AC0221 Annex 1

Optimal N application timings for maximising yield and grain quality – literature review

Summary

Winter wheat: Defra RB209 guidelines recommend that N should be applied from just before the start of stem extension (Mid February to mid March) until mid-stem extension (early May), with later amounts of about recommended for milling wheat to increase grain protein. This guidance is based on studies done in the 1980s, and no systematic N timing studies have been carried out since then, so it is not possible to conclude whether the current advice on timings is optimal or not. Certainly there appears to be a requirement to re-test the optimum timings due to significant changes in average wheat yields and farming practices, such as the end of stubble burning, increase in straw incorporation and reduction in tillage, in the last 20 years. From the published research that has been done on N timing in wheat it seems likely that RB209 guidelines are correct in that N for yield should not be applied after the end of leaf production (GS39), however evidence is conflicting about whether or not yields may be reduced by applying a significant amount of N before the start of stem extension (Petersen, 2004; Howard *et al*., 2002; Kindred *et al.,* 2009). Research carried out to identify the optimum N management for wheat grown as a bioethanol feedstock, RB209 recommended total N application rates should be reduced by 10-12% to optimise ethanol yield/ha (Clarke *et al*., 2008), and there is likely to be some benefit from applying a greater proportion of N in mid-February to mid-March. However, more evidence is needed to confirm that this change to timings is effective, and to quantify the benefit.

Winter barley: RB209 guidelines recommend that small proportion of the N may be applied before the start of stem extension between mid February and mid March with the bulk applied by early stem extension (GS31) in April. As with wheat the field experiments used to develop these guidelines were carried out in the 1980s (Lord & Vaughn, 1987) and few experiments have been carried out on N timings since then. Recent experiments funded by GrowHow UK Ltd and carried out by ADAS have shown that both yield and quality can be improved by applying N earlier than is recommended by RB209. Trials have shown that applying 50% of the N between late February and early March and 50% in mid to late March improves yield by an average of 0.3-0.5 t/ha and reduces grain N concentration by 0.07-0.1% which is important for malting quality. Alternatively, the earlier timings can allow use of 30 kg/ha less N to achieve the same yield as with RB209 timings. These trials also showed that the optimum N rates were 40 to 80 kg N/ha greater than recommended by RB209, which may be due to the higher yield potential of modern varieties. Using methods similar to those outlined in (Berry *et al*., 2008), it has been estimated that use of the earlier N timings could reduce the GHG emissions by 21 $kgCO_2e/t$ (3.7%) relative to RB209 timings. Use of the earlier timings to cut N application rates whilst maintaining yield would cut GHG emissions by 490 $kgCO_2e/ha$ (13.2%) or 73 $kgCO_2e/t$ (12.7%). Further work is ongoing to investigate whether these earlier timings increase the risk of lodging or nitrate leaching, and to confirm whether there are differences between 2-row and 6-row barley in optimal N strategy.

Spring barley: RB209 guidelines recommend that N should be applied between drilling and early stem extension (between early April and early May). All N applied to malting barley should be applied by the end of March to minimise grain protein. Overthrow (2005) showed that on average, the highest yields were achieved by applying N in two equal splits (seedbed and three-leaf stage). This gave an average yield increase of 0.11 t/ha across all N rates, and 0.19 t/ha at the highest N rate (200 kg N/ha), relative to a single application at the one-leaf stage. This indicates that yield increases could be achieved by applying N earlier than recommended in RB209, however, results from this study and McTaggart & Smith (1995) showed that changes in timing and the number of splits produced inconsistent effects on yield. Other studies outside the UK suggest that N may be applied at any time between sowing and tillering without impacting yield or quality. It has also been shown that RB209 recommendations underestimate the optimum N rate of modern spring barley varieties

(Overthrow, 2005; Sylvester-Bradley *et al*., 2008). There is no evidence that the RB209 recommended timings for N application can be improved for yield or grain quality.

