/ha additional yield.

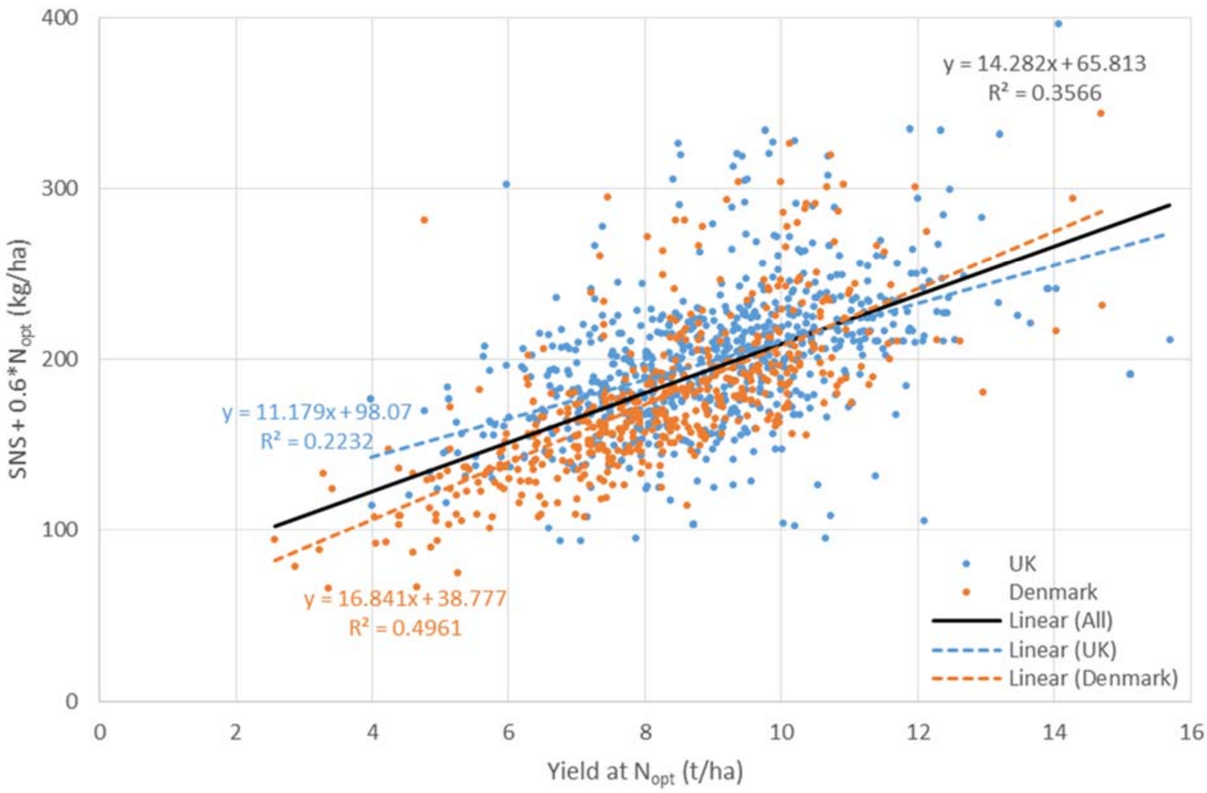

Figure 2. Effects of yield potential (yield at the economically optimal N rate (N_{opt})) on N requirement (site soil nitrogen supply + 0.6 * N_{opt}) for winter wheat. UK data is shown in blue and Danish data in orange; for details of data sources see Table 1.

Variation in yield at N_{opt} is affected by numerous factors, only some of which are predictable when growers are planning N applications, as detailed below:

- Predictable factors accounted for in RB209 (8th edition) N recommendations
  - SNS
  - Soil type (broad classes)
- Predictable factors not accounted for in RB209 (8th edition)

  - Variety
  - Previous crop (effects other than on SNS)
  - Soil type (greater detail)
  - Weed pressure
  - Field history
  - Crop progress so far – establishment, overwintering, etc.
  - Disease (known risks so far)
- Factors not predictable when N rates are determined
  - Spring and summer weather
  - Disease (unpredictable elements)

Earlier work has shown that increases in yield caused by more robust disease control are accompanied by increases in N_{opt} (Berry *et al*., 2010). Grower choices about disease control are one example of a predictable factor influencing yield potential.

To evaluate the relative importance of the different influences on yield potential, a multiple regression was done for the response variate yield at N_{opt} and the factors year, RB209 soil group and previous crop. As single factors, year explained 27.0% of the variation in yield at N_{opt}, RB209 soil group explained 3.8% variation, and rotational position (first or subsequent cereal) explained 2.7% variation. This suggests that the majority of variation in yield potential is due to factors other than season (which is largely unpredictable), RB209 soil group or rotational position, hence further investigation is justified.

To remove the factors already accounted for in the N recommendations (soil type and SNS), we looked at the effects of yield potential on the deviation of N_{opt} from the RB209 recommendation; to remove variations in yield between harvest years, we calculated yield at N_{opt} as a percentage of the AHDB Recommended List (RL) mean fungicide treated control yield in the relevant season (Figure 3). Only 404 data points were included in this analysis, which was confined to UK data from 2002 to 2015 for which the RB209 soil group was known. The remaining correlation (R^2=0.16) shows that predictable but unaccounted for influences on yield potential do influence N requirement, such that RB209 (8^{th} edition) recommendations are too low for crops with yield potential greater than 91% of RL mean yield, and too high for crops with crops yielding less than 91% RL mean.

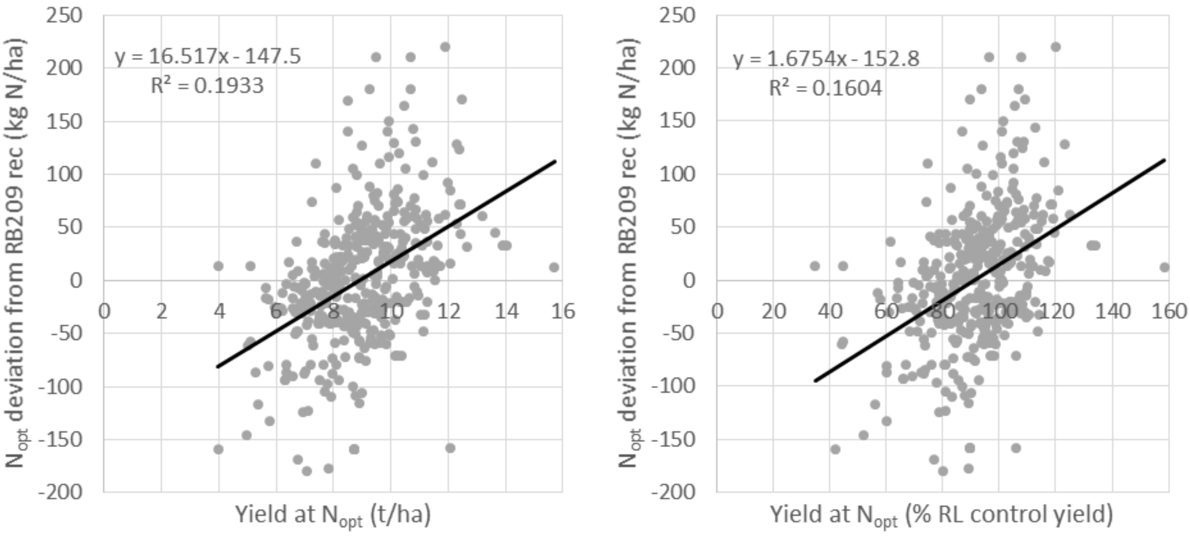

Figure 3. The effects of winter wheat yield potential (yield at the economically optimal N rate (N_{opt}), in t/ha or as a percentage of the mean control yield in AHDB Recommended List trials, on the deviation of N_{opt} from the RB209 (8th edition) recommended N rate.

If yield potential were to be considered in the calculation of wheat N requirement, it would be necessary to give a reference or standard yield, from which the size of the difference in predicted yield could be used to increase or reduce the N rate. Figure 3a shows that RB209 (8th edition) recommendations are most accurate for crops achieving 8.9 t/ha at N_{opt}, with higher yielding crops requiring an additional 16.5 kg/ha applied N per additional t/ha yield, and lower yielding crops requiring 16.5 kg/ha less applied N for each t/ha reduction in yield. However, it is important to recognise that these are yields from small plot trials, which are typically higher than farm yields due to the avoidance of wheelings, headlands, etc.; a 9 t/ha plot yield roughly equates to an 8 t/ha farm yield. This slope is slightly lower than that shown in Figure 2 for the same dataset, presumably because the differences in RB209 recommendation for different soil types have already addressed some of the differences in yield potential between sites.

The effect of variety on yield potential and N requirement may be discerned by examining individual site seasons at which multiple varieties were grown, for instance the five experiments done for the HY-LO project (Sylvester-Bradley *et al*., 2016). For these experiments, there is a significant difference in the constant but not the slope of the regression between yield at N_{opt} and N requirement (Figure 4). For these experiments, the slope was 6.1 kg/ha N requirement per t/ha yield, or 10.1 kg/ha applied N per t/ha yield.

The effects of soil factors on yield can be seen in data from the six 'chessboard' experiments conducted for the Auto-N LINK project (Kindred *et al*., in press). These large experiments allowed the calculation of N optima for each of between 250 and 528 plots within a field, each at least 9m x

9m. Only one of the six sites had no correlation between N_{opt} and yield at N_{opt}. The strongest correlation had R^2=0.62; at most other sites the correlation was significant, but lower due to the N_{opt} for many plots being either 0 kg N/ha or greater than the maximum N rate used.

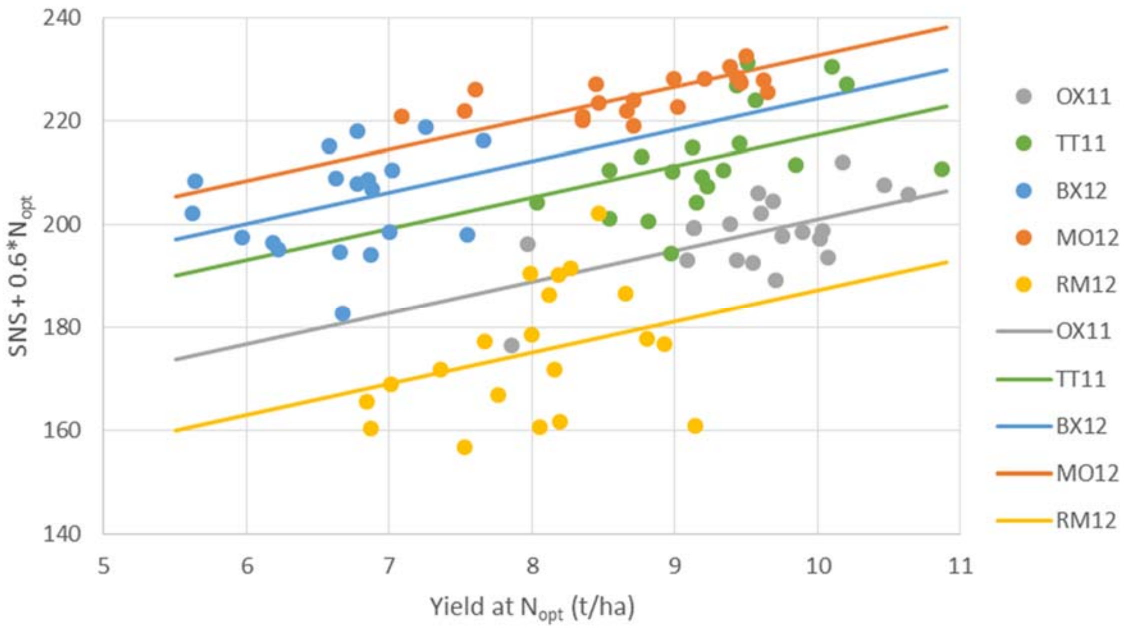

Figure 4. The relationship between yield at the economically optimal N rate (N_{opt}) and N requirement (soil nitrogen supply (SNS) + 0.6*N_{opt}) for differing wheat varieties within individual site seasons (data from Defra HY-LO project; Sylvester-Bradley et al., 2016).

4.2.5. Testing alternative N recommendations

A comparison was done of a range of alternative approaches to calculating N recommendations, to establish whether the current approach can be improved upon. The methods tested were:

1. RB209 (8th edition), using measured SNS
2. RB209 (8th edition), using SNS from Field Assessment Method (FAM) look-up tables
3. N Management Guide (Sylvester-Bradley *et al*., 2009), using measured SNS
4. N Management Guide, using SNS from FAM look-up tables
5. RB209 (8th edition) with measured SNS, plus or minus 20 kg N/ha for each t/ha deviation of yield at N_{opt} from 9 t/ha
6. RB209 (8th edition) with measured SNS, plus or minus 10 kg N/ha for each t/ha deviation of yield at N_{opt} from 9 t/ha
7. N Management Guide, using measured SNS and with recommendations capped at 350 kg N/ha.

These approaches were tested on a set of 381 N responses for which all the necessary data were available (measured N_{opt}, measured SNS, RB209 soil type, rainfall category, previous crop). All N responses were from UK experiments, carried out in harvest years 2003 to 2015. For approaches involving adjustments for yield potential (3-7), perfect prediction of yield at N_{opt} was assumed.

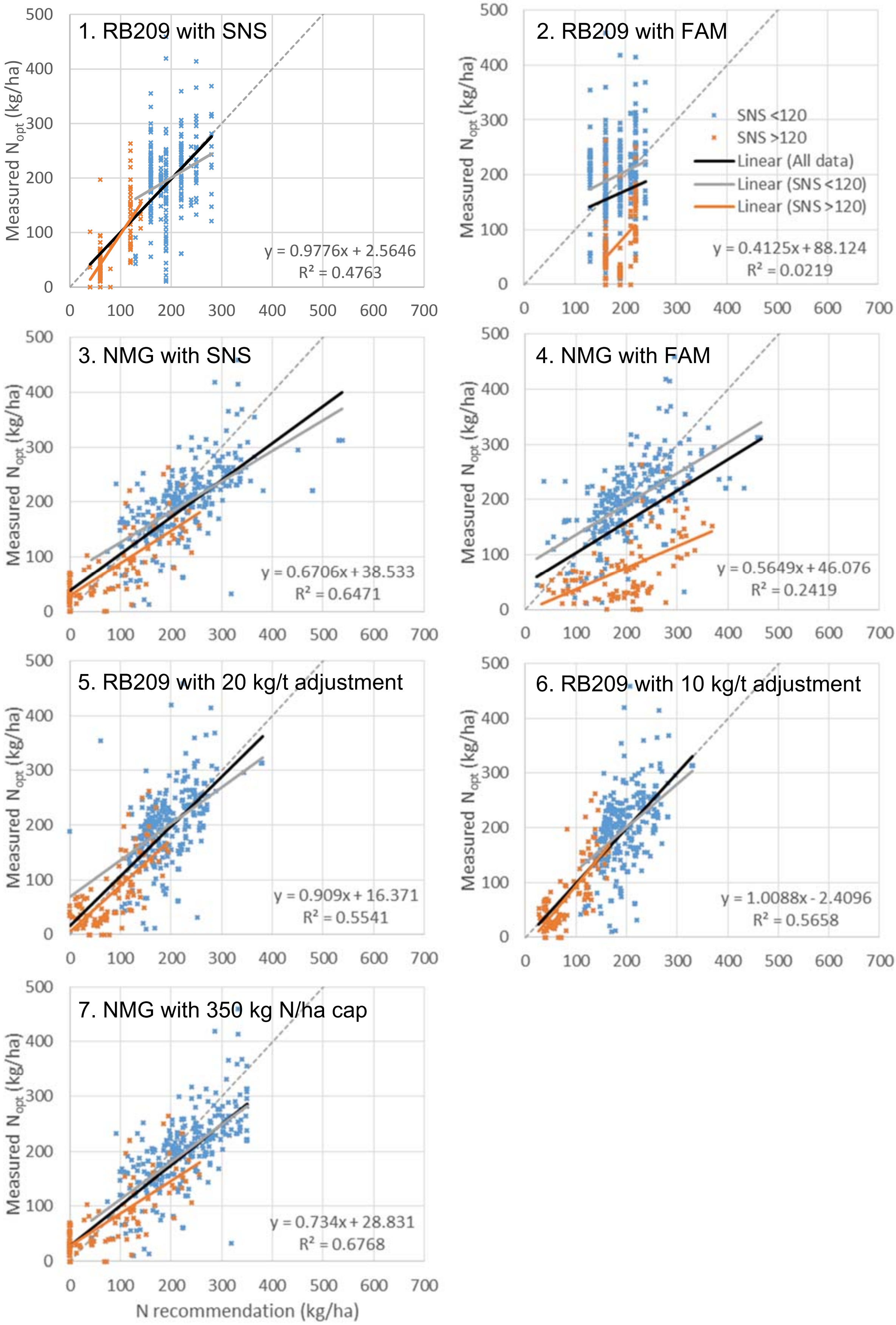

Figure 5. Correlations between N recommendations and measured optimal N rates (N_{opt}) for seven alternative N recommendation approaches. Sites with SNS <120 kg N/ha shown in blue and sites with SNS >120 kg N/ha in orange. Black regressions, equations and R^2 values refer to the full dataset.

