AC0221 Annex 4

Estimate the level of imprecision in N fertiliser use and the effect on GHG emissions

Summary

Data from a total of 189 Nitrogen (N) response experiments carried out on modern varieties in England since 2003 in winter wheat, winter oilseed rape, and winter and spring barley were analysed. The aim was to estimate the level of imprecision in N fertiliser use from RB209 recommendations (Anon., 2010) using both the Field Assessment (FAM) and soil mineral N measurement (SMN) methods, and the effects of this on yields, margin over N costs and greenhouse gas (GHG) emissions taking account of indirect effects of land use change (LUC). An alternative scenario of always applying a fixed rate of N to a crop was also tested. The fixed rate was the average rate of N applied to crops over the last 3 seasons, taken from the British Survey of Fertiliser Practice.

In wheat, RB209 gave similar recommendations to the average calculated optimum N rate (Nopt; Table 1). This was also the case with the spring barley experiments, but the oilseed rape and winter barley recommendations were, on average, 27 and 32 kg N/ha lower than the average Nopts. With all crops, the ranges of Nopts were significantly larger than those recommended by RB209.

Table 1. Winter wheat: Comparison of N recommendation systems (fixed at 180 kg N/ha, RB209 with FAM and RB209 with SMN) with the optimum N rate (Nopt). Data from 112 N response experiments.

	Units	Max.	Min.	Median	Mean
Nopt at BER 5:1	*kg/ha*	340	49	201	189
Grain yield at Nopt	*t/ha*	13.89	5.79	9.53	9.44
Fixed N rate	*kg/ha*	180	180	180	180
N recommended by FAM	*kg/ha*	240	130	190	191
N recommended by SMN	*kg/ha*	280	120	180	178
N difference at 180 kg N/ha	*kg/ha*	136	-160	-20	61*
N difference at Nrec by FAM	*kg/ha*	165	-180	-2	59*
N difference at Nrec by SMN	*kg/ha*	136	-155	-10	54*
Yield change at 180 kg N/ha	*t/ha*	0.40	-1.65	-0.16	-0.25
Yield change at Nrec by FAM	*t/ha*	0.32	-2.00	-0.06	-0.22
Yield change at Nrec by SMN	*t/ha*	0.39	-2.08	-0.08	-0.23
Margin change at 180 kg N/ha	*£/ha*	5.96	-87.84	-9.52	-17.95
Margin change at Nrec by FAM	*£/ha*	2.70	-133.64	-8.67	-20.99
Margin change at Nrec by SMN	*£/ha*	7.28	-105.26	-7.50	-14.75
GHGs change at 180 kg N/ha	*kg CO_2 e/t*	245	-110	-16	16
GHGs change at Nrec by FAM	*kg CO_2 e/t*	289	-87	-3	28
GHGs change at Nrec by SMN	*kg CO_2 e/t*	314	-131	-9	10

* Means of N difference calculated with all differences as positive

There were no relationships found between the amount of N recommended using FAM and the actual Nopts in either oilseed rape or winter wheat. The amount of N recommended by SMN was significantly related to actual Nopts, in both wheat (Figure 1a) and oilseed rape. It could also be seen that the average error in the amount of N applied from using the RB209

SMN measurement method compared to the actual Nopt was less than that associated with using the FAM in winter wheat (Table 1), oilseed rape and winter barley. However, in wheat the errors still fell outside the 'target zone' of within +/- 50 kg N/ha of the optimum which is the aim according to the latest HGCA N management guidelines (Sylvester-Bradley, 2009). In fact, assuming a fixed N rate of 180 kg N/ha led to errors outside the zone in 58% of cases. Using FAM recommendations would lead to errors outside the zone in 50% of cases, and if the SMN method was assumed, this led to the lowest proportion outside the zone, of 46%.

The fixed rates were always lower than the average calculated Nopts (e.g. Table 1), with particularly large differences found in winter and spring barley (69 & 30 kg N/ha lower than average Nopts).