Winter oilseed rape: RB209 guidelines recommend that 30 kg N/ha may be applied in autumn to fields with a low or moderate SNS. The main N applications are recommended to be split equally between mid February to early March and late March to mid April. Published literature and unpublished data indicate that the RB209 recommendation of 30 kg N/ha applied in autumn may be unnecessary for most crops, apart from possibly crops with a large amount of straw incorporated from the previous crop and with minimal soil cultivations. Evidence suggests that crops can take up sufficient N from spring applications to achieve the optimal canopy size for yield, and that spring applications of N are taken up more efficiently than autumn or winter applications. Currently autumn N is applied to 29% of oilseed rape crops at a rate of 37 kg N/ha and while further research is required to test the value of autumn N in different situations, it seems likely that autumn N could be applied to fewer crops. If current autumn N applications were reduced by half and the resulting net reduction in N use for these crops was 23 kg N/ha, then this would result in a total reduction in N use of 1,778 t for the UK (based on an average winter oilseed rape area of 533,000 ha between 2006 and 2008). This would equate to a reduction in GHG emissions of 29 kt CO_2e per annum. RB209 guidelines for oilseed rape could also be improved by applying spring N later to crops with large canopies following winter (Berry and Spink, 2009). This has been shown to increase yield by up to 0.36 t/ha, or reduce N application rate by up to 50 kg N/ha while maintaining yield. It is estimated that this size of effect will reduce the GHG emissions of cropping by 114 kgCO_2e/t (8.8%) relative to RB209 timings, at the optimum N rate. Use of the canopy management timings to cut N application rates whilst maintaining yield would have cut GHG emissions by 522 kgCO_2e/ha (12.4%) or 157 kgCO_2e/t (12.1%). However, it should be recognised that these gains will only apply to a proportion of crops which will vary by season.

Introduction

For the major crops wheat, barley and oilseed rape, research has been done to establish the optimal N application timings for maximising yield and grain quality. Much of this research has already been used in the design of the current Defra RB209 fertiliser recommendations (Anon, 2000) and the soon-to-be-published revised RB209 fertiliser recommendations (Anon, 2010), which guide farmers on how much N fertiliser to apply and when to apply it. In this review, for each of the crops winter wheat, winter barley, spring barley and winter oilseed rape, the recommended timings from the RB209 guidelines will be described, followed by a summary of recent research suggesting potential improvements to the RB209 guidance. The effects of these potential changes to N timings on yield and crop quality will be discussed, as well as the effects of altered timings on the risk of adverse weather conditions during or following fertiliser application. The RB209 timings described here are from the current (7^{th}) edition of the guidelines (Anon, 2000), but will not change in the forthcoming 8^{th} edition (Anon, 2010).

Estimates are also made of the Greenhouse gas (GHG) emissions savings which could be achieved by use of the improved N timings described. GHG emissions have been calculated that are directly associated with growing a crop and indirectly as a result of land use change due to changes in crop productivity. GHG associated with growing the crop have been calculated using the method of Berry *et al*. (2008). This method includes direct and indirect N_2O emissions from soil following the application of N fertiliser and following the incorporation of crop residues, and emissions associated with seed production, fertiliser manufacture, pesticides, field operations (fuel and machinery manufacture), and grain drying. Standard figures for seed, P, K, S and lime inputs, pesticides, energy associated with field operations and grain drying were used, whilst crop yield and N rate were varied. GHG emissions were calculated per hectare and per tonne of grain and expressed as kg of CO_2 equivalent (CO_2e) after accounting for the different global warming potentials of the greenhouse gases. GHG emissions associated with the manufacture, packaging and transport of ammonium nitrate fertiliser were assumed to be 7.11 kg CO_2e per kg N (Anon. 2007). Direct and indirect N2O emissions from soil were calculated following the IPCC methods detailed by McCarthy *et al*. (2010). Soil emissions of N_2O following the application of fertiliser N were assumed to be linearly related to N fertiliser rate as per IPCC Tier 1 methodology, with 0.0177 kg N_2O per kg N from direct emissions; plus 0.0105 kg N_2O per kg N indirect emissions from leaching and

0.0016 kg N_2O per kg N from volatilisation, giving a total of 0.030 kg N_2O per kg N, or 9.215 kg CO_2e per kg N. The global warming potential (GWP) used for N_2O is 310 kg CO_2e per kg N_2O, from IPCC (1997). Emissions associated with crop residues were linearly related to crop yield as per IPCC Tier 1 methodology, at 0.327 kg N_2O per t/ha for wheat, 0.322 kg N_2O per t/ha for oilseed rape and 0.302 kg N_2O per t/ha for winter and spring barley.

Winter Wheat – RB209 recommendations

The current and forthcoming RB209 fertiliser recommendations for winter wheat are that N fertiliser should be split between one and four applications, depending on the total amount of N to be applied, the risk of take-all, the shoot numbers and whether the crop is destined for feed or for bread-making. The total amount of N is determined using look-up tables which take account of the soil N supply (SNS), soil type and target grain protein levels.