Given the conclusions of WP1 regarding SNS, that FAM is an appropriate method of assessing SNS up to 120 kg N/ha but measurement may be more accurate at sites with higher SNS, the data were plotted separately for sites with measured SNS levels of over and under 120 kg N/ha.

The approach used in the 8th edition of RB209, using measured SNS, gave a good correlation with N_{opt} (Figure 5.1). The N Management Guide tended to overestimate N rates where N requirement was high, and vice versa, suggesting that the adjustment for yield is too large (Figure 5.3). Both approaches were less accurate when the Field Assessment Method was used to estimate SNS (Figure 5.2 and Figure 5.4); there was little difference for sites with SNS <120 kg N/ha, but the FAM method performing poorly on sites with SNS >120 kg N/ha. This is consistent with the conclusions of WP1, that measurement of SNS is rarely justified at low SNS levels but gives more accuracy than FAM when SNS is greater than 120 kg N/ha. The N Management Guide could be improved by capping the recommendation at 350 kg N/ha (Figure 5.7). Adjusting RB209 (8th edition) recommendations for yield potential smoothed the recommendations, and did not disrupt the correlation from the 1:1 line (Figure 5.5 and Figure 5.6).

For each N response curve in this analysis and for each of the seven approaches for calculating N recommendation, gross margin was calculated at N_{opt}, using a wheat price of £145/t and ammonium nitrate price of £250/t, equivalent to a break even ratio (k) of 5. The best methods for maximising gross margin was RB209 (8th edition) adjusted by 10 kg N/ha or 20 kg N/ha for each t/ha deviation of expected yield from 9 t/ha. For these the reduction in gross margin compared with the gross margin at the perfect N optimum, was <£25/ha for 77% sites and <£50/ha for 92% sites (Figure 6). The RB209 (8th edition) method without yield adjustment was the next best method with about 70% of sites having a gross margin reduction <£25/ha. However, paired t-tests comparing RB209 (8th edition) with the two yield adjustments against RB209 (8th edition) did not show significant improvements in gross margin. The N Management Guide approach was worse than RB209 (8th edition), and both RB209 (8th edition) and the N Management Guide recommendations were considerably worse with the Field Assessment Method for estimating SNS than with measured SNS.

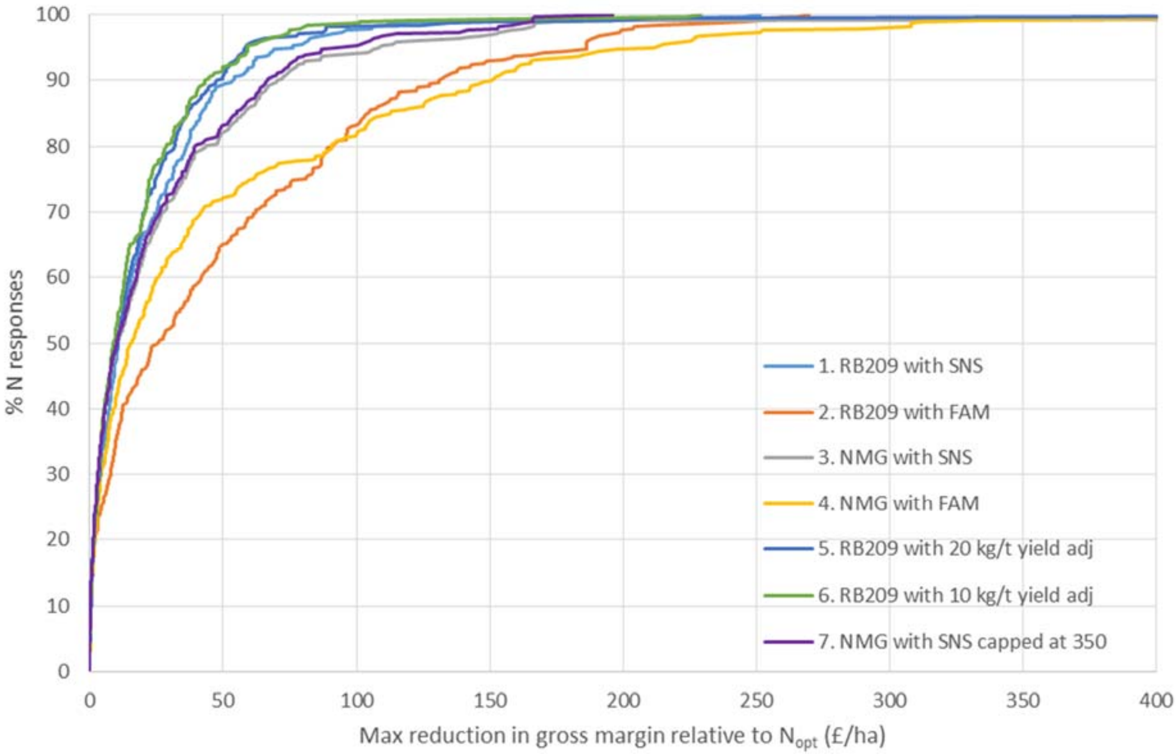

Figure 6. Reductions in gross margin relative to N_{opt} for seven alternative methods of calculating N recommendation.

4.2.6. Use of grain %N as a retrospective test

The use of grain %N as a retrospective test of N strategy for winter wheat (RB209, 8th edition p.105) was based on an AHDB Cereals & Oilseeds project involving analysis of a large dataset of wheat yield and protein responses to N (Sylvester-Bradley & Clarke, 2009). The dataset used by Sylvester-Bradley & Clarke overlaps heavily with that outlined in Table 1. They concluded that optimally managed feed wheat had around 11.5% grain protein, and that deviation from this level indicated under or over-fertilisation with 70-80% success. This success rate could be improved by examining protein data from several fields or over several seasons.

To re-evaluate the value of grain %N as a retrospective test of N strategy, fitted %N curves were used to calculate %N at RB209 (8th edition) recommended N rates, which was then compared with the size of the deviation of the RB209 (8th edition) recommendation from N_{opt} (Figure 7). This was done using the recent UK data described above, for which sufficient %N data was available for 218 feed wheat N responses and 92 milling wheat N responses. Where N was applied at the N_{opt}, grain %N was 2.12 for milling wheats and 1.99 for feed wheats, close to the 2.1% and 1.9% described in RB209 (8th edition). However, the correlations between N application deviation from N_{opt} and grain %N were weak, particularly for milling wheat (R^2 = 0.0578 for milling varieties and 0.1492 for feed wheats).

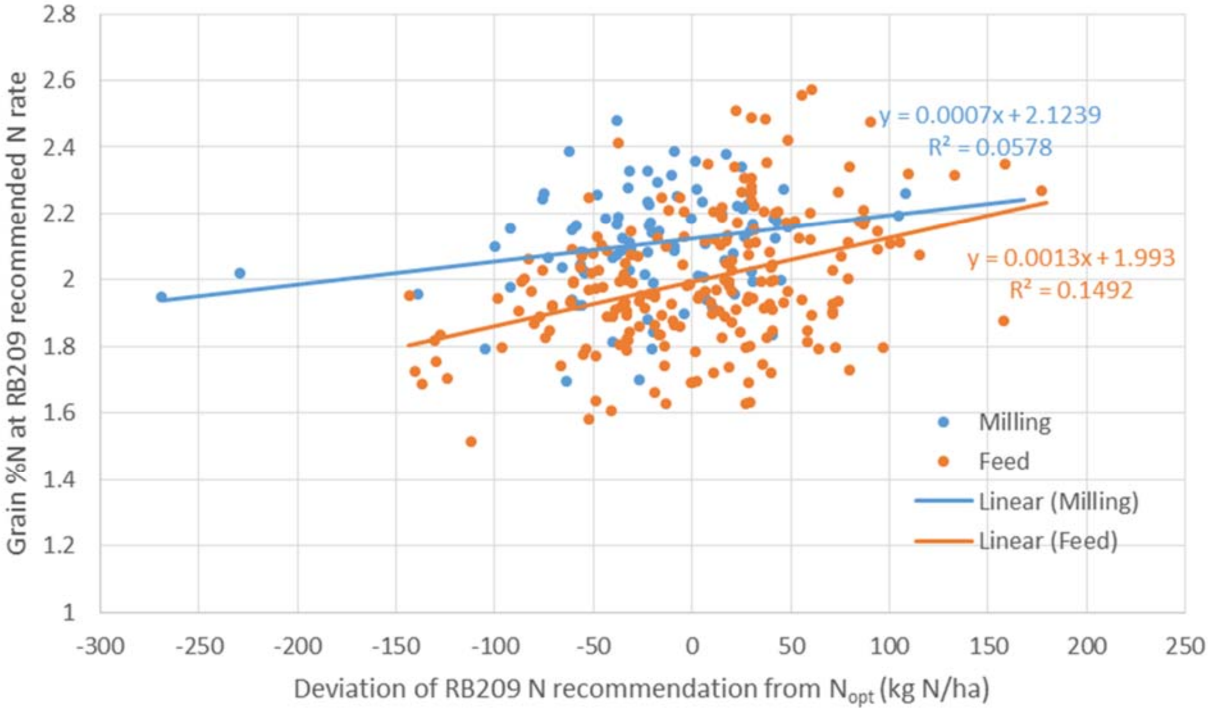

Figure 7. Relationship between the deviation of N applications from the economically optimal N rate (N_{opt}) and grain %N.

4.2.7. Conclusions: winter wheat N recommendations

For light sand soils, our data show that RB209 (8th edition) recommendation were 20-50 kg/ha lower than measured N_{opt} values (Figure 1), hence we recommend raising recommendations by 20 kg/ha across all SNS levels. The low N rates previously recommended for sandy soils were partly due to the lower yields typically achieved; the revised N rates are aimed at 8 t/ha crops, and should be reduced for lower yields as described below. For silty soils our data show that RB209 (8th edition) recommendations were 20-30 kg/ha lower than measured N_{opt} values, particularly at low SNS, hence we recommend raising recommendations by up to 20 kg/ha. For shallow, medium and deep clay soils, 8th edition recommendations were approximately in line with data (Figure 1) and required no changes; for organic and peat soils no data was available, and hence recommendations should not be changed (Table 3).

Given that most combinable crops are grown in NVZs, users should be signposted to the NVZ guidance, and an asterisk placed by recommended N rates that exceed the N max limit (220 kg N/ha, or 240 kg N/ha on shallow soils), as follows.

Table 3. Proposed N recommendations for wheat (sown up to the end of January), valid for predicted yield 8 t/ha. Values in bold are different from those in the 8th edition of RB209.

	SNS Index 0	1	2	3	4	5	6
Light sand soils	**180**	**150**	**120**	**90**	**60**	**0-60**	0-40
Shallow soils	280*	240	210	180	140	80	0-40
Medium soils	250*	220	190	160	120	60	0-40
Deep clay soils	250*	220	190	160	120	60	0-40
Deep silt soils	**240***	**210**	**170**	130	100	40	0-40
Organic soils				120	80	40-80	0-40
Peat						0-40	

***The N recommendation exceeds the N max limit that applies within 2013-16 NVZs. NB the N max limit is calculated for the whole of the area of a crop type grown on farm and not for individual fields. For more details see www.gov.uk/nitrate-vulnerable-zones**

We propose introducing an adjustment to the rate in Table 3 where high or low yields are expected, to reflect the correlation between yield and N requirement described above. This change is consistent with NVZ regulations, which state that "an additional 20 kg N/ha is permitted for every tonne that the expected yield exceeds the standard yield."

"Research has shown that the economically optimal rate of N fertiliser increases with yield. Where previous experience of growing wheat indicates that yields above 8 t/ha can be realistically expected, the recommended rate should be increased by 20 kg N/ha for each t/ha additional yield, up to a maximum of 14 t/ha. Similarly for low yielding crops, the recommended rate should be reduced by 20 kg N/ha for each t/ha reduction in expected yield."

We propose no changes to the advice about N timings, but the text under the heading "Yield variation and the use of grain nitrogen concentration" (p105-106) should be amended to:

"Farm nitrogen strategies for wheat can be assessed periodically using information on grain protein concentration. Grain protein at the economic optimum rate of nitrogen is about 11% (1.9% N) for feed wheat and 12% (2.1% N) for breadmaking wheat. Where concentrations in yields from a number of adjacent fields are consistently above or below these values during several years, nitrogen fertiliser application rates should be adjusted down or up by 25 kg N/ha per 0.5% difference in grain protein (30 kg N/ha per 0.1%

difference in grain %N). To convert grain %protein to grain %N, divide by 5.7. Both N and protein are reported on a 100% dry matter basis."

4.3. Winter barley N requirement

4.3.1. "Fertiliser Manual (RB209)" advice and NVZ guidance

In RB209 (8th edition) Section 4 (p.107-108), a table was presented of N recommendations for winter sown barley. The recommended N rate depended on whether the crop was being grown for feed or malting, the SNS Index and the soil type, with the maximum recommendations being 210 kg N/ha for feed barley and 160 kg N/ha for malting barley. It was recommended that N rates should be reduced by 25 kg N/ha where lodging risk was high.

In the Nitrate Pollution Prevention Regulations (2015), the N max limit for winter barley is 180 kg N/ha, with an extra 20 kg N/ha permitted on shallow soils and an extra 20 kg N/ha for each t/ha increase in expected yield over 6.5 t/ha. N max limits were mentioned only on p.50-51 of RB209 (8th edition) Section 1.

4.3.2. Effects of SNS, soil type and yield potential on N requirement

To evaluate N requirement for winter barley, a database of N response experiments was collated and analysed as for winter wheat. The database included UK experiments from 2008-2015 (Table 4).

Table 4. Data sources for review of winter barley N requirements.

Project	Reference	Harvest years	No. site seasons	No. site x season x treatment combinations
Nitric database	ADAS UK Ltd	1981-1993	77	77
Scottish agronomy trials	Gilchrist *et al*. 2012	2007-2009	9	14
ADAS N x Species trials	Commercial in confidence	2009-2010	2	5
ADAS N x fungicide trials	Commercial in confidence	2010	2	2
MIN-NO	Sylvester-Bradley *et al*., 2015	2010-2012	2	2
ADAS trials for GrowHow	Commercial in confidence	2008-2010	6	24
Updating WB N guidance	AHDB Current Project 216-0006	2014-2015	5	28

To check whether N_{opt} should be analysed separately for feed and malting varieties, data was selected from six site seasons which included both feed and malting varieties, from harvest years

2009 to 2015. The mean N_{opt} values were 210 kg N/ha for feed varieties and 176 kg N/ha for malting, and the mean yields at N_{opt} were 9.8 t/ha and 8.0 t/ha respectively. However, the means failed to show the large differences between varieties within the feed and malting groups: across four sites which included the same five varieties, mean N_{opt} values were 158 and 188 kg N/ha for the malting varieties Maris Otter and Venture, and 188, 195 and 249 kg N/ha for the feed varieties Volume, Cassia and Meridian. Variation in the data was such that only the most extreme varieties, Maris Otter and Meridian, were significantly different from each other. Consequently, it was concluded that malting varieties differed from each other as much as they do from feed varieties, and vice-versa, so it is not necessary to consider feed and malting varieties separately, in the absence of grain %N targets.