The effects of N rate errors on yields, margins over N costs and GHG emissions were similar for all crops. Examples of effects of over- and under-fertilising compared to Nopts due to using SMN recommendations can be seen in Figures 1 b, c and d. Under-fertilisation led to significant reductions in yield, whereas over-fertilisation led to only slight yield increases (Figure 1b). Margins over N costs were reduced compared to those at Nopt whether crops were under- or over-fertilised (Figure 1c; Table 1). Under-fertilisation led to low yields and so lower margins over N costs, whereas although over-fertilisation led to slightly higher yields, the yield increases did not compensate for the extra N costs, and so margins again decreased.

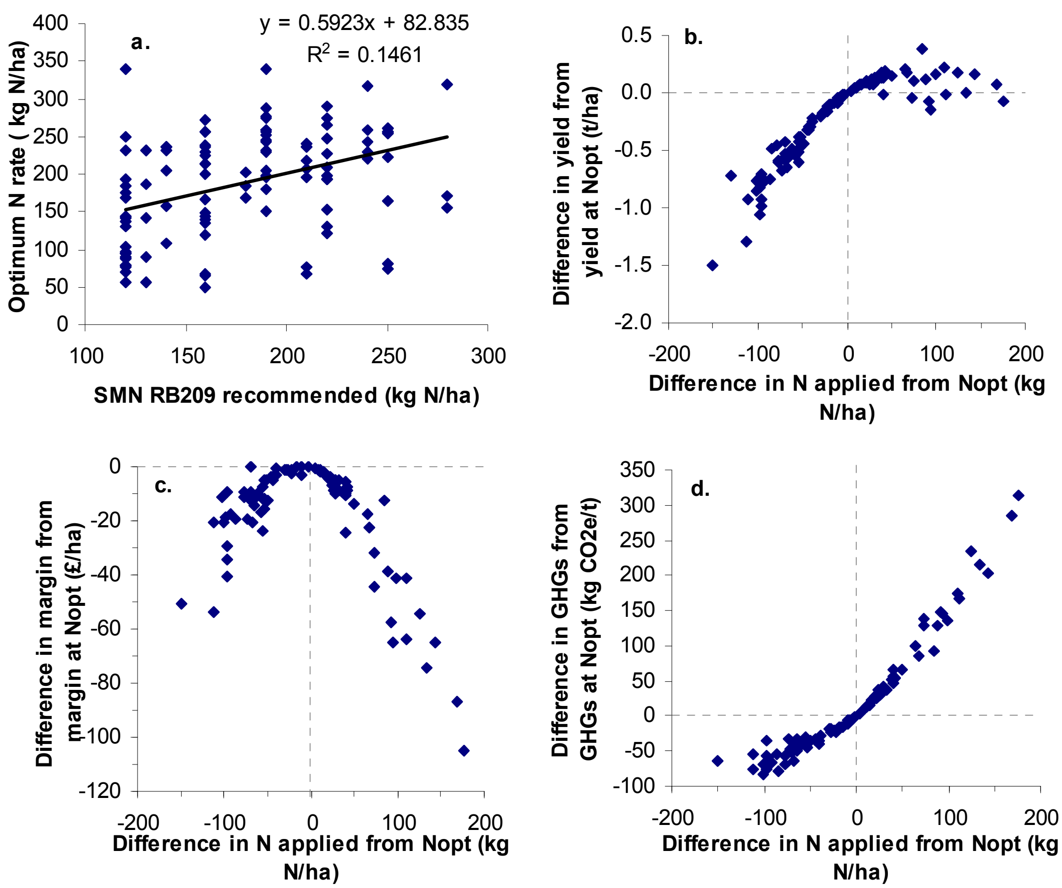

Figure 1. Using N recommendations for winter wheat generated using the RB209 Soil Mineral N measurement method (SMN) compared to calculated optimum N rate (Nopt): a. relationship between the actual Nopts and SMN recommendations, and the effects of applying N rates different to Nopt on: b. yield (t/ha at 15% moisture content); c. margin over N costs (£/ha); and d. Greenhouse Gas (GHG) emissions taking account of indirect land use change (LUC).