Where the total N applied over the season is less than 120 kg N/ha, it should be applied as a single dressing, between early April and early stem extension (GS 31).

Where more than 120 kg N/ha is to be applied, there should be at least two application timings. Where shoot numbers are low, and/or there is a risk of take-all, 40 kg N/ha should be applied early, between mid-February and mid-March. The remainder should be applied as above, if below 120 kg N/ha, or split equally between two applications at the start of stem extension (not before April) and at least two weeks later (but not later than early May).

Where there is a need to boost protein levels to meet bread-making requirements, an additional application of around 60 kg N/ha foliar urea at the milky ripe stage may be applied. This is expected to increase grain protein, but not yield.

Winter Wheat – Additional literature on optimal timings for yield and crop quality

The last systematic N timings studies on UK wheat were conducted in the 1980s for the development of the RB209 guidelines. Given the significant changes in average wheat yields and farming practices since then, such as the end of stubble burning, increase in straw incorporation and reduction in tillage, it should be worthwhile to repeat these timing experiments.

The last major project on N timings for UK wheat was done between 1992 and 1998 (Stokes *et al*., 1998). This project investigated the principles of 'canopy management' which involve building an optimum sized canopy with a green area index (GAI) of between 5 and 7 by ear emergence and then to maintain this GAI during grain filling. This project effectively compared two N management systems and therefore did not include experiments for systematically comparing different N timings. The canopy management approach also involves aiming to build a GAI (green area index) of 2 by the start of stem extension (GS31). To achieve this, Stokes *et al*. recommended that if the SNS is <60 kg N/ha, 30-50 kg N/ha should be applied in March to promote tillering. Current RB209 recommendations use this guidance, stating that if the total N application rate is >120 kg N/ha (which only occurs at low SNS indices) and shoot numbers are low, 40 kg N/ha should be applied between mid-February and mid-March. The canopy management principles also stated that from GS31, wheat crops take up N at a minimum rate of 2 kg/ha/day. This uptake rate gave rise to the recommendation by Stokes *et al*. that large N rates should be split between two applications, timed to allow time for sufficient N to be taken up before early June, when the canopy reaches its maximum size. Again, current RB209 guidance follows these rules, including the guidance that N rates of >120 kg N/ha should be split, with the second half applied no later than early May to allow time for uptake by the crop.

Further understanding of N uptake by wheat has been provided by Limaux *et al*. (1999), who showed that the proportion of applied N taken up by a wheat crop (fertiliser N uptake efficiency) increases linearly with crop growth rate on the day of application. This study involved applying N at a range of timings during tillering and stem extension, to winter wheat crops with various crop densities on three soil types in France. The implications of this finding are clear from a more recent trial in Denmark in which N was applied at 16 timings from tillering to the start of grain filling (Petersen, 2004). Fertiliser N uptake efficiency was found to increase by 0.47% per day from tillering to GS32 (early stem extension), and decrease by 0.19% per day from GS47 (booting) to maturity. However, Petersen did not assess the effects of these N timings on yield, so it cannot be assumed that the optimum timings for N uptake efficiency will be the same as those for yield. Similar work in Tennessee showed that there are yield penalties from applying N at sub-optimal timings, with yield reductions resulting from N timings before GS31 (beginning of stem extension) or after GS39 (flag leaf fully emerged) (Howard *et al*., 2002).

Late applications of N to boost grain protein levels have been investigated in the UK by Dampney *et al*. (1995; 2007). In trials conducted between 1988 and 1991, it was found that controlled use of late N applications could raise grain protein by more than 3% (Dampney *et al*., 1995). Foliar urea applied at GS70-79 was found to raise protein by more than additional ammonium nitrate applied at GS39, giving an increase of 1.03% in response to 40 kg N/ha urea. Grain protein responses in trials conducted from 2002-2005 were smaller, at only 0.66% with 40 kg N/ha foliar urea, probably because average yields were higher than in the early 1990s, causing the additional N uptake to be diluted (Dampney *et al*., 2007). This recent work has informed the latest revision of RB209, such that the recommended typical late N application rate is now 60 kg N/ha rather than 40 kg N/ha, to give an increase in protein content of 1.1%. Similar results were obtained by Varga & Svečnjak (2006), who found that 30 kg N/ha applied as foliar urea at flowering increased grain protein concentration by an average of 0.5% across a range of varieties and earlier N application rates.