For winter barley, insufficient data was available to thoroughly evaluate the accuracy of RB209 N recommendations across the range of SNS indices, as most of the experimental data collected was from sites with SNS Index 0 or 1 (Table 5). For most soil type x SNS Index combinations, the mean N_{opt} was higher than the RB209 recommendation, with the exception of medium and deep clay soils at SNS Index 0 (Table 5). The low value for this combination may be because most of the 14 sites were from the 1980s and early 1990s, when yields and N requirements were lower. Across all soil types and SNS indices, the mean deviation from the RB209 recommendation was 22.6 kg N/ha. Deviations from RB209 (8th edition) recommendation were highest for light sandy soils and silty soils, at means of 40 kg N/ha and 44 kg N/ha respectively (Figure 8).

Table 5. Mean economically optimal N rate (N_{opt}) for winter barley and RB209 (8th edition) recommended N rates (feed), by soil type and SNS Index, for sites at which soil type was known. N_{opt} calculated using a break even ratio of 5. Figures in brackets show number of site x treatment combinations included in mean.

		Economically optimal N rate (kg/ha)											
		SNS Index											
Soil group		**0**		**1**		**2**		**3**		**4**		**5**	
Light sand	Mean	196	*(23)*	135	*(6)*	129	*(3)*	71	*(1)*	94	*(4)*	63	*(1)*
	RB209	150		120		90		60		30-60		0-30	
Shallow	Mean	216	*(18)*	221	*(8)*		*(0)*	118	*(2)*		*(0)*		*(0)*
	RB209	210		190		150		120		60		20-60	
Medium & deep clay	Mean	162	*(14)*	177	*(12)*	140	*(5)*	188	*(8)*	51	*(1)*	31	*(1)*
	RB209	190		170		140		110		60		20-60	
Deep silt	Mean	209	*(9)*	163	*(5)*		*(0)*		*(0)*		*(0)*		*(0)*
	RB209	160		140		110		70		30		0-20	

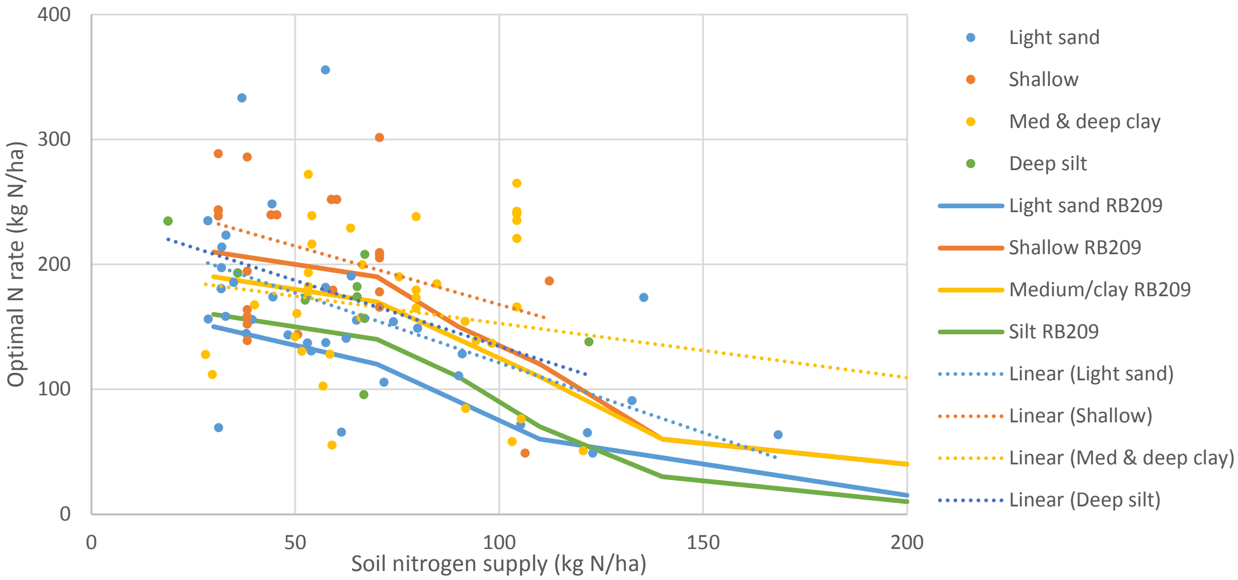

Figure 8. Effects of soil nitrogen supply (SNS) on economically optimal N rate (N_{opt}) of winter barley, calculated at a break-even ratio of 5. Solid lines show RB209 (8th edition) recommendations, plotted at the central value of each SNS Index.

For winter barley, N requirement was plotted against yield at N_{opt}, as for winter wheat, giving a similar positive correlation (Figure 9). The slope of the line was also similar to that for winter wheat, at 13.8 kg/ha extra N required for each t/ha extra yield, or 23.1 kg N/ha extra fertiliser applied.

The impact of soil type on yield potential was removed as for wheat by considering deviation of yield potential on deviation of N_{opt} from the RB209 (8th edition) recommended N rate (Figure 10a). The impact of harvest year was then removed by considering yield at N_{opt} as a percentage of RL mean treated yield (Figure 10b), although this was only possible for a subset of the data, gathered since 2002. It is evident from this subset of the data that there has been an increase in the N requirement of winter barley over the last few decades. After the effects of soil type and harvest year were removed, there remained a correlation between yield and N_{opt}, as for winter wheat, which gives justification for adjusting the N recommendations according to yield potential. Figure 10a shows that RB209 (8th edition) recommendations are most accurate for crops yielding 6.9 t/ha, with more N required at higher yields and less at lower yields. However, yields in plots trials are typically slightly higher than on farm, so a reference yield of 6.5 t/ha is probably more appropriate for farm crops.

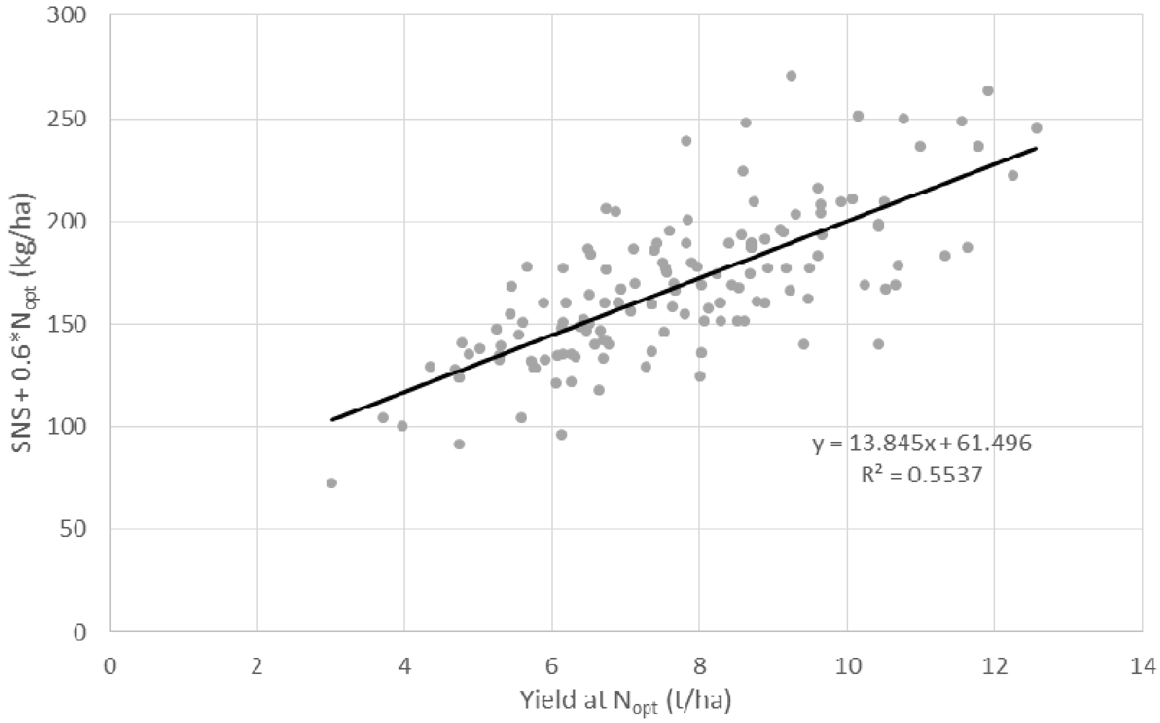

Figure 9. Effects of yield potential (yield at the economically optimal N rate (N_{opt})) on N requirement (site soil nitrogen supply + 0.6 * N_{opt}) for winter barley.

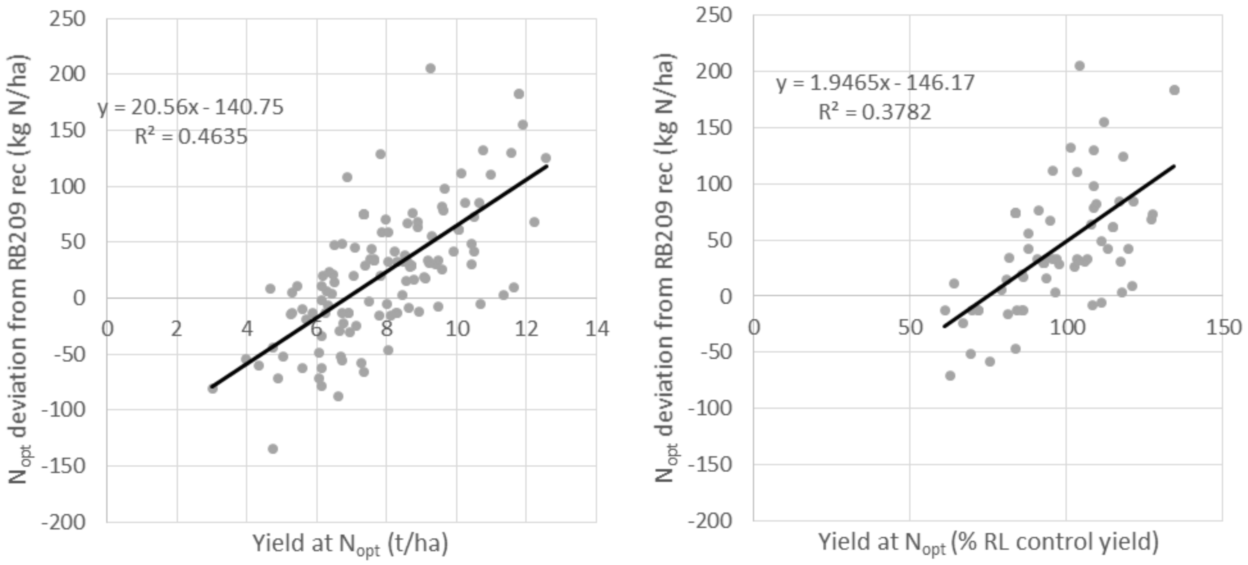

Figure 10. The effects of winter barley yield potential (yield at the economically optimal N rate (N_{opt})) in t/ha or as a percentage of the mean control yield in AHDB Recommended List trials, on the deviation of N_{opt} from the RB209 (8th edition) recommended N rate.

4.3.3. Grain quality

Whilst the data in Figure 8 clearly indicate a need to apply more N than RB209 (8th edition) recommended to optimise yields of feed barley, for malting barley it is also important to consider grain %N. For the 24 site x treatment combinations where %N data was available and a malting variety was used, mean N_{opt} was 161 kg N/ha and mean %N at N_{opt} was 1.76%. These 24 site x treatment combinations comprised four on light sand soils, six on shallow soils, and 14 on medium soils. Fitted grain %N curves were used to calculate the N rates at which grain %N would have been 1.8%, 1.7% or 1.6%, where these were lower than the N_{opt}.

The shape of the grain %N curve was consistent across most sites, with the exception of two varieties in the same experiment for which grain %N was very unresponsive to N rate (Figure 11). However, there was a wide range in %N at the N_{opt}; even excluding the outlying site, this ranged from 1.46% to 2.09%.

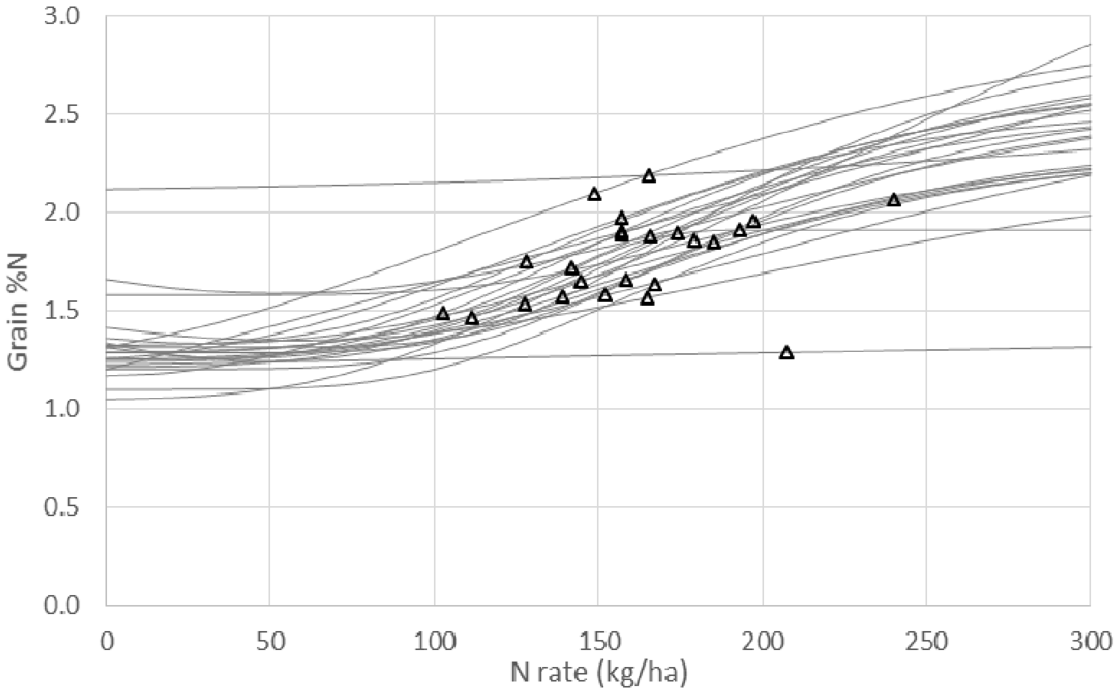

Figure 11. The response of grain %N to applied N rate for 24 winter malting barley site x treatment combinations. Open triangles show grain %N at the economically optimal N rate (N_{opt}).

Across the 22 site x treatment combinations showing a typical %N response to N rate, the slopes of the curves around the N_{opt} were such that a reduction of about 18 kg N/ha was necessary for each 0.1% reduction in grain %N; in the lower areas of the curve, larger reductions in N rate would be needed for the same 0.1% reduction in grain %N, as the curves become more shallow (Figure 11). These figures are in the same region as those calculated by Sylvester-Bradley & Clarke (2009), who suggested that around the N_{opt}, a 25 kg /ha change in applied N gave a 0.1% change in winter barley grain %N.

The curves in Figure 11 can be brought together by plotting grain %N against total N supply: site SNS + 0.6 * fertiliser N rate, where the factor of 0.6 is applied to fertiliser N to approximate uptake efficiency. However, to make it easier to consider equivalent effects of fertiliser N rate, curves have been plotted against SNS / 0.6 + fertiliser N (Figure 12). These show that for 20 out of the 22 sites with typical response curves, a grain %N target of 1.8% can be achieved with an applied N rate + SNS / 0.6 of 230, which equates to applied N rates of 147 kg N/ha with 50 kg N/ha SNS (Index 0), 113 kg N/ha with 70 kg N/ha SNS (Index 1), 80 kg N/ha with 90 kg N/ha SNS (index 2), and 47 kg N/ha with 110 kg N/ha SNS (Index 3). These rates were between those recommended in the 8th edition of RB209 for malting barley on light sand soils and 'other mineral soils'; four of the 22 sites had light sand soils. Successive reductions of 15-25 kg N/ha applied N are necessary for each 0.1% reduction in grain %N target (Table 6), with the size of the reduction increasing as %N target falls, due to the shape of the grain %N response curve (Figure 12).