On average, GHG emissions were increased when a fixed rate of N or RB209 recommendations were applied compared to Nopt (Table 1, Figure 1c). Where N recommendations or the fixed N rate were higher than Nopt, GHG emissions per tonne of grain increased significantly. This was because N, the biggest contributor to emissions, is increasing with little associated increase in yield. The small increase in yield above the Nopt means there is little or no effect of LUC. At N levels below Nopt, GHG emissions tended to decrease slightly and level off (Figure 1c). Here, although N is decreasing, the yield foregone by using lower N levels means that more land would have to be converted to make up the shortfall in production, resulting in further GHG emissions. In the case of other crops, below a difference in N applied from Nopt of approximately -50kg N/ha, GHGs increased to levels higher than at Nopt.

Overall, it could be seen that using the RB209 SMN method was generally more precise than using the FAM, and led to smaller N rate errors than applying a fixed N rate. When N rate errors were within 50 kg N/ha in either direction, only small reductions in margins over N costs resulted. Over-fertilisation was associated with slight increases in yield and large increases in greenhouse gas emissions. Under-fertilisation was associated with dramatic reductions in yield and slight reductions in greenhouse gases with low levels of under-fertilisation, or increases in emissions with significant under-fertilisation.

Introduction

There is a range of management tools for agronomists and growers designed to recommend appropriate Nitrogen (N) applications to crops to optimise yields and maximise profit. Fertiliser manufacturers, such as GrowHow and Yara have their own systems, but The Fertiliser Recommendations, known as RB209, published by Defra (Anon., 2000), is likely to be the most commonly used.

In RB209, the soil N supply (SNS), soil type of the field, and for some crops a realistic estimate of yield, is used to generate recommendations of fertiliser N requirements for different crops. The SNS can be calculated through two methods; field assessment method and measurement. With the field assessment method (FAM), information about previous cropping, soil type and over-winter rainfall is used to generate a SNS using look-up tables. With the measurement method, Soil Mineral N (SMN) measurements are taken in autumn or early spring and used, along with an estimate or measurement of the amount of N in the crop, to determine the SNS.

This study will use N response experiments where actual optimum N rates have been determined to examine the potential level of error in N fertiliser rate from using RB209 recommendations, and the effects of this on yield, margin over N costs and greenhouse gas emissions. An alternative scenario of always applying a fixed rate of N to a crop is also tested.

Materials and methods

Data

A total of eight datasets were used for this study (Table 2), comprising both published and unpublished N response experiments carried out between 2003 and 2009. For the purposes of this study, an experiment comprised replicated data for a particular cultivar at a particular site. Each experiment had been carried out using between five and seven N rates (including Nil N) on winter wheat, winter barley, winter oilseed rape, or spring barley and had measured grain/seed yield (t/ha at 15% moisture content (mc) for cereals, or at 9% mc for oilseed rape).

Not all data from the datasets were included in the analysis. Instead data were restricted to experiments that had been carried out in England using modern varieties which have been on the HGCA Recommended List from 2000 onwards.

As well as yield data, information was collated for each experiment including soil type, previous crop, overwinter rainfall and soil mineral N (SMN) in spring. This information was then used to generate N rate recommendations from the new version of the Fertiliser Recommendations (RB209; Anon., 2010) using both the field assessment method (FAM) and the SMN measurement method.

Table 2 Sources of data used in this project (ww = winter wheat, wb = winter barley, sb = spring barley, osr = oilseed rape).