RB209 recommends earlier N application where there is a risk of take-all. Again, the suitability of this advice has been confirmed by recent studies showing that yield reductions resulting from take-all are increased by later N applications (Roberts *et al*., 2004) and take-all can reduce N uptake rates (Pillinger *et al*., 2005).

One study which disagreed slightly with RB209 timings was conducted by Farrer *et al*. (1998). This American study on Canadian red wheat showed that earlier N applications than currently recommended (mid-tillering (GS25), rather than the beginning of stem extension (GS30)) slightly raised yield and grain protein content and reduced variability in grain protein content. However, there are significant differences between standard UK milling and feed wheats and Canadian red wheat, which currently comprises only <1% of the UK wheat area. Together with differences between the UK and North American climates, this makes this study of doubtful relevance for informing UK N timings.

Scope for improving RB209 recommended N timings exists for wheat grown for the bioethanol industry. This is a relatively new and growing market with different grain quality requirements: whereas bread-makers require milling wheat with high protein levels, bioethanol yields are highest from wheat with low grain protein. The most effective method of reducing grain protein is reducing overall N application rates – it has been shown that on average, the economically optimum N rate for maximising ethanol yield per ha is 10-12% lower than that for maximising grain yield (Clarke *et al*., 2008). Regarding N timing, it has been suggested that as late N applications can increase grain N in milling wheat, so earlier N applications may reduce grain N, without the yield penalties seen when N rate is reduced. Research funded by One North East and the North East Processing Industries Cluster (NEPIC) (Kindred *et al*., 2009) have shown that applying up to 50% of N in mid-Feb to mid-March, when RB209 recommends applying no more than 40 kg N/ha, can reduce grain protein and increase ethanol yield per tonne of grain by 3-4 litres, without damaging grain yields. Further work is required to confirm these results, and growers will have little incentive to change N rates or timings without premiums from the bioethanol industry for low-protein wheat. Care should also be taken in advising earlier N timings because 1) soils are likely to be wetter in the early spring, which may make applications more difficult and increase the risk of N leaching and 2) the risk of lodging will be increased.

Winter Barley – RB209 recommendations

The current and forthcoming RB209 fertiliser recommendations for winter barley are that fertiliser should be applied at either one or two timings, depending on the total amount to be applied. The total amount of N is determined using look-up tables which take account of the SNS, soil type, a realistic estimation of yield and target grain N concentration.

Where the total N applied over the season is less than 100 kg N/ha, it should be applied as a single dressing, between late March and early stem extension (GS 31).

Where more than 100 kg N/ha is to be applied, 40 kg N/ha should be applied between mid-February and early March, and the remainder by early stem extension but not before late March.

Winter Barley – Additional literature on optimal timings for yield and crop quality

The last extensive set of trials on N rates and timings for winter barley was carried out in the 1980s, for the development of the RB209 guidelines (Lord & Vaughn, 1987). These involved applying a range of N rates entirely at GS30, or with 40 kg N/ha applied early (in February), late (at GS32) or both. The effects of timing on yield were small and inconsistent, but applying 40 kg N/ha early was found to reduce grain N%, hence the recommendation in RB209 to apply 40 kg N/ha early for total rates of more than 100 kg N/ha. As for wheat, there would be value in conducting systematic timing experiments on modern varieties and with modern farming practices, to establish how the optimal N applications for winter barley have changed.

Some studies have suggested that barley yield is not highly sensitive to N application timing. In trials in China, Sardana & Zhang (2005) found no significant difference in yield between crops which received a single N application at tillering and crops which received the same rate of N split equally between tillering and booting stages. In Germany, Maidl *et al*. (1996) found that autumn N applications were ineffective, but that the yield differences between a range of spring split timings were small and sometimes inconsistent, particularly for 2-row barley. The best N strategy for 6-row barley involved applications between the beginning of spring growth, GS32 (early stem extension) and GS47 (booting).