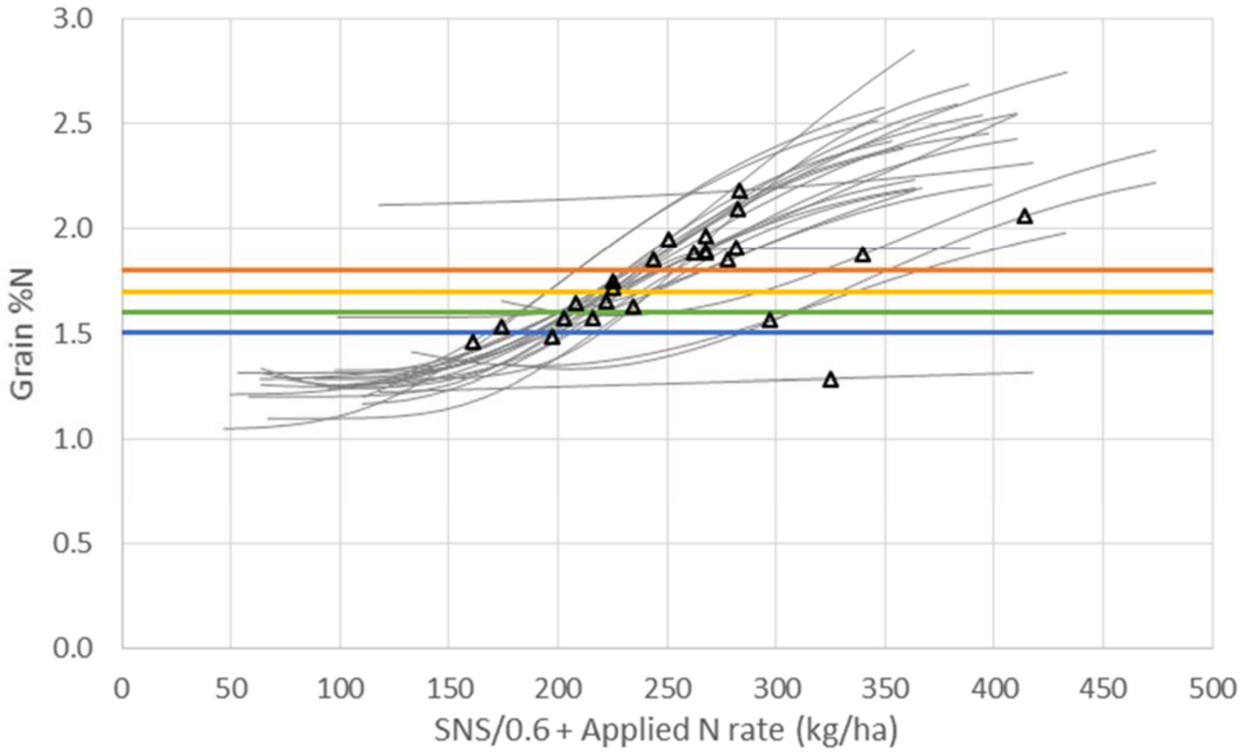

Figure 12. The effects of N supply on (including SNS and applied N, weighted for their different uptake efficiencies) on grain %N in winter malting barley. Horizontal lines show grain %N targets of 1.8% (orange), 1.7% (yellow), 1.6% (green) and 1.5% (blue). Open triangles show grain %N at the economically optimal N rate (N_{opt}).

Table 6. Maximum N supplies to meet grain %N targets in winter malting barley.

		Grain %N target			
		1.8%	**1.7%**	**1.6%**	**1.5%**
Maximum SNS/0.6 + applied N to meet grain %N target at ≥19/22 sites (kg N/ha)		230	215	195	170
Applied N at	50 kg/ha SNS (Index 0)	147	132	112	87
	70 kg/ha SNS (Index 1)	113	98	78	53
	90 kg/ha SNS (Index 2)	80	65	45	20
	110 kg/ha SNS (Index 3)	47	32	12	0

4.3.4. N timing

An AHDB project (216-0006) is underway to update N fertiliser management guidelines for winter barley. One objective of the project is to review N timing, using data from 25 experiments carried out between 2004 and 2012.

RB209 (8th edition) advice, when more than 100 kg N/ha was required, was to apply 40 kg N/ha in mid-February or early March and the remainder by early stem extension, but not before late March. The analysis for project 216-0006 involved two comparisons: >30% N applied before 1st April versus ≤30% N applied before 1st April; and >50% N applied before 1st April versus ≤50% N applied before 1st April. For each comparison, t-tests were done for a range of seven total N rates. 1st April was used as a surrogate for the start of stem extension because the GS at which N was applied was not specified in many experiments.

The analysis found that applying >30% of the total N before 1st April gave a higher yield than applying ≤30% before 1st April at all but one of the N rates investigated, although the difference was significant only at 200 and 160 kg N/ha. Applying >50% of the total N before 1st April similarly gave a higher yield than applying ≤50% before 1st April at five of the seven N rates, but the yield benefit was significant only at the same two N rates. Across all N rates, applying >30% N before 1st April raised yield by 0.45 t/ha (P=0.026) compared with applying ≤30% before 1st April, and applying >50% N before 1st April raised yield by 0.82 t/ha (P<0.001) compared with applying ≤30% before 1st April.

Given that early N applications tend to raise grain %N by less than late N applications (CF Fertiliser Reports), applying N earlier to winter barley than recommended in the 8th edition should also help barley growers meet grain quality specifications.

4.3.5. Conclusions: winter barley N recommendations

For feed barley, the evidence suggests that N recommendations in the 8th edition should be raised by 20 kg N/ha for sandy soils and 10 kg N/ha for silty soils, across the SNS levels for which data were available. The recommendation for shallow soils at SNS Index 0 should also be raised slightly (Table 7). For malting barley, less data is available for sandy soils so we propose raising N recommendations by only 10 kg N/ha, to avoid exceeding grain %N targets.

For malting barley, the evidence shows that to meet a 1.8% N specification, N rates should be at least 30-40 kg N/ha below the N_{opt} for feed barley, with further reductions of 15-25 kg/ha for each further 0.1% reduction needed in grain N down to 1.5% N. This involves small increases to the recommendations for sandy soils, and small reductions to the recommendations for other mineral soils (Table 7). Using RB209 (8th edition) recommendations for winter malting barley, six out of 22 sites used in our analysis would have exceeded 1.8% grain N; using the revised N rates in Table 7, only two out 22 sites would have exceeded 1.8% grain N. Using the new guidance on how to reduce the N recommendations to meet lower grain %N targets, two sites would exceed the 1.7% target, three would exceed the 1.6% target and two would exceed the 1.5% target.

Given that most combinable crops are grown in NVZs, users should be signposted to the NVZ guidance, and an asterisk placed by recommended N rates that exceed the N max limit, as follows.

Table 7. Proposed N recommendations for winter barley, valid for predicted yield 6.5 t/ha. Values in bold are different from those in the 8th edition of RB209.

	SNS Index						
	0	**1**	**2**	**3**	**4**	**5**	**6**
Feed barley							
Light sand soils	**170**	**140**	**110**	**80**	**60**	**0-40**	0
Shallow soils	**220***	190	150	120	60	20-60	0-20
Medium and deep clay soils	190*	170	140	110	60	20-60	0-20
Deep silty soils	**170**	**150**	**120**	**80**	**40**	**0-30**	0
Organic soils				110	60	0-40	0
Peaty soils						0-40	
Malting barley (for 1.8% grain N limit)							
Light sand soils	**130**	**90**	**60**	0-40	0	0	0
Other mineral soils	**150**	**120**	**90**	**50**	0-40	0	0
Organic soils				**50**	0-40	0	0
Peaty soils						0	

***The N recommendation exceeds the N max limit that applies within 2013-16 NVZs. NB the N max limit is calculated for the whole of the area of a crop type grown on farm and not for individual fields. For more details see www.gov.uk/nitrate-vulnerable-zones**

The evidence described above shows that the relationship between yield potential and N requirement is the same for barley as for wheat. Hence we propose the same 20 kg/t yield adjustment, which again will improve consistency between RB209 and NVZ regulations:

"Research has shown that the economically optimal rate of N fertiliser increases with yield. Where previous experience of growing winter barley indicates that yields above 6.5 t/ha can be realistically expected, the recommended rate should be increased by 20 kg N/ha for each t/ha additional yield, up to a maximum yield of about 12 t/ha. Similarly for low yielding crops, the recommended rate should be reduced by 20 kg N/ha for each t/ha reduction in yield."

The 8th edition text should be revised as follows, to give the same timing advice for both feed and malting barley, and greater detail about how to revise N recommendations for grain %N targets below 1.8%.

Nitrogen timing

"There is no requirement for seedbed nitrogen.

"Where the total nitrogen rate is less than 100 kg N/ha, apply this amount as a single dressing **by GS30/31**.

"Where the total nitrogen rate is between 100 and 200 kg N/ha or more, split the dressing with **50%** during late tillering in mid-February/early March and **50% at GS30/31. Where the total nitrogen rate is above 200 kg N/ha, apply three splits with 40% during late tillering, 40% at GS30/31 and 20% at GS32.**

"These recommendations assume appropriate measures are taken to control lodging (e.g. choice of variety, use of plant growth regulator). Reduce the recommendation by 25 kg N/ha if the lodging risk is high."

Nitrogen – malting barley

"Careful judgement of the nitrogen rate is important to ensure that the grain nitrogen concentration is neither too high nor too low for the requirement of the target market. Previous experience and consultation will be important in deciding the nitrogen rate to use. Where quality premiums are expected to be low, applying a slightly higher nitrogen rate will maximise the yield potential of the crop".

"Where the target grain %N is below 1.8%, **the nitrogen rate from the malting section of the table above should be adjusted as necessary for predicted yield, then reduced by approximately 15 kg N/ha to achieve 1.7% grain N, 35 kg N/ha to achieve 1.6% grain N, or 60 kg N/ha to achieve 1.5% grain N.** This nitrogen should all be applied by GS30/31."

4.4. Winter triticale N requirement

4.4.1. "Fertiliser Manual (RB209)" advice

In RB209 (8th edition) Section 4 (p.109), a table was presented of N recommendations for winter-sown oats, rye and triticale. The recommended N rate depended on the SNS Index and the soil type, but did not vary with species. The maximum recommendation was 150 kg N/ha. It was recommended that N rates should be reduced by 25 kg N/ha where lodging risk was high.

RB209 (8th edition) did not mention crops grown for anaerobic digestion, but there were separate recommendations for forage rye and forage triticale later in Section 4, with a maximum recommended N rate of 80 kg N/ha.

4.4.2. Review of new information

To evaluate N requirement for winter triticale, a database of N response experiments was collated and analysed as for winter wheat. The database included UK experiments from 2009-2014 (Table 8).

Table 8. Data sources for review of winter triticale N requirements.

Project	Reference	Harvest years	No. site seasons	No. site x season x treatment combinations
ADAS N x Species trials	Kindred *et al*. 2010a	2009-2010	2	7
Triticale (PR478)	Weightman *et al*., 2011a	2010	2	4
HY-LO	Sylvester-Bradley *et al*. 2016	2011-2012	5	5
Triticale (PR556)	Innovate UK project 101093; Clarke *et al*. 2016	2011-2014	13	31

Most of the experiments listed in Table 8 were part of Innovate UK project 101093, which was reported as part of AHDB Cereals & Oilseeds Project Report 556 (Clarke *et al*., 2016). A comparison of the N responses of wheat and triticale found no significant difference in the N requirements of these species, however, it was recognised that triticale has a greater lodging risk than wheat, so less N may be required in situations of high lodging risk. It is also important to recognise that unlike in these experiments, where triticale was grown alongside wheat on fertile sites, in practice triticale is often grown on marginal sites and with low inputs.

Given that RB209 (8th edition) N recommendations were about 100 kg/ha lower for triticale than for wheat, these projects indicate that RB209 (8th edition) N recommendations for triticale were insufficient to meet crop demand. Of 43 available triticale N responses, only three had N_{opt} rates lower than RB209 (8th edition) recommendations; the mean deviation from the recommendation was 69 kg N/ha (Figure 13). There was insufficient data to show how recommendations should vary with soil type, as no data was available for light sandy soils, and a maximum of 17 N responses for any other RB209 soil type.

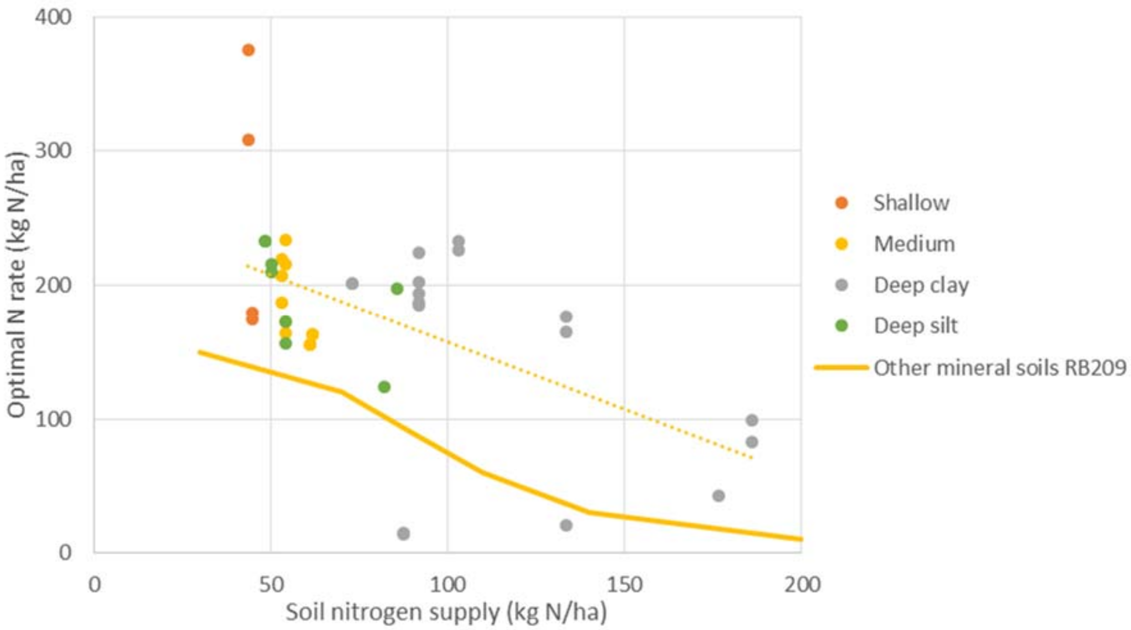

Figure 13. Effects of soil nitrogen supply (SNS) on economically optimal N rate (N_{opt}) of winter triticale, calculated at a break-even ratio of 5. Solid line shows RB209 (8th edition) recommendations for mineral soils other than light sands, plotted at the central value of each SNS Index. Dotted line shows regression of N response experiments, all of which were carried out on 'other mineral soils'.

There was a correlation between yield at N_{opt} and N requirement for triticale as for other cereals, although R^2 was only 0.205 and the slope was shallower, at 9.8 kg/ha N (or 16.3 kg/ha applied N) for each extra t/ha yield (Figure 14). Neither the slope nor the intercept of the regression line was significantly affected by rotational position, perhaps because triticale yield is less affected by rotational position than wheat, due to its greater tolerance of take-all.