Name of dataset	# Exp'ts used	Years	Crops	Reference to experimental detail
N management for new group 1 & 2 wheat varieties	16	2003-05	ww	Dampney *et al.* (2006)
Crop response to different N fertiliser materials	37	2004-05	ww, wb	Dampney *et al.* (2006b)
Optimising N for modern cereal crops	69	2005-07	ww, sb	Sylvester-Bradley *et al.* (2008)
Canopy management & late N to improve OSR yield	36	2006-08	osr	Berry and Spink (2009)
Effect of N timings and rates on 2- and 6-row barley	6	2008-2009	wb	Roques and Berry (2009, 2010)
N timing to wheat to optimise bioethanol production	4	2009	ww	Kindred *et al.* (2009)
Differences in N requirements of different cereal species	9	2009	ww, wb	Kindred *et al.* (2010, in preparation)
Optimising N for modern OSR varieties	12	2009	osr	Berry (2009, *Pers. comm.*)

Data analyses

Fitting N response curves and deriving the economic optimum N rate

Fitting of N response curves to yield data had already been carried out for the majority of datasets. Although small differences in methods were found, a thorough check of the data found most relationships were appropriate. A small number were re-fitted for the purposes of this study. The method used to estimate the response of yield to N rate was the linear plus exponential function (LEXP). This has been the standard method since a comparison of approaches by George (1984), and has been used in the preparation of the RB209 recommendations. The function is:

$$y = a + b.r^{N} + c.\mathrm{N}$$

where y is yield in t/ha at 15% mc for cereals or 9% mc for oilseed rape, N is total fertiliser N applied in kg/ha, and a, b, c and r are parameters determined by statistical fitting. Although a, b, c and r have no distinct meaning, they can be associated with different features of the response, as described by Sylvester-Bradley *et al.* (2008), namely:

a: a measure of the asymptote, or maximum achieved yield.

b: the change in yield from the maximum if no fertiliser N was applied. Thus $a+b$ always gives the fitted yield with no N applied.

c: the slope of the response well beyond the region of maximum curvature. Where large N rates cause increasing yield loss (e.g. due to lodging), this parameter value tends to be increasingly negative.

r: the shape of the response in the region of maximum curvature. This value tends to be larger for flatter response shapes and smaller for sharper response shapes (i.e. those with a more distinct shoulder).

It was assumed that responses were unique to a site. With most datasets studied here, a 'Parallel curve' approach was used when determining the optimum N rate (Nopt) for each variety at each site. This involved four stages:

i) Fit a common curve to all varieties (i.e. keeping *a, b, c* and *r* constant for all varieties at a site).

ii) Fit separate curves for each variety, with a common response but different intercepts (i.e. varying *a* but keeping *b, c* and *r* constant).

iii) Fit separate curves for each variety allowing *a*, *b* and *c* to vary (i.e. just keeping *r* constant).

iv) Fit separate curves for each variety, allowing all parameters to vary.

Occasionally there was a difficulty in estimating the parameter *r*. Therefore, if *r* was outside an acceptable range, the function was re-fitted using an *r* value of 0.99. In the majority of experiments, there was no improvement in the fit of the function between stage 3 and 4, and so the method at stage 3 was used to determine the optimum N rate.

Optimum N rates (Nopt) were derived from the fitted LEXP parameters using:

$$N_{OPT} = \frac{[\ln(k/1000 - C) - \ln(B(\ln R))]}{\ln R}$$

where *k* is the breakeven price ratio (BER) between fertiliser N (£/kg) and grain (£/tonne). The breakeven ratios used in this study were 5 for cereals and 2.5 for oilseed rape, so that direct comparisons could be made with the new RB209 revision (Anon., 2010).

Parameters from the fitting of LEXP were also used to determine yields at Nopt, at a fixed N rate, and at the N rates recommended using FAM and SMN measurement methods of RB209. The fixed rates were the average amounts of N applied to feed crops between 2006 and 2008 according to the British Survey of Fertiliser Practice (Defra, 2009). These were 180 kg N/ha for winter wheat, 144 kg N/ha for winter barley, 96 kg N/ha for spring barley and 192 kg N/ha for oilseed rape.