Recent UK research has suggested that significant improvements could be made to the RB209 recommended N rates and timings, to increase yields of winter barley. GrowHow UK Ltd funded ADAS experiments at two sites in harvest years 2008 and 2009, which have shown that RB209 recommended N rates are 40-80 kg N/ha below the experimentally determined economically optimum N rates (unpublished data). In these trials, applying N earlier than recommended by RB209 were shown to increase yields by 0.3 to 0.5 t/ha while reducing grain N content by between 0.07 and 0.1%, which helped achieve specification for malting. There was also some evidence that the earlier N timings increased the yield of 6-row barley by more than that of 2-row barley, although this contradicts earlier work by Maidl *et al*. (1996) which found early spring N to be more important for 2-row barley. The early N timings tested involve applying 50% of the N fertiliser in late February, before GS30, and 50% in mid-March, while RB209 recommends applying 40 kg N/ha in late February or early March, if the total N rate is high, and the remainder not earlier than late March. Potential disadvantages of these earlier timings are that plant height is increased by 5-10 cm, which may increase lodging risk, and soils are likely to be wetter in the early spring, which may make application difficult or increase the risk of nitrate leaching.

Earlier N applications could be used to reduce N rate while maintaining yield, rather than to increase yield at a given N rate. Across the two varieties tested, grown in four site seasons, statistical curve fitting showed that the yield achieved at optimal N rates and RB209 timings could be achieved using an average of 30 kg N/ha less fertiliser, applied at the earlier timings. This is an average reduction of 13% on the experimentally determined optimal N application rates. More detailed work needs to be done to establish the optimum N application timing for winter barley, by testing a greater range of early timings.

Using the methods outlined above, we estimate that use of the earlier N timings could reduce the GHG emissions of cropping by 21 kgCO_2e/t (3.7%) relative to RB209 timings, assuming the optimum N levels and yields obtained in the ADAS trials described above. Use of the earlier timings to cut N application rates whilst maintaining yield would cut GHG emissions by 490 kgCO_2e/ha (13.2%) or 73 kgCO_2e/t (12.7%).

Spring Barley – RB209 recommendations

The current and forthcoming RB209 fertiliser recommendations for spring barley are that fertiliser should be applied at either one or two timings, depending on the total amount to be applied, the drilling date, and whether the crop is for feed or malting.

For feed barley drilled before March with a total N recommendation of over 70 kg N/ha, 40 kg N/ha should be applied in the seedbed, except on light sandy soils where it should be applied at the 3-leaf stage (not before March). The remainder should be applied at early stem extension, between early April and early May. For feed barley drilled before March with a total recommendation of under 70 kg N/ha, the fertiliser should be applied as a single dressing at early stem extension, between early April and early May.

For feed barley drilled from March onwards, all the fertiliser should be applied in the seedbed, except on light sandy soils where 40 kg N/ha should be applied in the seedbed and the remainder at the 3-leaf stage.

For malting barley, all the fertiliser should be applied by early stem extension, and not later than the end of March.

Spring Barley – Additional literature on optimal timings for yield and crop quality

Little research has been done to establish the optimal N timings for spring barley. The only recent study on UK crops was conducted by Overthrow (2005), who investigated the effects of applying N at one, two or three split timings to spring malting barley, using trials at three sites from 2002-2004. The N rates tested were 100, 150, 175 and 200 kg N/ha, which are high given that the highest N rate recommended for spring malting barley by the forthcoming 8th edition of RB209 is 140 kg N/ha, and the average fertiliser application to spring barley in 2008 was 94 kg N/ha (Defra, 2009). The yield benefits of splitting N to more than one timing were small and inconsistent, even at N rates of 200 kg N/ha. Applying N in three equal splits (seedbed, three-leaf and tillering stages) often reduced yields at low N rates. On average, the highest yields were achieved by applying N in two equal splits (seedbed and three-leaf stage). This gave an average yield increase of 0.11 t/ha across all N rates, and 0.19 t/ha at the highest N rate (200 kg N/ha), relative to a single application at the one-leaf stage. Similarly inconsistent yield responses to split N applications were obtained by McTaggart & Smith (1995) in trials in Eastern Scotland, using total N rates of up to 150 kg N/ha.

Sylvester-Bradley *et al*. (2008) showed that RB209 recommended N rates for spring barley are around 40 kg N/ha too low, as has similarly been shown for winter barley in the recent ADAS trials described above (unpublished data). Recommended N rates for spring malting barley are around 20 kg N/ha higher in the forthcoming 8th edition of RB209 than in the current (7th) edition, but still lower than recommended by Sylvester-Bradley *et al*. Given this, it seems that yield benefits could result from splitting the highest N application rates to spring malting barley, but that the RB209 recommendation of a single dressing is appropriate in most situations, where N rates are below 100 kg N/ha. More research should be done to find the optimal timing for this single application, as Overthrow tested applications at the one-leaf stage, whereas RB209 recommends slightly later applications. The trials conducted by Overthrow did not include enough N rates to allow the fitting of N response curves, and so it is not possible to determine exactly how much N could be saved by optimising timings, while keeping yields unchanged.