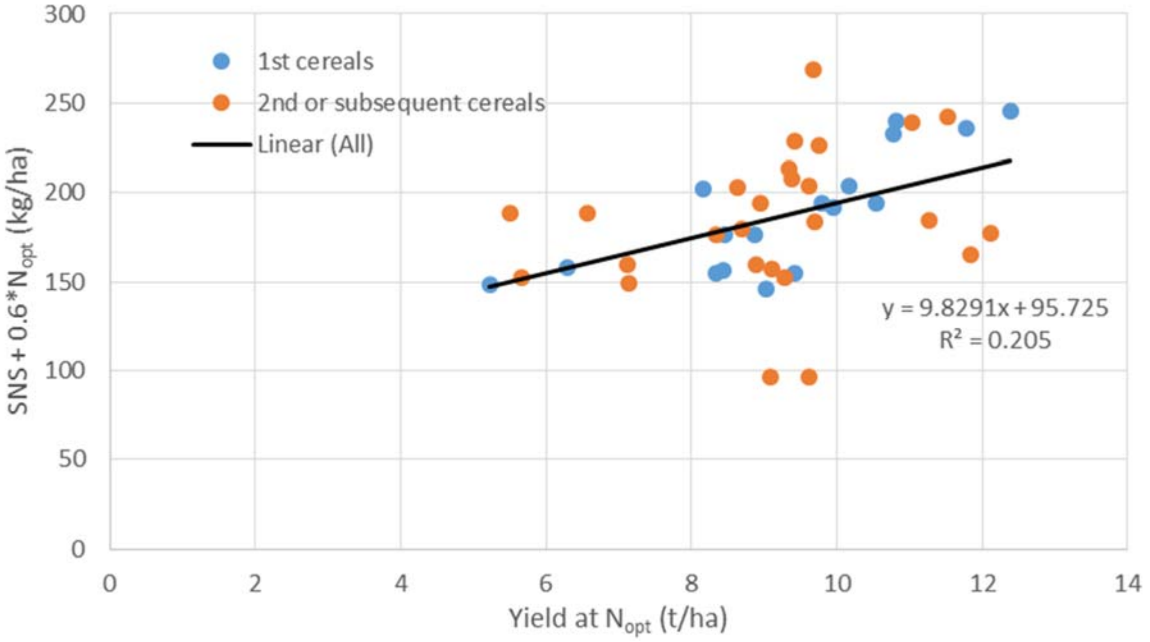

Figure 14. Effects of yield potential (yield at the economically optimal N rate (N_{opt})) on N requirement (site soil nitrogen supply + 0.6 * N_{opt}) for winter triticale, with data points coloured to indicate rotational position.

4.4.3. Conclusions: winter triticale N recommendations

It is proposed that winter triticale should use the same N recommendation table as wheat, due to the similarity between the N requirements of wheat and triticale, rather than the situation in the 8th edition where it shared recommendations with rye and oats. We propose that the wheat N table is headed "Wheat and triticale" and that following the text relating to wheat, there is a sub-heading for triticale with the following text:

"The N requirements of triticale are the same as those of wheat in most situations. Hence N recommendations should be calculated as for feed wheat, including the adjustment for yield potential, with the following exceptions:

- **If the variety chosen is known to have a high lodging risk, the total N rate should be reduced by 40 kg N/ha.**
- **If the grain price is expected to be significantly below that which would be received for wheat, N rates should be reduced accordingly.**

There are currently no specific N max limits for triticale, so it is recommended that the same limits are used as for wheat."

4.5. Winter oats N requirement

4.5.1. "Fertiliser Manual (RB209)" advice

In RB209 (8th edition) Section 4 (p.109), a table was presented of N recommendations for winter-sown oats, rye and triticale. The recommended N rate depended on the SNS Index and the soil type, but did not vary with species. The maximum recommendation was 150 kg N/ha. It was recommended that N rates should be reduced by 25 kg N/ha where lodging risk was high.

4.5.2. Review of new information

As part of the Sustainable Arable Link project (LK09124), three N response experiments were carried out on winter oats in the 2013-14 season by IBERS (Aberystwyth University), ADAS and Agrii. A further experiment was done in the 2014-15 season as part of AHDB project 2200002 (Table 9). Prior to these projects, ADAS experiments in 2009 and 2010 funded by plant breeders included three and two oats varieties, respectively (Kindred *et al*. 2010a). Rothamsted Research carried out an AHDB Cereals & Oilseeds-funded single oats N response experiment in 2015. We are not aware of any other N response experiments carried out on oats since the last revision of RB209.

Table 9. Details of experiments included in the review of the N requirements of winter oats.

Experiment	Soil type	Varieties tested	N rates tested (kg N/ha)	Spring SNS (kg N/ha)		
				SMN	Crop	SNS
ADAS 2009, Suffolk	Medium	2 husked oats (Mascani, Tardis) & 1 naked oat (Hendon)	0, 70, 140, 200, 260	48	5	53
ADAS 2010, Suffolk	Medium	2 husked oats (Balado, Tardis)	0, 70, 140, 220, 290, 360	49	5	54
IBERS 2014, Herefordshire	Medium	4 husked oats (Balado, Gerald, Mascani, Tardis) & 2 naked oats (Fusion, Grafton)	0, 50, 100, 150, 200	96	15	111
ADAS 2014, Herefordshire	Medium	4 husked oats (Balado, Gerald, Mascani, Tardis)	0, 50, 100, 150, 200, 250	22	20	42
Agrii 2014, Eastern England	Unknown	4 husked oats (Balado, Gerald, Mascani, Tardis) & 2 naked oats (Fusion, Grafton)	0, 50, 100, 150, 200	82	20	102
ADAS 2015, Herefordshire	Medium	4 husked oats (Balado, Gerald, Mascani, Tardis)	0, 60, 120, 180, 230 280	24	20	44
RRes 2015, Hertfordshire		Gerald	0, 60, 90, 120, 150	FAM: SNS Index 1		

In two of the six experiments described, N response curves could not be fitted to the yield data because yields were still increasing, despite a high SNS Index and a low RB209 (8th edition) recommendation. Where N response curves could be fitted, optimum N rates were almost always higher than recommended in RB209 (8th edition), the only exceptions being the Rothamsted experiment and the two oats varieties in the 2010 ADAS N x Species experiment (Table 10). The low N_{opt} values in 2010 can be attributed to lodging, as weather conditions resulted in delayed harvest and both oats varieties suffered >95% lodging at N treatments 140 kg/ha and above.

The mean difference between N_{opt} and the RB209 (8th edition) recommendation was 84 kg N/ha, using whichever was lower of the N_{opt} or maximum N rate in the trial for each site x variety combination.

Further evidence of optimum N rates is required for oats, particularly on sandy soils, since all the experiments described above were done on "other mineral soils".

Table 10. Summary of economically optimal N rates (N_{opt}) in winter oats experiments, compared with RB209 (8th edition) recommendations for those sites.

Experiment	Variety	RB209 recommendation (kg N/ha)	Economically optimal N rate (kg N/ha)
ADAS 2009	Hendon	150	142
	Mascani	150	>260
	Tardis	150	181
ADAS 2010	Balado	150	92
	Tardis	150	97
IBERS 2014	Balado, Fusion, Gerald, Grafton, Mascani & Tardis	60	All >200
ADAS 2014	Balado, Gerald, Mascani & Tardis	150	All >250
Agrii 2014	Balado, Fusion, Gerald, Grafton, Mascani & Tardis	60	All >200
ADAS 2015	Balado	150	172
	Gerald	150	160
	Mascani	150	207
	Tardis	150	170
RRes 2015	Gerald	120	103

4.5.3. Conclusions: winter oats N recommendations

Although there is insufficient data to derive robust N recommendations for winter oats, it is clear that the RB209 (8th edition) recommendations were too low. We propose that recommendations be raised by 40 kg N/ha for all soils (Table 11). There are currently no specific N max limits for oats, so these do not need integrating.

Table 11. Proposed N recommendations for winter oats. Values in bold are different from those in the 8th edition of RB209.

	SNS Index						
	0	**1**	**2**	**3**	**4**	**5**	**6**
Light sand soils	**150**	**110**	**80**	**20-60**	**0-40**	0	0
All other mineral soils	**190**	**160**	**130**	**100**	**70**	**0-40**	0
Organic soils				**100**	**70**	**0-40**	0
Peaty soils						**0-40**	

We propose that the current advice on timings is unchanged, as no timing experiments have been done. The suggested reduction in N rate when lodging risk is high should increase from 25 kg N/ha to 40 kg N/ha.

Insufficient data is available to justify an adjustment for yield potential, or to give a reference yield from which to work.

4.6. Winter rye N requirement

4.6.1. "Fertiliser Manual RB209" advice

In RB209 (8^{th} edition) Section 4 (p.109), a table was presented of N recommendations for winter-sown oats, rye and triticale. The recommended N rate depended on the SNS Index and the soil type, but did not vary with species. The maximum recommendation was 150 kg N/ha. It was recommended that N rates should be reduced by 25 kg N/ha where lodging risk was high.

RB209 (8^{th} edition) did not mention crops grown for anaerobic digestion, but there were separate recommendations for forage rye and forage triticale later in Section 4, with a maximum recommended N rate of 80 kg N/ha.

4.6.2. Review of new information

Only one winter rye N response experiment was available: a nitrogen x species experiment located in Suffolk in 2010 (Kindred *et al*. 2010a). This involved comparison of a single winter rye variety (Festa) against multiple varieties of wheat, barley, triticale and oats. The rye had a differently shaped N response curve to the other species, and was the only variety not to reach N_{opt} over the range tested (Figure 15).

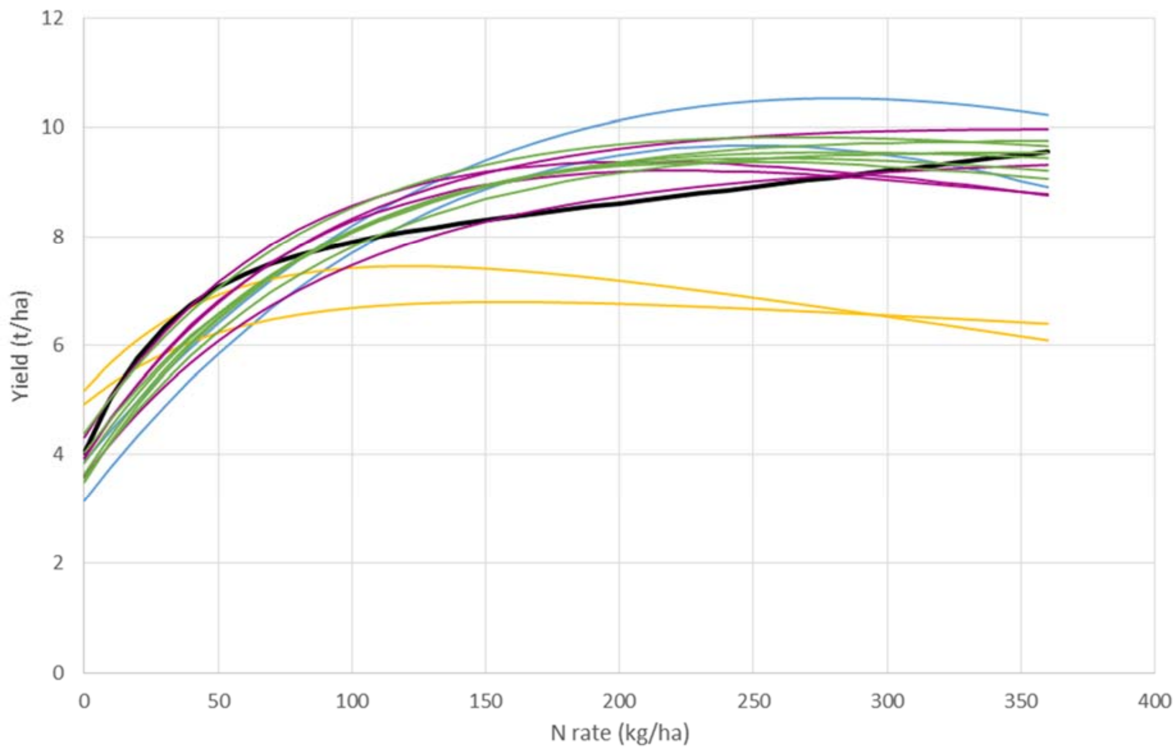

Figure 15. N responses of one rye variety (bold black line), two barley varieties (blue), four triticale varieties (purple), two oats varieties (gold) and six wheat varieties (green) in a single experiment in Suffolk, harvest 2010*.*

Since RB209 (8th edition) did not refer to rye grown for anaerobic digestion, it is likely that growers looked elsewhere for N recommendations. A literature search revealed a range of recommendations, all around or above the top end of the N rates recommended for rye in the 8th edition of RB209: 150 kg N/ha (www.elsoms.com), 120-160 kg N/ha (www.kws-uk.com), 200 kg N/ha (www.agrii.co.uk). In Scotland for both oats and rye, SRUC recommend applying 30-40 kg N/ha less than would be applied to winter barley, giving a maximum recommendation of 160 kg N/ha (Sinclair & Wale, 2013).

4.6.3. Conclusions: winter rye N recommendations

Given the lack of data on the N requirements of rye, it was agreed with the RB209 Review Arable Technical Working Group (TWG) that the N recommendations for rye remain unchanged. This will lead to an extra table, since rye currently has the same recommendations as oats. There are currently no specific N max limits for rye, so these do not need integrating. Research is required to derive new N recommendations for modern rye varieties, across and range of soil types, and to show whether it is necessary to differentiate N recommendations for crops grown for grain and for anaerobic digestion.

4.7. Spring wheat N requirement

No new data was available to review the N requirements of spring wheat.

It seems likely that the correlation between yield and N requirement demonstrated for winter wheat, winter barley and spring barley also occurs for spring wheat, but this cannot be confirmed without fresh data. NVZ regulations for spring wheat include consideration of yield, as for the other cereals, with an N max limit of 180 kg N/ha plus 20 kg N/ha for each t/ha yield expected above 7 t/ha. Including a yield adjustment in the new RB209 recommendations would have the advantage of consistency with the N max limit and with the winter wheat, winter barley and spring barley recommendations, but would lack a firm evidence base.

It is proposed that the base N recommendations for spring wheat should be unchanged, except to integrate the signposting to NVZ guidance. No adjustment for yield will be recommended, due to a lack of evidence (Table 12).

Table 12. Proposed N recommendations for spring wheat. Values in bold are different from those in the 8th edition of RB209.

	SNS Index						
	0	**1**	**2**	**3**	**4**	**5**	**6**
Feed barley							
Light sand soils	160	130	100	70	40	0-40	0
Other mineral soils	210*	180	150	120	70	40	0-40
Organic soils				120	70	40	0-40
Peaty soils						0-40	0-40

***The N recommendation exceeds the N max limit that applies within 2013-16 NVZs. NB the N max limit is calculated for the whole of the area of a crop type grown on farm and not for individual fields. For more details see www.gov.uk/nitrate-vulnerable-zones**

4.8. Spring barley N requirement

4.8.1. "Fertiliser Manual (RB209)" advice and NVZ guidance

In RB209 (8th edition) Section 4 (p.111), a table was presented of N recommendations for spring sown barley. The recommended N rate depended on whether the crop was being grown for feed or malting, the SNS Index and the soil type, with the maximum recommendations being 160 kg N/ha for feed barley and 140 kg N/ha for malting barley.

Under Nitrate Pollution Prevention Regulations (2015), the N max limit for spring barley is 150 kg N/ha, with an extra 20 kg N/ha permitted for each t/ha increase in expected yield over 5.5 t/ha. N max limits were mentioned only on p.50-51 of RB209 (8^{th} edition) Section 1.

4.8.2. Effects of SNS, soil type and yield potential on N requirement

To evaluate N requirement for spring barley, a database of N response experiments was collated and analysed as for winter wheat. The database included UK experiments from 1987-2015 (Table 13 Table 4).

Table 13. Data sources for review of spring barley N requirements.

Project	Reference	Harvest years	No. site seasons	No. site x season x treatment combinations
	McTaggart & Smith, 1992	1987-1988	4	12
Optimum N	Sylvester-Bradley *et al*., 2008	2005-2007	15	60
Scottish agronomy trials	Gilchrist *et al*. 2012	2007-2009	9	18
MIN-NO	Sylvester-Bradley *et al*., 2015	2010-2012	1	1
Yara trials	Commercial in confidence	2006-2015	4	4

For spring barley, the available data gave no correlation between SNS Index and measured N_{opt} (Figure 16). For light sandy soils, the N_{opt} for all but one site x variety combination was higher than the RB209 (8^{th} edition) recommendation, by an average of 90 kg N/ha. However, all the experiments on light sand were conducted in Scotland, and hence may not be representative of England and Wales. The high N_{opt} values for these sites may result partly from leaching of applied N in wet spring weather. For other mineral soils, N_{opt} values fell on both sides of the RB209 (8^{th} edition) recommendations (Table 14), with a mean deviation across all N rates of only -3 kg N/ha. There were possible differences between types of 'other mineral soils', with the N_{opt} values for deep silt soils all falling below RB209 (8^{th} edition) recommendations, but there was insufficient data to draw firm conclusions.