Determining Greenhouse Gas emissions

Greenhouse Gas (GHG) emissions associated with yields at Nopt, at fixed N rates, and RB209 recommended rates were calculated for each experiment 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 N_2O emissions from soil were calculated following the IPCC methods detailed by McCarthy *et al*. (2010). Soil emissions of N_2O 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 (1996). 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.

The indirect effects of land use change (LUC) on GHG emissions were also estimated on per hectare and per tonne of yield bases. This was based on the method of Kindred *et al.* (2008) and estimated as follows. The yield foregone compared with the N input option with the greatest yield was calculated for each N input option. It was assumed that all of the foregone yield was produced on land converted from temperate grassland. The area of LUC to meet this production was obtained by dividing the foregone yield by the expected yield on the newly cropped land, taken as the yield of the particular N input option in question. Over a 30 year period the GHG emissions resulting from converting temperate grassland to arable crop land have been estimated at on average 6000 kg CO_2 e per ha per year (Anon., 2006; Searchinger *et al*., 2008).

Margin over N costs

The economic margins over the costs of N were calculated for the yields associated with each of the N input options in each of the experiments. The cost of ammonium nitrate was assumed to be £190/t (Source: Farmers Weekly/ NFU price monitor week ending 26th February 2010). It was assumed that all crops were sold as feed grain. The average prices of the crops, quoted in the Farmers Weekly (27th February 2010) were: winter wheat - £90/t; barley - £75/t; and oilseed rape - £245/t.

Results and discussion

Winter wheat

A total of 112 winter wheat experiments were included in the analysis. From these experiments, the average Nopt was found to be 189 kg N/ha, associated with an average yield of 9.44 t/ha (at 85% DM; Table 3).

The N rates recommended by RB209 were, on average, similar to the actual Nopt (191 and 178 kg N/ha for the FAM and SMN methods, respectively). However, the range of actual Nopts (291 kg N/ha) was substantially greater than the range in N rates recommended by RB209 (110 and 160 kg N/ha for FAM and SMN methods, respectively; Table 3). Moreover, when the relationships between the actual Nopts for individual experiments and the RB209 recommendations were examined, there was no significant relationship between the amount of N recommended by the FAM and the actual Nopt (Figure 2a). When the SMN measurement method was used to recommend N rates, a significant ($P < 0.05$) positive relationship with actual Nopts was found (Figure 2b), although the variation accounted for was still low ($R^2 = 0.146$). Part of this poor agreement between the recommended N rates and actual Nopts could be due to the fact that there is always an error associated with the Nopt determined from the fitting of the LEXP curve. However, in this study data were removed from experiments where standard errors associated with Nopts were large.

Table 3. Winter wheat: Comparison of N recommendation systems (fixed at 180 kg N/ha, RB209 with FAM and RB209 with SMN) with the optimum N rate (Nopt). Data from 112 N response experiments.

	Units	Max.	Min.	Median	Mean
Nopt at BER 5:1	*kg/ha*	340	49	201	189
Grain yield at Nopt	*t/ha*	13.89	5.79	9.53	9.44
Fixed N rate	*kg/ha*	180	180	180	180
N recommended by FAM	*kg/ha*	240	130	190	191
N recommended by SMN	*kg/ha*	280	120	180	178
N difference at 180 kg N/ha	*kg/ha*	136	-160	-20	61*
N difference at Nrec by FAM	*kg/ha*	165	-180	-2	59*
N difference at Nrec by SMN	*kg/ha*	136	-155	-10	54*
Yield change at 180 kg N/ha	*t/ha*	0.40	-1.65	-0.16	-0.25
Yield change at Nrec by FAM	*t/ha*	0.32	-2.00	-0.06	-0.22
Yield change at Nrec by SMN	*t/ha*	0.39	-2.08	-0.08	-0.23
Margin change at 180 kg N/ha	*£/ha*	5.96	-87.84	-9.52	-17.95
Margin change at Nrec by FAM	*£/ha*	2.70	-133.64	-8.67	-20.99
Margin change at Nrec by SMN	*£/ha*	7.28	-105.26	-7.50	-14.75
GHGs change at 180 kg N/ha	*kg CO_2 e/t*	245	-110	-16	16
GHGs change at Nrec by FAM	*kg CO_2 e/t*	289	-87	-3	28
GHGs change at Nrec by SMN	*kg CO_2 e/t*	314	-131	-9	10