In trials in Argentina, Lázzari *et al*. (2005) found no differences in yield between N applied at crop emergence, at tillering, or split between these timings. In Brazil, Wamser & Mundstock (2007) found that N applications after the start of stem extension cause increased grain protein, which is undesirable for spring malting barley. Both these trials provide further support for RB209 timings, although the former suggests that yield is not highly sensitive to N application timing within the window tested.

Winter Oilseed Rape – RB209 recommendations

The current and forthcoming RB209 fertiliser recommendations for winter oilseed rape are that fertiliser should be applied at between one and three timings, depending on the total amount to be applied.

Where the SNS (soil N supply) index is 2 or below, 30 kg N/ha can be applied in the seedbed or as an autumn top-dressing, although this is not recommended for crops drilled later than mid-September.

Where the total spring fertiliser to be applied is less than 100 kg N/ha, it should be applied as a single dressing at the start of spring growth, between late February and early March. Where more than 100 kg N/ha is to be applied, it should be split equally between two applications in late February to early March and late March to early April.

Winter Oilseed Rape – Additional literature on optimal timings for yield and crop quality

A canopy management approach for optimising N rates and timings for winter oilseed rape has been developed and tested in the years since the last revision of RB209 (Berry *et al*., 2009; Lunn *et al*., 2001; 2003). The canopy management principles mean that N rates are determined by SNS, achieving an optimum canopy size of GAI by early flowering and yield potential. It has been shown that with RB209 N rates and timings, many crops produce canopies above this optimum size, which leads to increased lodging risk and reduced yield. The canopy management approach usually often applying N at later timings than is recommended by RB209 guidelines, to avoid development of an over-large canopy at flowering.

The timings recommended by the canopy management approach are that, where SNS levels are moderate or high, the first N application should be at the beginning of stem extension in late March to early April, the second split timing recommended by RB209, and the second N application should be timed between yellow bud and early flowering. At sites with low SNS, 40-60 kg N/ha should be applied at the first split timing recommended in RB209, in late February to early March, to give the crop sufficient time to take up all the N required to build an optimum sized canopy.

Testing over a number of sites and seasons has shown that canopy management N timings can increase yield by up to 0.36 t/ha in situations where canopies are at a high risk of becoming over-large. These yield increases were associated with reduced stem growth leading to shorter plants, less lodging, and possibly increased seed set. The recommendation for an early application of 40-60 kg N/ha at sites with low SNS was developed following yield reductions on crops with very small canopies following winter. With this refinement, the approach usually has no effect on yield in situations where crops are small following winter. The canopy management principles for calculating total N requirement also predicted the observed economic optimum N levels more accurately than RB209 guidelines.

As an alternative to increasing yield, the canopy management approach could be used to reduce N application rates while achieving the same yields. Statistical curve fitting using data from the trials described in Berry *et al*. (2009) and similar trials conducted in 2008/09 (unpublished data) shows that using canopy managed timings, N rates could be reduced by up to 53 kg N/ha while achieving the same yields as at RB209 timings and economic optimum N rates. However, it must be stressed that canopy managed timings are only beneficial when canopies are at risk of becoming overlarge: canopy management gave a significant ($P<0.05$) yield increase in only 1 of the 12 site seasons tested. This is because slow crop growth during the autumn/winter period and spring drought were unusually common in the 2006-2009 field seasons.

Using the methods outlined above, we estimate that in the site season with the strongest effect, use of the canopy management N timings reduced the GHG emissions of cropping by 40 $kgCO_2e/t$ (6.6%) relative to RB209 timings, at the optimum N rate. Use of the canopy management timings to cut N application rates whilst maintaining yield would have cut GHG emissions by 522 $kgCO_2e/ha$ (12.3%) or 134 $kgCO_2e/t$ (22.1%). However, optimum N rates in this site season were unusually low. If a 0.36 t/ha yield gain or 32 kg N/ha fertiliser saving were achieved on an average yielding crop at average N application rates, the GHG savings would be 114 kgCO_2e/t (8.8%) or 157 kgCO_2e/t (12.1%) respectively.