Table 14. Mean economically optimal N rate (N_{opt}) for spring barley and RB209 (8th edition) recommended N rates (feed), by soil type and SNS Index, for sites at which soil type is known. N_{opt} calculated using a break even ratio of 5. Figures in brackets show number of site x treatment combinations included in mean.

		Economically optimal N rates (kg/ha)											
		SNS Index											
Soil group		**0**		**1**		**2**		**3**		**4**		**5**	
Light sand	Mean	153	*(14)*	196	*(14)*	114	*(2)*	196	*(4)*	189	*(4)*		*(0)*
	RB209	110		80		50		30		0-30		0	
Other mineral soils	Mean	109	*(16)*	91	*(4)*	171	*(12)*		*(0)*		*(0)*	76	*(4)*
	RB209	160		140		110		70		30		0-30	

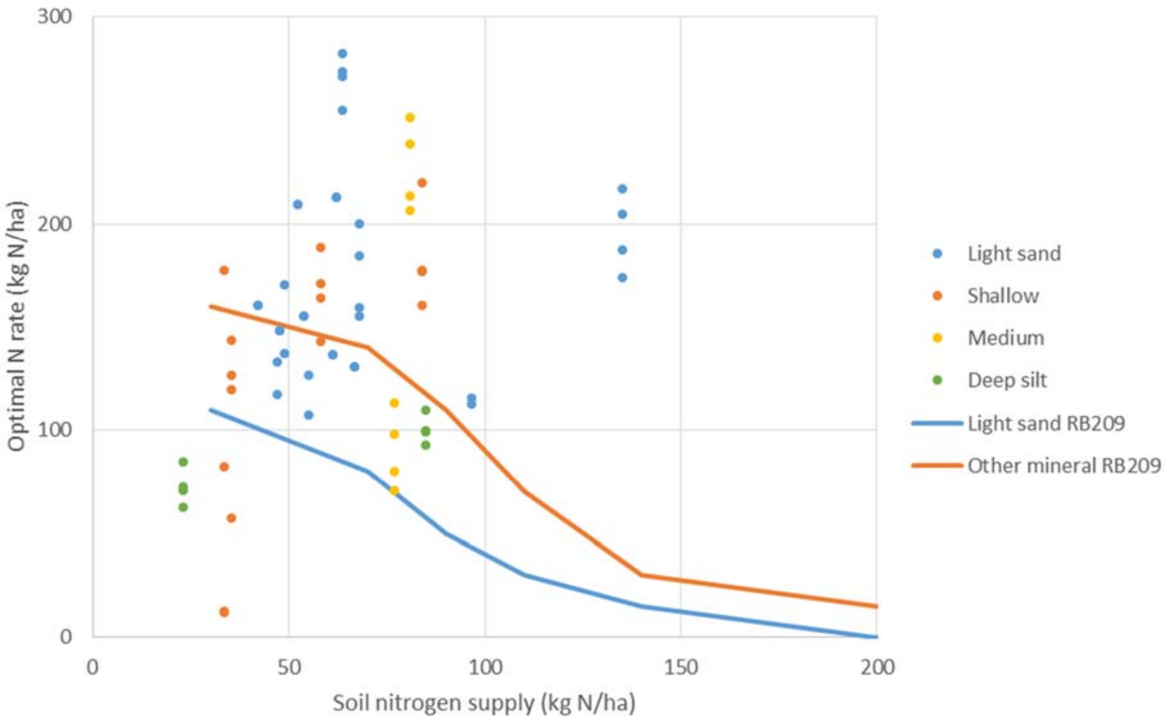

Figure 16. Effects of soil nitrogen supply (SNS) on economically optimal N rate (N_{opt}) of spring barley, calculated at a break-even ratio of 6. Solid lines show RB209 (8th edition) recommendations, plotted at the central value of each SNS Index.

For spring barley, the correlation between N requirement and yield was weaker than for winter wheat (Figure 17). Only 71 N response curves were available, giving R^2=0.2099. The slope of the line was slightly steeper than for winter wheat, at 16.7 kg/ha extra N required for each t/ha extra yield, or 27.8 kg N/ha extra fertiliser applied. RB209 (8th edition) recommendations were most accurate at a yield of 5 t/ha (Figure 18). Comparison of yield at N_{opt} against the difference between the RB209 (8th edition) recommendation and measured N_{opt} indicated that each additional t/ha above 5 t/ha would necessitate and additional 33 kg N/ha (Figure 16).

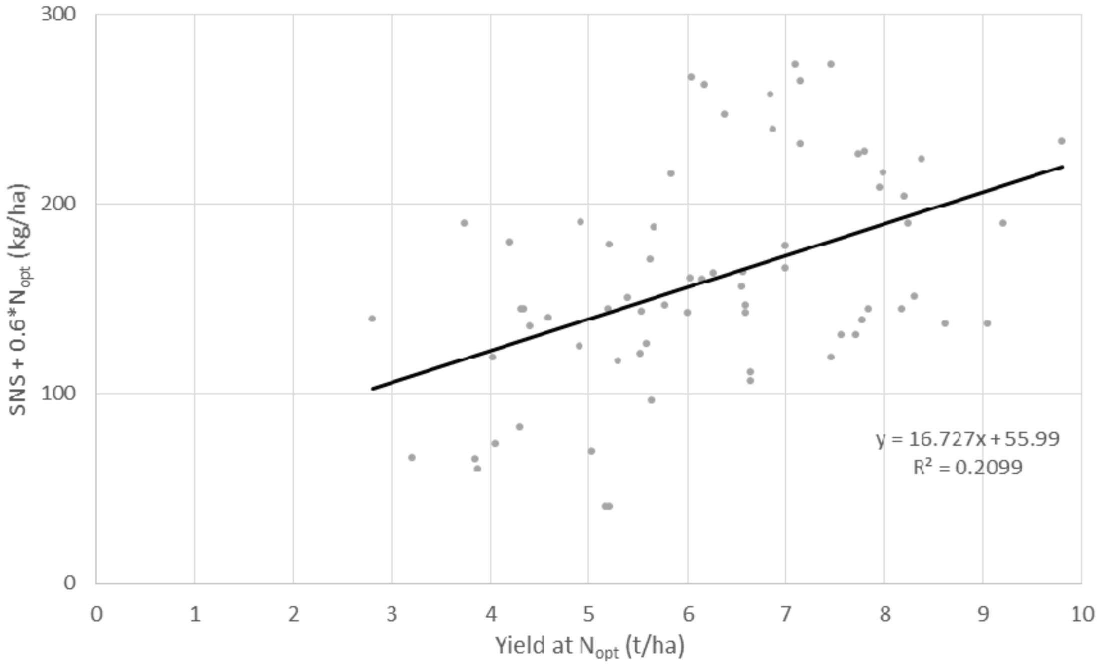

Figure 17. Effects of yield potential (yield at the economically optimal N rate (N_{opt})) on N requirement (site soil nitrogen supply + 0.6 * N_{opt}) for spring barley.

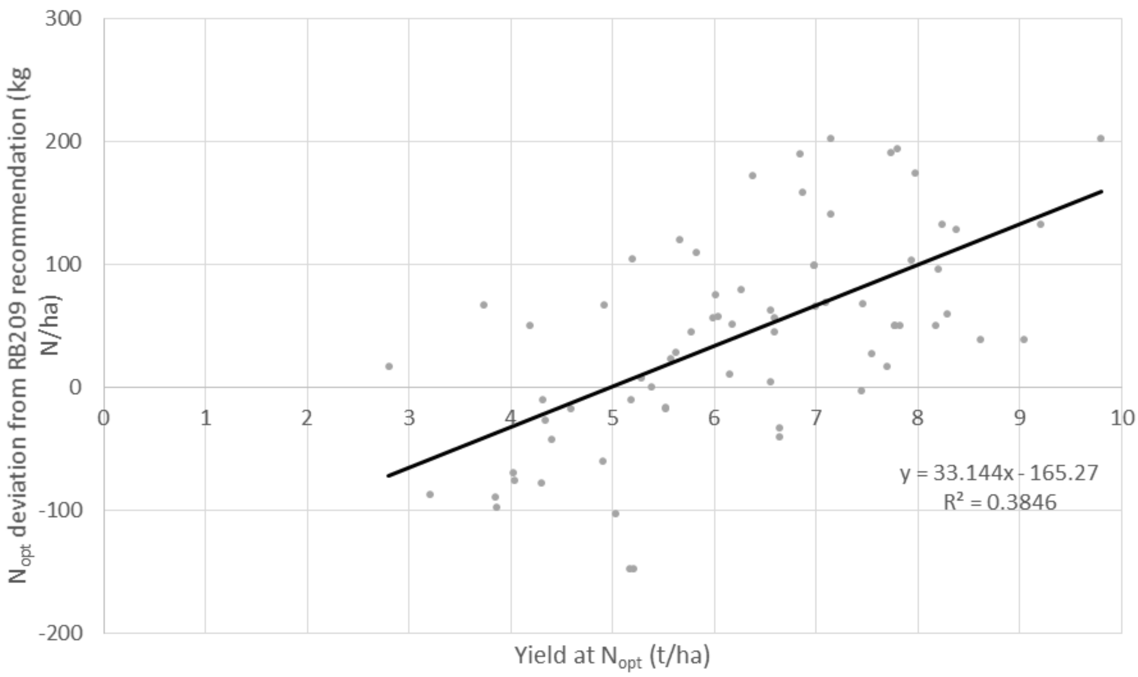

Figure 18. The effects of spring barley yield potential (yield at the economically optimal N rate (N_{opt})) in t/ha on the deviation of N_{opt} from the RB209 (8th edition) recommended N rate.

4.8.3. Grain quality

As for winter barley, N recommendations for spring barley must be lower than the economically optimal rate for yield, if malting quality targets are to be met. Of the 39 spring malting barley site x treatment combinations for which sufficient %N data was available to allow curve fitting, 29 exceeded 1.8% grain N at the N_{opt} for yield, and seven of these exceeded 1.8% grain N even at nil applied N (Figure 19). At RB209 (8th edition) recommended rates for spring barley, 14 of the 39 sites exceeded 1.8% grain N.

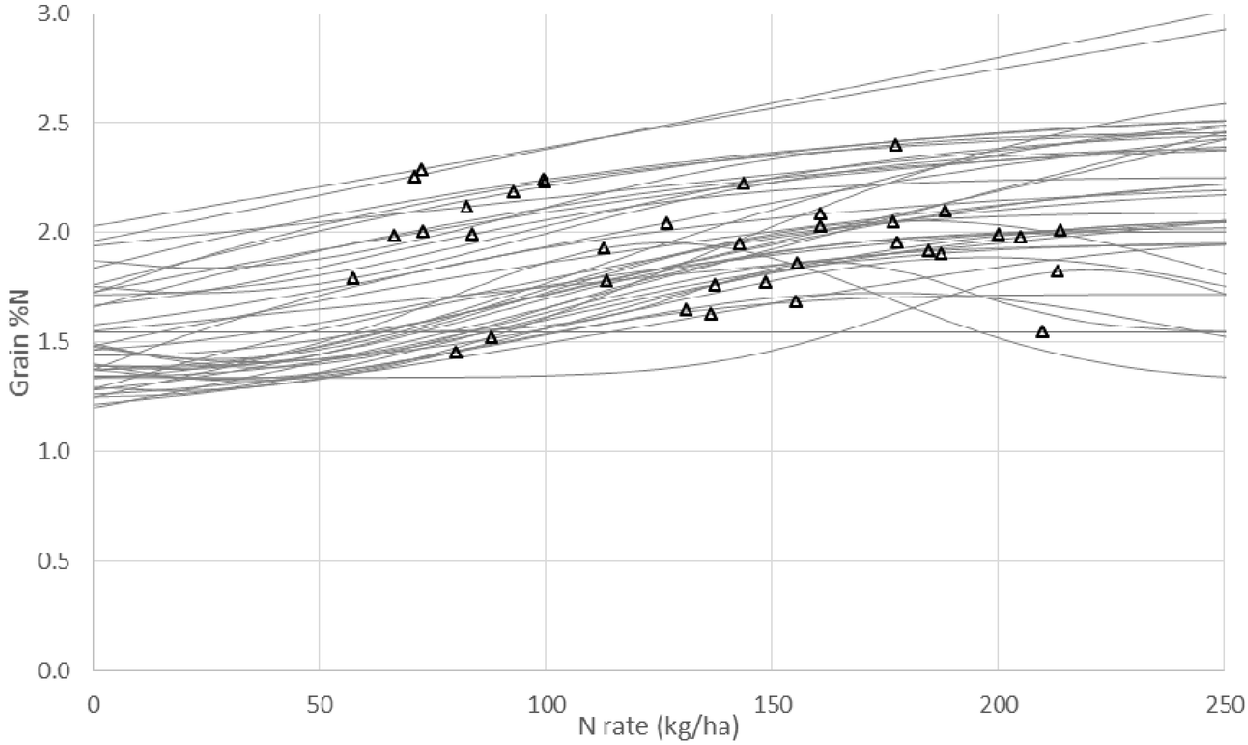

Figure 19. The response of grain %N to applied N rate for 39 spring malting barley site x treatment combinations. Open triangles show grain %N at the economically optimal N rate (N_{opt}).

Plotting grain %N against total N supply (including SNS and applied N) (Figure 20) did not bring the curves together as closely as for winter barley (Figure 12), but is still a useful way to consider what N recommendations are appropriate to meet malting quality targets. Given that grain quality targets could not be met even at nil N in seven site x treatment combinations, a realistic target was set of meeting targets in at least 60% cases (24 out of 39 site x treatment combinations). The resulting maximum N rates to meet 1.8% grain N (Table 15) are between those currently recommended for light sand soils and other mineral soils.

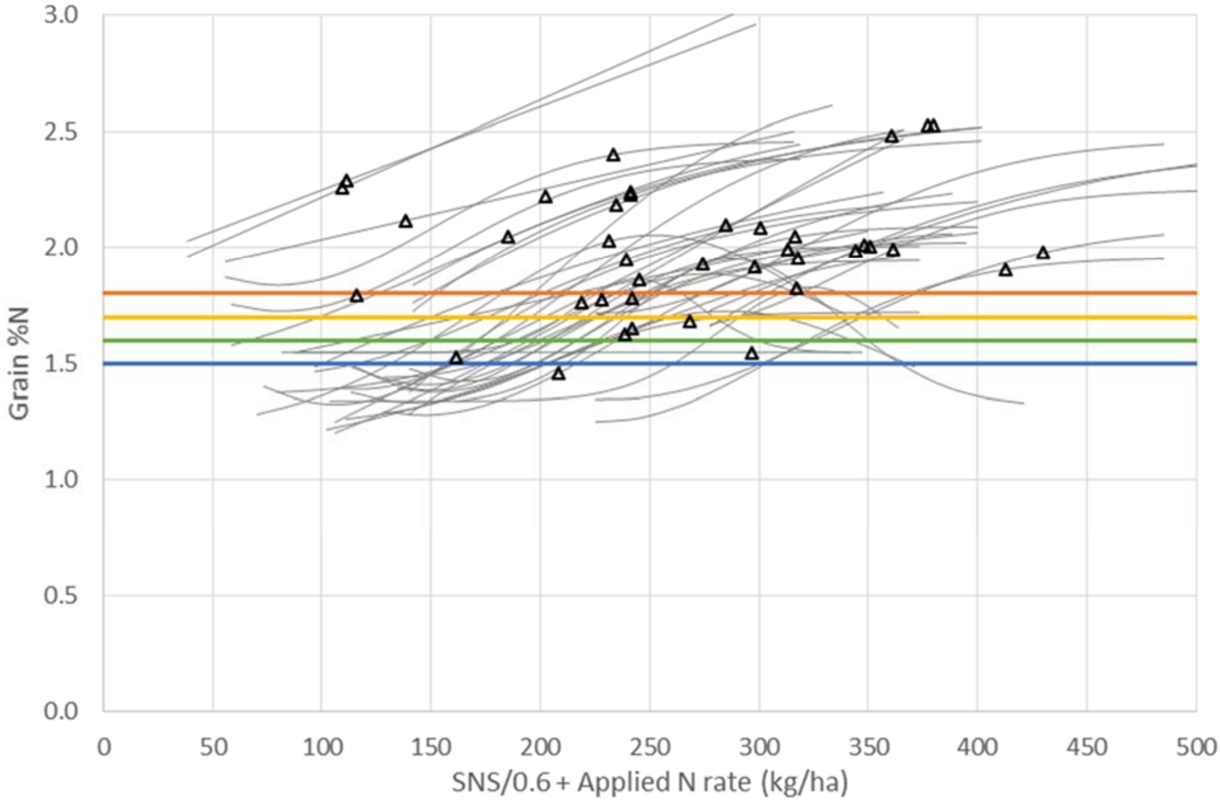

Figure 20. The effects of N supply on (including SNS and applied N, weighted for their different uptake efficiencies) on grain %N in spring malting barley. Horizontal lines show grain %N targets of 1.8% (orange), 1.7% (yellow), 1.6% (green) and 1.5% (blue). Open triangles show grain %N at the economically optimal N rate (N_{opt}).

Table 15. Maximum N supplies to meet grain %N targets in spring malting barley.

		Grain %N target			
		1.8%	**1.7%**	**1.6%**	**1.5%**
Maximum SNS/0.6 + applied N to meet grain %N target at ≥24/39 sites (kg N/ha)		205	175	145	*
Applied N at	50 kg/ha SNS (Index 0)	122	92	62	
	70 kg/ha SNS (Index 1)	88	58	28	
	90 kg/ha SNS (Index 2)	55	25	0	
	110 kg/ha SNS (Index 3)	22	0	0	

*Only 23 out of the 39 site x treatment combinations had <1.5% grain N at nil N.

4.8.4. Conclusions: spring barley N recommendations

For feed barley, the evidence suggests that N recommendations for sandy soils are too low; the mean deviation of the measured N_{opt} from RB209 (8th edition) recommendations was 90 kg N/ha, but this was based on a limited dataset, so we propose raising recommendations by only 20-30 kg N/ha. Recommendations for mineral soils should remain unchanged (Table 16).

For malting barley, the evidence shows that RB209 (8th edition) recommendations were suitable to meet a 1.8% N specification in at least 60% cases, and that this is difficult to improve on without severely compromising yield. It is recommended that rates for sandy soils be increased slightly, as for feed barley, and rates for other soils be reduced slightly. Further reductions of around 30 kg/ha are needed for each further 0.1% reduction needed in grain N.

Given that most combinable crops are grown in NVZs, users should be signposted to the NVZ guidance, and an asterisk placed by recommended N rates that exceed the N max limit, as follows.

Table 16. Proposed N recommendations for spring barley, valid for predicted yield 5.5 t/ha. Values in bold are different from those in the 8th edition of RB209.

	SNS Index						
	0	**1**	**2**	**3**	**4**	**5**	**6**
Feed barley							
Light sand soils	**140**	**110**	**70**	**50**	**0-40**	0	0
Other mineral soils	160*	140	110	70	30	0-30	0
Organic soils				70	30	0-30	0
Peaty soils						0-30	
Malting barley (up to 1.8% grain N)							
Light sand soils	**110**	**80**	40	0-40	0	0	0
Other mineral soils	**130**	**110**	**70**	**40**	**0-30**	0	0
Organic soils				**40**	**0-30**	0	0
Peaty soils						0	

***The N recommendation exceeds the N max limit that applies within 2013-16 NVZs. NB the N max limit is calculated for the whole of the area of a crop type grown on farm and not for individual fields. For more details see www.gov.uk/nitrate-vulnerable-zones**

The evidence described above shows that the relationship between yield potential and N requirement is the same for spring barley as for winter barley and winter wheat. Hence we propose the same 20 kg/t yield adjustment, which again will improve consistency between RB209 and NVZ regulations:

"Research has shown that the economically optimal rate of N fertiliser increases with yield. Where previous experience of growing spring barley indicates that yields above 5.5 t/ha can be realistically expected, the recommended rate should be increased by 20 kg N/ha for each t/ha additional yield, up to a maximum yield of about 10 t/ha. Similarly for low yielding

crops, the recommended rate should be reduced by 20 kg N/ha for each t/ha reduction in expected yield."

No changes are proposed to the advice on N timings because no new data was available. The second paragraph of text for malting barley should be clarified as follows:

"Apply all the nitrogen by early stem extension but not after end March. Where the target grain %N is below 1.8%, **the nitrogen rate from the malting section of the table above should be adjusted as necessary for predicted yield, then reduced by approximately 30 kg N/ha to achieve 1.7% grain N or 60 kg N/ha to achieve 1.6% grain N.** Grain %N may be diluted in high yielding crops. This nitrogen should all be applied by mid-March."

4.9. Spring oats, rye and triticale N requirement

No new data was available to review the N requirements of spring oats, rye or triticale, so it is proposed that no changes be made to the recommendations.

4.10. Winter oilseed rape N requirement

4.10.1. "Fertiliser Manual (RB209)" advice and NVZ guidance

In RB209 (8^{th} edition) Section 4 (p.115), autumn N could be applied to the seedbed or as a top dressing to encourage autumn growth. A table was presented of N recommendations for autumn and winter sown oilseed rape. The recommended N rate depended on the SNS Index and the soil type, with the maximum recommendation being 220 kg N/ha. Extra N was recommended for crops with high yield potential, at 30 kg N/ha extra for each 0.5 t/ha yield increase over 3.5 t/ha, up to 4.5 t/ha. When the total N to be applied was less than 100 kg N/ha it was recommended that this should be applied in one dressing during late-February-early March at the start of spring growth. For amounts greater than 100 kg N/ha it was recommended that half should be applied at the start of spring growth and half by late March-early April.

Under Nitrate Pollution Prevention Regulations (2015), the N max limit for winter oilseed rape is 250 kg N/ha, including up to 30 kg N/ha in autumn. N max limits were mentioned on p.50-51 in RB209 (8^{th} edition) Section 1.

4.10.2. Review of new information

The current link between yield potential and N requirement was added into the RB209 recommendations in 2010 and the consultation did not indicate that further improvement is required in this area of oilseed rape N nutrition. However, the consultation did indicate a need to review the N timings for oilseed rape particularly with reference to 'canopy management' principles.

The majority of research carried out on oilseed rape N timings is included in AHDB Cereals & Oilseeds reports OS49 (Lunn *et al*., 2001), PR447 (Berry & Spink, 2009), PR494 (Berry *et al*., 2012) and Topic Sheet 103 (2009). These projects developed 'Canopy Management' principles for applying sufficient N fertiliser to achieve an optimum GAI of 3.5 units by mid-flowering, with additional 30 kg N/ha applied at yellow bud / early flowering for each additional 0.5 t/ha of yield potential above 3.5 t/ha. These projects showed that the Canopy Management principles predicted the N_{opt} well (Berry *et al*. 2011; Figure 21). In fact the Canopy management principles predict N rates which are usually within 10-20 kg N/ha of RB209.

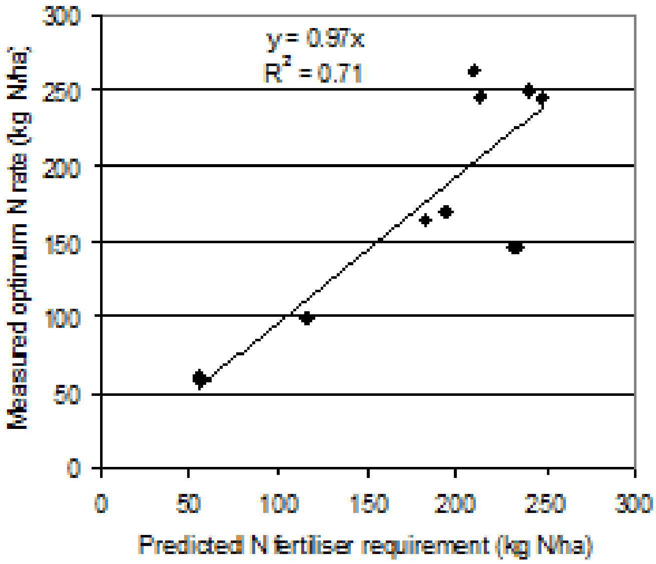

Figure 21. Relationship between the N fertiliser requirement predicted using Canopy Management principles. Each data point represents the mean value across cultivar and N timing treatments for an individual experimental site. From Berry et al. (2011).

These projects also showed that crops with a GAI of more than one just before the start of stem extension will often undergo a yield increase if the first N dressing is delayed until after the currently recommended first dressing timing of late February-early March (start of spring growth). Yield increases of between 0.2 and 0.4 t/ha were observed in experiments at Nottingham University (1996), ADAS Boxworth (2006) and ADAS Rosemaund (2010) due to avoidance of producing an over-large canopy at flowering and less lodging. There were exceptions which included experiments in 2007 where the GAI was above one, but delaying N did not increase yield. The reason for this was attributed to a very dry spring which delayed uptake of the early N treatments. Also at ADAS Rosemaund in 2008, delaying N did not increase yield even though the GAI was 1.36 units. This effect was attributed to the very low SMN following winter of just 12 kg N/ha which probably resulted in the delayed N management strategy running out of N. It should be recognised that none of the delayed N treatments described about significantly reduced yield. The information described above was distilled into AHDB Cereals & Oilseeds Topic Sheet 103, which recommends delaying the first N dressing for crops with a combined SMN plus crop N content at the end of winter of >100 kg N/ha (which often occur for crops with a GAI of more than one unit).

Experiments describing the effect of foliar N (solution of urea at 20 kg N per 100 litres) are described in AHDB Cereals & Oilseeds PR481 (Berry & Roques, 2011) and Innovate UK Project 101087. These projects collated data from 29 foliar N response experiments to show that the average seed yield increase to foliar N (30 to 60 kg N/ha) applied between mid-flowering and two weeks after the end of flowering was 0.3 t/ha. There was an average reduction in oil content of 0.7% associated with the use of foliar N which resulted in an increase in gross output of 0.26 t/ha. The experiments showed that the same yield response occurred with 40 kg N/ha foliar N irrespective of whether the crop had already received an optimal amount of soil applied N and irrespective of timing between mid-flowering and two weeks after the end of flowering. It was shown that foliar N should be applied in cool conditions (< 19^{o}C).

No new information was available for improving recommendations about the use of autumn N on winter oilseed rape.

4.10.3. Conclusions: winter oilseed rape N recommendations

No changes are required to the N rates in the 8th edition of RB209, except to add signposting to N max limits in the NVZ guidance, as for cereals (Table 17).

Table 17. Proposed N recommendations for winter oilseed rape. Values in bold are different from those in the 8th edition of RB209.

	SNS Index						
	0	**1**	**2**	**3**	**4**	**5**	**6**
Autumn	30	30	30	0	0	0	0
Spring							
All mineral soils	220	190	160	120	80	40-80	0-40
Organic soils				120	80	40-80	0-40
Peaty soils						40-80	

***The N recommendation exceeds the N max limit that applies within 2013-16 NVZs. NB the N max limit is calculated for the whole of the area of a crop type grown on farm and not for individual fields. For more details see www.gov.uk/nitrate-vulnerable-zones**

We propose that the N timings should be amended in bold as follows;

“Autumn nitrogen can be applied as seedbed or as a top-dressing to encourage autumn growth but research suggests that crops sown after early September are unlikely to respond.

“If the green area index (GAI) of the canopy measured towards the end of winter is less than 1.5, or less than 2.0 with an SMN in the top 60 cm soil of less than 25 kg N/ha, apply the nitrogen in two equal splits at the start of spring growth (end February-early March) and green bud (mid-March - early April), with any additional nitrogen for crops yielding above 3.5 t/ha applied between yellow bud and early flowering.

“Where the green area index (GAI) of the canopy measured towards the end of winter is greater than 2.0, or greater than 1.5 with an SMN in the top 60 cm soil of at least 25 kg N/ha, then the first nitrogen should be reduced to between zero and 40 kg N/ha.

“Foliar N applied as a solution of urea (20 kg N per 100 litres) applied at 40 kg N/ha between mid-flowering and two weeks after the end of flowering will often increase gross output by an average of 0.25 t/ha, and this may occur even where the optimum amount of soil applied N has been applied. Temperature at application should be less than 19^{o}C. The economic benefit of this treatment will depend upon the cost of the product and the price of oilseed rape. Note that this foliar applied N contributes towards the N max allowance.”

4.11. Spring oilseed rape, linseed and sunflower N requirement

No new data was available to review the N requirements of spring oilseed rape or linseed, so it is proposed that no changes be made to the recommendations.

The only available information for sunflowers from the UK is the Growers’ Guide published by AHDB Cereals & Oilseeds (Cook, 2009), which concludes that nitrogen fertiliser applications of more than 25-50 kg N/ha are rarely required and N fertiliser is often unnecessary altogether. The National Sunflower Association of the USA (http://www.sunflowernsa.com) offers no general nutrition advice, but provides a link to a recently developed N calculator for sunflowers grown in North Dakota (https://www.ndsu.edu/pubweb/soils/sunflower/), which is based on yield responses. Depending on the data entered, this calculator advises 0-140 kg N/ha, with choices most reflective of the likely situation in the UK resulting in recommendations within the 0-50 kg/ha range given in the UK Growers’ Guide. The following text will be added to the “Nutrient Management Guide (RB209)”:

“In typical arable rotations, sunflowers are likely to benefit from 25-50 kg N/ha. Nitrogen fertiliser is unlikely to be required in situations where the soil N supply is high. Over-

application of N can reduce yield and oil content due to excessive vegetative development, which encourages disease and delays maturity.”

4.12. Sulphur requirements for cereals and oilseed rape

4.12.1. “Fertiliser Manual (RB209) advice and AHDB recommendations

RB209 (8th edition) Section 1 (p.43-44) provided background information on sulphur including sulphur deposition, the occurrence of sulphur deficiency and diagnostic methods.

Section 4 contained sulphur recommendations for specific crops, as follows:

- All cereals (p.114): “Cereals are becoming more responsive to sulphur as atmospheric deposition of sulphur declines. See page 43 for more details and a map showing current deposition and areas where deficiency could occur. Where deficiency has been recognised or is expected, 25-50 kg SO_3/ha as a sulphate-containing fertiliser should be applied in early spring before the start of stem extension.

  “Sulphur deficiency can be diagnosed by analysing whole plant shoots sampled at stem extension. A value of less than 0.2% S in dry-matter indicates deficiency. At this stage of growth there is little opportunity to correct any deficiency, but identifying deficiency allows remedial action to be taken for subsequent crops.”

- Oilseed rape and linseed (p.118-119): “Oilseed rape will respond to an application of sulphur on all mineral soils. Spring crops may be less susceptible to sulphur deficiency than winter crops. See page 43 for more details and a map showing current deposition and areas where deficiency could occur. Where deficiency has been recognised or is suspected, 50-75 kg SO_3/ha as a sulphate containing fertiliser should be applied in early spring.

  “Sulphur deficiency can be diagnosed by analysing young fully expanded leaves at early flowering stage. Critical values of less than 0.4% S in dry-matter or an N: S ratio of more than 17: 1 indicate deficiency. At this stage of growth there is little opportunity to correct any deficiency, but identifying deficiency allows remedial action to be taken for subsequent crops. The leaf sulphate: malate ratio test can predict potential deficiency at an earlier stage of growth. Sulphur deficiency symptoms include stunting, interveinal yellowing of middle and upper leaves and pale flower petals.”

AHDB Cereals & Oilseeds updated their guidance on ‘Sulphur for cereals and oilseed rape’ in 2014 (Information Sheet 28). The Information Sheet is broadly in agreement with the recommendations in RB209 (8th edition), but provides additional guidance to help growers assess the likely responsiveness of cereal crops to S.

For cereals, where a response to S is likely, the guidance is to apply 50 kg/ha SO_3 to wheat crops in early March to early May, and 25-50 kg/ha SO_3 to barley crops in mid-March to mid-April. The guidance notes that not all winter cereal crops will require S and includes a risk matrix based on soil type and over-winter rainfall to estimate likely responsiveness of winter wheat and winter barley to S (Table 18).

Table 18. Estimating likely responsiveness of winter wheat and winter barley to S (from AHDB Cereals & Oilseeds Information Sheet 28)

	Winter rainfall (Nov–Feb)		
Soil texture	Low (<175mm)	Medium (175–375mm)	High (>375mm)
Sandy	High		
Loamy and coarse silty	Low	High	
Clay, fine silty or peaty	Low		Intermediate

For oilseed rape, the guidance is to apply 50-75 kg/ha SO_3 to all winter oilseed rape grown on mineral soils in late February to early March.