The effectiveness of autumn N applications to oilseed rape, recommended by RB209 in certain situations and applied to 29% of the UK winter oilseed rape area at a rate of 37 kg N/ha (Defra, 2009), has not been well established. This practice is often perceived to be of benefit for crops which are slow to establish and on soils which have had a large amount of straw incorporated. However, there is no published experimental data to support this. The most extensive work done in the UK on seedbed N was a series of trials done at 27 sites from 1988-1990, funded by MAFF for the development of the RB209 guidelines (unpublished data). These found small yield responses to seed bed N (Table 1), although uptake efficiencies of seedbed N were poor and economic yield responses occurred at a minority of sites. On average across cultivation treatments (straw either burned, baled or incorporated) 30 kg N/ha applied in autumn increased yield by a non-significant amount of 0.03 t/ha, but the economic optimum N rate was 19 kg N/ha greater, which would usually result in a net loss of profit. Yield responses to 30 kg/ha autumn N were 0.1 t/ha greater following straw incorporation than straw burning. Intermediate yield responses occurred at sites where the straw was baled and only the stubble incorporated. More research is required to test the effects of seedbed N, now that straw incorporation is common and tillage is typically much reduced, relative to the 1980s. If current autumn N applications were reduced by half and the resulting net reduction in N use for these crops was 23 kg N/ha (as indicated by Table 1), then this would result in a total reduction in N use of 164,000 kg over the UK (based on an average winter oilseed rape area of 533,000 ha between 2006 and 2008). This would equate to a reduction in GHG emissions of 29 kt CO_2e per annum.

Table 1 Optimum rates of spring nitrogen, associated yields and seedbed nitrogen efficiencies for average yields (unpublished data from MAFF-funded trials at 25 sites from 1988-1990).

	Seedbed N, kg/ha			
	0	30	60	90
Optimum spring N rate (kg N/ha)	191	180	163	161
Yield at optimum N rate (t/ha at 91% dry matter)	3.30	3.33	3.34	3.36
Seedbed N efficiency (%)	-	37	47	33

Average yield responses across cultivation treatments (straw either burned, baled or incorporated)

The canopy management principles described by Berry *et al*. (2009) did not include autumn N applications, and yet achieved above average yields even with the crops which were slow to establish. The canopy management principles state that crops must take up 175 kg N/ha by mid-flowering to maximise yield, and can take up around 3 kg N/ha/day. This means that even if crops have taken up very little N during the winter, sufficient N can be taken up by flowering if the first application is made in late February to early March, the first spring split timing recommended by RB209. The canopy management principles also calculate that the spring N rates recommended by RB209 are sufficient for optimal yield without the autumn extra N applications recommended for some soils, so it would not be necessary to increase spring applications to compensate for the removal of autumn applications. In trials in NW Germany, Sieling *et al*. (1998) found that on average, autumn applications of slurry had no effect on oilseed rape yield, when followed by a range of spring slurry and mineral N treatments. An average of only 5% of the N in autumn-applied slurry was taken up by the crops, leading to a high risk of leaching. If the very low uptake rates of autumn-applied slurry measured by Sieling *et al*. also occur for autumn-applied mineral fertilisers in the UK, this is further evidence that the RB209 guidelines for oilseed rape could be improved by removing the recommendation for 30 kg N/ha in autumn on soils with a low SNS index. Colnenne *et al*. (2002) confirmed that N deficiency in autumn does not have a negative impact on oilseed rape yields, and Rathke *et al*. (2008) claim that autumn N applications can even reduce yield, by increasing susceptibility to frost damage.

Further N timings which have been tested on oilseed rape are late applications of foliar N, applied around the end of flowering. Such applications have been promoted within the industry, but the first year of data from a current HGCA project has shown that the increases in yield in response to late foliar N are modest – an average of 0.25 t/ha increase following application of 40 kg foliar N/ha (unpublished data). A second season of trials is underway to provide robust data on whether late foliar N applications to winter oilseed rape are economically viable.

One Canadian study has suggested that oilseed rape grown under reduced tillage may be more sensitive to N source and timing than oilseed rape grown with conventional tillage practices (Grant *et al*., 2002). Given the increased use of reduced tillage in the UK in recent years, this suggests that N timing studies on oilseed rape are now of increased value.