The Information Sheet notes that spring crops are less likely to respond to S and recommends that "if deficiency is suspected, however, tissue and grain analysis can be used to make a diagnosis and the deficiency should be treated, if necessary."

The guidance in both RB209 (8th edition) and the AHDB Information Sheet avoided specific S recommendations for spring crops (cereals and OSR). Consequently, it was not clear whether the S recommendations only applied to winter crops or to both winter and spring sown crops.

4.12.2. Review of new information: sulphur for cereals

The need for sulphur in some cereal crops was first mentioned in the 6th edition (1994) of Defra's "Fertiliser Recommendations (RB209)" although a recommended rate was not given until the 7th edition (2000) (25-40 kg/ha SO_3) and this was increased slightly to the current 25-50 kg/ha SO_3 in the 8th Edition (2010). Zhao *et al*. (2002) reviewed published and unpublished research on the sulphur response to cereals and found that in most cases, in the trials that were responsive to S, 50 kg/ha SO_3 was sufficient for wheat and barley. The majority of AHDB Cereals & Oilseeds-funded research has focussed on the response to S in winter sown wheat and barley, although Zhao *et al.* (2005) and Carver (2005) tested the effect of S application on both winter and spring sown barley.

Carver (2005) tested the effect of S application (0 and 50 kg/ha SO_3) in 90 winter wheat experiments, 45 winter barley experiments and 20 spring barley experiments between 2002 and 2004; significant yield responses to S were recorded in 10% of the winter wheat trials, 13% of the winter barley trials and 15% of the spring barley trials. Cussans *et al.* (2007) subsequently collated data from 204 field experiments on S response in cereals and used detailed analysis of a subset of 88 winter wheat trials to determine the key factors affecting yield response to S in cereals. A risk matrix was developed based on the relative contribution of over-winter rainfall, soil type and sulphur deposition, and was published in AHDB Information Sheet 28 'Sulphur for cereals and oilseed rape' to guide cereal growers on S applications to cereals.

Since the last revision of RB209 in 2010, six S rate response experiments on winter wheat have been carried out as part of AHDB Cereals & Oilseeds Project Report 522 to quantify the S supply from farm manures to winter wheat crops (Sagoo *et al.*, 2013). The project included field experiments at three sandy loam sites over three harvest years (2 years at each site; 6 harvest years in total) at Frostenden (Suffolk), Brockhampton (Herefordshire) and Woburn (Bedfordshire). In each of these experiments, manufactured S fertiliser was applied as potassium sulphate at five rates (0, 12.5, 25, 50 & 75 kg/ha SO_3). All fertiliser treatments were applied in early spring and replicated 4 times and arranged in a randomised block design.

A significant ($P<0.10$) yield response to S was observed at only 1 of the 6 sites; application of S fertiliser increased yields ($P=0.06$) by about 1.2 t/ha at Woburn in 2011 and the S rate for maximum yield was 25 kg/ha SO_3. Application of S fertiliser at the Frostenden site in 2009 increased yields by c.0.6 t/ha; this yield increase was achieved at the first S rate tested (12.5 kg/ha SO_3), but was not statistically significant ($P>0.10$).

Hoel (2011) tested the effect of S fertilisation in 26 winter wheat field trials in Norway between 2004 and 2006. Application of S fertiliser significantly increased grain yields on sandy soils in southeast Norway and on loam and silt loam in central Norway, whereas no yield increase was found on clay soils. Generally there were no significant yield responses at application rates greater than 30 kg/ha SO_3. The results presented by Hoel (2011) from Norway are broadly in agreement with results from research carried out in the UK.

Sulphur is also an important factor determining the quality of wheat and barley through its effects on the synthesis of the S-amino acids cysteine, cysteine and methionine. AHDB Cereals & Oilseeds-funded research prior to the last revision of RB209 has demonstrated the positive effect of S on bread making quality (Zhao *et al*., 1999a, 1999b) and the malting quality of barley (Zhao *et al*., 2005). Recent research since the last revision of RB209 has also demonstrated the positive effect S can have on bread making quality through reducing the acrylamide-forming potential of wheat (Shewry *et al*., 2009; Curtis *et al*., 2014). The study by Curtis *et al*. (2014) analysed grain from the S response experiments described by Sagoo *et al*., (2013); importantly Curtis *et al*. (2014) also found a reduction in acrylamide forming potential of wheat from experiments at the Brockhampton site which had not shown a yield response to S. AHDB Cereals & Oilseeds Project Report 525 concluded that the optimum S rate for minimising acrylamide formation in bread making wheat was 50 kg SO_3/ha (Curtis *et al*. 2014).

The literature review did not identify any research (pre or post last review of RB209) looking at the effect of S application on oats, rye or triticale.

4.12.1. Review of new information: sulphur for oilseed rape

Fertiliser S recommendations for OSR were first included in the 6th Edition (1994) of Defra's "Fertiliser Recommendations (RB209)". The recommended S rate (50-75 kg/ha SO_3) was based on a limited number of experiments carried out in the early 1990s. Table 19 summarises details of S experiments on OSR carried out prior to the last revision of RB209 (8th Edition); review of these shows that most experiments have looked at winter (rather than spring) OSR, and that the earlier research on OSR and S tended to focus on glucosinolates (Withers, 1992; Milford *et al*., 1994), and later research on diagnosis of S deficiency (Withers, 1995; Blake-Kalff *et al*., 2000, 2004; Carver, 2005), rather than dose responses in terms of yield. There are only two AHDB Cereals & Oilseeds-funded projects (Withers, 1992; Blake-Kalff *et al*., 2000) and one other project (McGrath & Zhao, 1996) on winter OSR. There is only one AHDB Cereals & Oilseeeds-funded project (Chalmers *et al*., 1998) on spring OSR, which included sufficient rates of S to give dose-response information. Of the experiments on winter OSR, only two (Withers 1992; McGrath & Zhao, 1996) gave a significant yield response to S (and in both these experiments, a yield response was recorded at one site only).

Table 19. Summary of OSR sulphur experiments carried out prior to the previous RB209 revision.

Reference	AHDB report	Winter/ Spring	Harvest year(s)	SO_3 rates (kg/ha)	Number of trials	SO_3 rate to achieve max yield
Withers (1992)	OS2	WOSR	1992	0,25,50,75,125,200 50,125 50	5 5 5	25-125
Milford *et al.,* (1994)	OS8	WOSR	1994	0,125,250	4	
Withers (1995)	OS11	WOSR		100 or 125	16	
McGrath and Zhao (1996)	N/A	WOSR	1991, 1992, 1994	0,25,50,100	3	50
Chalmers *et al*. (1998)	OS34	SOSR	1995-1997	0, 25, 50, 100, 200 0, 25. 50, 100	6 5	50
Blake-Kalff *et al.,* (2000)	PR217	WOSR	1997, 1998	0,12,25,50,100,200	2	*No effect of S*
Riley *et al*., (2000)	PR222		1998, 1999	0,75	2	
Blake-Kalff *et al.,* (2004)	PR327	WOSR SOSR	2000-2003	0,50,200	3	
Carver (2005)	PR374	WOSR	2002, 2003, 2004	0,110	28	

In 2002, AHDB Cereals & Oilseeds Topic Sheet 66 increased the S recommendation for winter OSR to 75-100 kg/ha SO_3. This recommended S rate was based on the same limited number of experiments as Defra's "Fertiliser Recommendations (RB209)". The decision to increase the recommended S rate to 75-100 kg/ha SO_3 in TS66 was based on the view of the authors, who considered that (i) rates of atmospheric S deposition had declined since the initial S response experiments, and were set to decline further; (ii) the work by McGrath & Zhao (1996) stated that any increase in yield was unlikely beyond 100 kg/ha SO_3; and (iii) OSR yields were projected to increase, potentially increasing crop demand for S. In fact, between 1994 and 2004 there was only minimal OSR yield improvement equivalent to 0.022 t/ha per year, but since 2004 the yield trend shows an average increase of 0.075 t/ha per year (Knight *et al*. 2012).

When Defra's "Fertiliser Manual (RB209)" was reviewed in 2008, comment was sought from the farming industry with regards to fertiliser S recommendations. The consensus view was that current recommendations for OSR were adequate and that there were no new data which would justify increasing OSR S recommendations, although comment was made that they should probably be towards the higher end of the 50-75 kg/ha SO_3 range quoted (Keith Goulding, pers. comm.). When AHDB Cereals & Oilseeds updated their guidance on 'Sulphur for cereals and oilseed rape' in 2014 (Information Sheet 28) the S recommendations were revised back to 50-75 kg/ha SO_3 to be consistent with advice in RB209.

Since the last revision of RB209 in 2010, 12 S rate response experiments on winter OSR have been carried out to determine optimum S application rates (Table 20). Between 2011 and 2013 CF Fertilisers (formally GrowHow) and Monsanto funded eight S rate response experiments on winter OSR, and have agreed to contribute this previously unpublished experimental S rate response data on OSR to the RB209 revision, representing a significant 'in-kind' contribution to the project. Following on from this work, an on-going AHDB and industry funded project (AHDB Cereals & Oilseeds project 216-0007) includes an additional ten S rate response experiments on winter OSR between 2014 and 2017, four of which were completed in 2014 and 2015.

Table 20. Summary of recent sulphur response experiments on oilseed rape. Experiments in harvest years 2014 and 2015 were part of AHDB Cereals & Oilseeds project 216-0007. Experiments in harvest years 2011-13 were funded by CF Fertilisers and Monsanto. Site code HM = ADAS High Mowthorpe, North Yorkshire; RM = ADAS Rosemaund, Herefordshire; TT = ADAS Terrington, Norfolk; FR = Frostenden, Suffolk; WB = Woburn, Bedfordshire; GT = ADAS Gleadthorpe, Nottinghamshire.

Harvest year	**Site**	**Soil type**	**Optimum SO_3 rate (kg/ha)**		**Approx yield increase from S fertiliser (t/ha)** †	**Mean site yields (t/ha)** ‡
			Yield	Yield & oil content		
2011	HM	Shallow silty clay loam over chalk	62	58	0.6	2.9
	RM	Sandy loam	45	45	0.8	4.6
	TT	Sandy clay loam	63	63	0.4	2.6
2012	HM	Shallow silty clay loam over chalk	*No response*		-	3.8
	RM	Sandy loam	112	30	0.3	4.0
	TT	Sandy clay loam	*No response*		-	3.6
2013	RM	Sandy clay loam	82	Not calculated	1.0	2.7
	TT	*Silty clay loam*	*No response*		-	4.7
2014	FR	Loamy sandy	72	71	4.0	5.0
	WB	Sandy loam	57	57	3-4	5.0
2015	GT	Sandy loam	30	30	0.9	5.2
	RM	Sandy loam	44	44	0.5	5.2

† Approximate yield increase from S fertiliser is the difference in yields between the zero S control treatment and the average yield from all other S fertiliser treatments (i.e. 30 to 150 kg/ha SO_3 application rates).

‡ Mean site yield is the average yield from all S fertiliser treatments, excluding the zero S control treatment.

In each of these experiments, manufactured S fertiliser was applied as ammonium sulphate at six rates (0, 30, 60, 90, 120 and 150 kg/ha SO_3) and N as ammonium nitrate at two N rates (balanced for the N in the ammonium sulphate and sufficient to achieve target yields of 3.5 t/ha and 5.0 t/ha, respectively) to determine optimum S rates and whether increasing the N rate increases the S requirement. Sulphur fertiliser was applied in late February/early March at or before GS 3.3. All fertiliser treatments were replicated either three or four times and arranged in a randomised block design.

Nine of the 12 recent experiments showed a yield increase from S fertiliser, with yield increases varying from 0.3 to 4.0 t/ha (Table 20). In all experiments where there was a response to S, a linear plus exponential response curve was fitted to the yield data and the economic optimum S rate was calculated based on the current value of OSR and price of S fertiliser. Economic optimum S rates were calculated based on OSR seed yields and also taking into account oil yields. In most cases there was very little difference in the optimum S rate between the two methods of calculation; with the exception of the Rosemaund site in 2012. At this site, increasing S application rates caused a reduction in seed oil content and therefore whilst the economic optimum S rate for OSR yields was 112 kg/ha SO_3, this optimum reduced to 30 kg/ha SO_3 (i.e. the lowest rate of SO_3 tested) for oil yields. Economic optimum S rates at the other sites varied between 30 and 80 kg/ha SO_3 and were therefore mostly within or slightly below the current RB209 recommendation range of 50-75 kg/ha SO_3.
The literature review did not identify any other new (i.e. since 2009) published research from Northern Europe looking at the effect of S application on OSR yields.

4.12.2. Conclusions: sulphur

For cereals, the main conclusions are:

- There has been limited new work looking at S response in cereals and there was no evidence to change the RB209 (8th edition) recommended rate of 25-50 kg/ha SO_3.
- In view of the limited work on spring sown cereals and in the absence of any research to quantify the S response from other cereal crops (oats, rye and triticale), we recommend the 25-50 kg/ha SO_3 recommendation is applied to all winter and spring sown cereal crops in high or intermediate risk situations or where a deficiency has been identified.
- Not all cereal crops will respond to S. We recommend that the risk matrix developed by Cussans *et al*. (2007), and published in AHDB Information sheet 28, is included in a revised RB209.
- There has been no new work looking at the effect of S application timing and there is no evidence to change the current RB209 guidance to apply S in early spring before the start of stem extension.

The following text should replace the text relating to sulphur currently on p114:
“Not all cereal crops will respond to sulphur. Use the risk matrix to assess the risk of deficiency. Where deficiency has been recognised or is expected in winter or spring sown cereals, apply 25-50 kg/ha SO_3 as a sulphate-containing fertiliser in early spring before the start of stem extension.”

For cereals, the main conclusions are:

- Recent work on winter OSR supports the RB209 (8th edition) recommended rate of 50-75 kg/ha SO_3.
- In view of limited work specifically on spring OSR, we recommend that the 50-75 kg/ha SO_3 recommendation is applied to both winter and spring OSR.
- There has been no new work looking at the effect of S application timing. We recommend that the revised RB209 includes guidance on application timing currently in AHDB Cereals & Oilseeds Information Sheet 28 to apply in late February to early March.

The following text should replace the text relating to sulphur currently on p114:
"Most winter and spring sown oilseed rape grown on mineral soils will respond to an application of sulphur. Apply 50-75 kg/ha SO_3 as a sulphate containing fertiliser to all winter and spring sown oilseed rape grown on mineral soils in late February to early March."

5. Knowledge gaps

A summary of the knowledge gaps and their level of priority is given in Table 21. Note that knowledge gaps relating to the estimation of soil N supply, P, K, Mg and micronutrients are described in the review of the principles section. High priority knowledge gaps include; N management to achieve grain protein targets of high yielding milling varieties and spring barley, Optimum N rates for winter and spring oats, and spring wheat. N management for crops used for anaerobic digestion.

Table 21. Summary of knowledge gaps relating to cereals and oilseeds, and suggestions for work to address these gaps.

Area	Knowledge gaps	Relevant work underway	Future work	Level of priority
Winter wheat N	Achieving protein spec of high yield milling varieties			High
Winter barley N	Optimal rates and timing of N	AHDB project 216-0006		High
Spring barley N	Optimum N for wide range of malting %N specs on modern varieties			High
Winter triticale N	Optimal N rates on sandy soils. Optimal N timing.			Low due to low area
Winter oats	Optimal N rates and timings for modern varieties		Full N response experiments on range of soils	High
Winter rye	Optimal N rates for modern varieties, both for grain & AD		Include effects on biogas yield	High

Area	Knowledge gaps	Relevant work underway	Future work	Level of priority
Spring wheat, rye, triticale and oats	Optimal N rates for modern varieties		Spring wheat increasing in black grass areas	High
Spring oilseed rape & linseed N	N requirement of modern varieties			Low due to low area
General N	Autumn and placed N for direct drilled (or very minimal till) crops in presence of straw		Evaluate response of autumn sown wheat and barley	Medium (as direct drill increasing)

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8. Appendix 1: 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