* Means of N difference calculated with all differences as positive

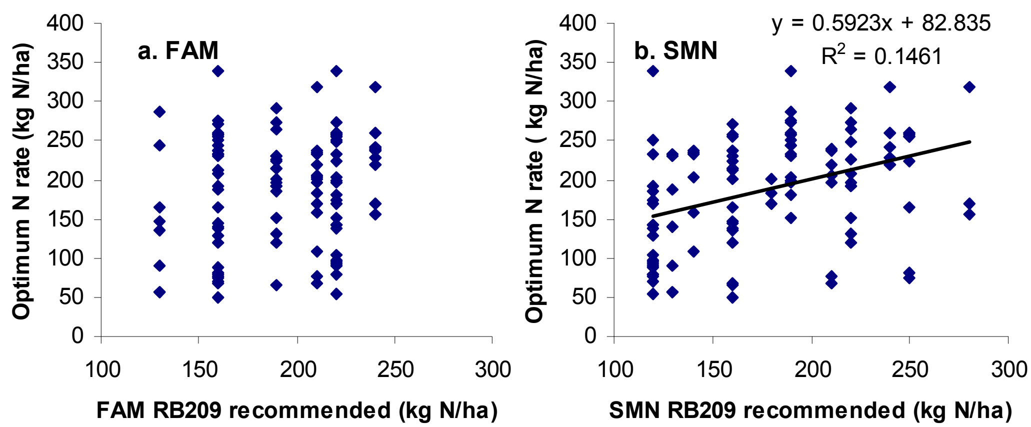

Figure 2. Relationships between the actual optimum N rate calculated of winter wheat N response experiments and RB209 N rate recommendations generated using the: a. field assessment method (FAM); or b. Soil Mineral N measurement method (SMN).

When the errors associated with using either RB209 recommendations or a fixed N rate (180 kg N/ha) compared to actual optimum N rates were examined further, it could be seen that the average errors in N rate from the optimum were 61 kg N/ha for the fixed N rate, 59 kg N/ha using the FAM method and 54 kg N/ha using the SMN method (Table 3).

These average errors fall outside the 'target zone' of within +/- 50 kg N/ha of the optimum which is the aim according to the latest HGCA N management guidelines (Sylvester-Bradley, 2009). In fact, assuming a fixed N rate of 180 kg N/ha led to errors outside the zone in 58% of cases. Using FAM recommendations would lead to errors outside the zone in 50% of cases, and if the SMN method was assumed, this led to the lowest proportion outside the zone, of 46% (data not shown).

The average differences in yield when applying a fixed N rate, FAM or SMN recommendation as opposed to Nopt were -0.25, -0.22, -0.23 t/ha, respectively (Table 3). The shape of the LEXP curve means that if fertiliser was applied at rates above the Nopt, yields were often higher than at Nopt, but effects were small (Figure 3). Hence, the maximum yield increase compared to Nopt was 0.4 t/ha (Table 3). In contrast the LEXP curve is a lot steeper at N rates below Nopt, which led to large reductions in yield (Figure 3). For example, if a SMN recommendation led to an N rate 100 kg N/ha higher than Nopt, yield was 0.14 t/ha higher than at Nopt, but if the rate was 100 kg N/ha lower that Nopt, yield was 0.84 t/ha lower than at Nopt (Figure 3b.).

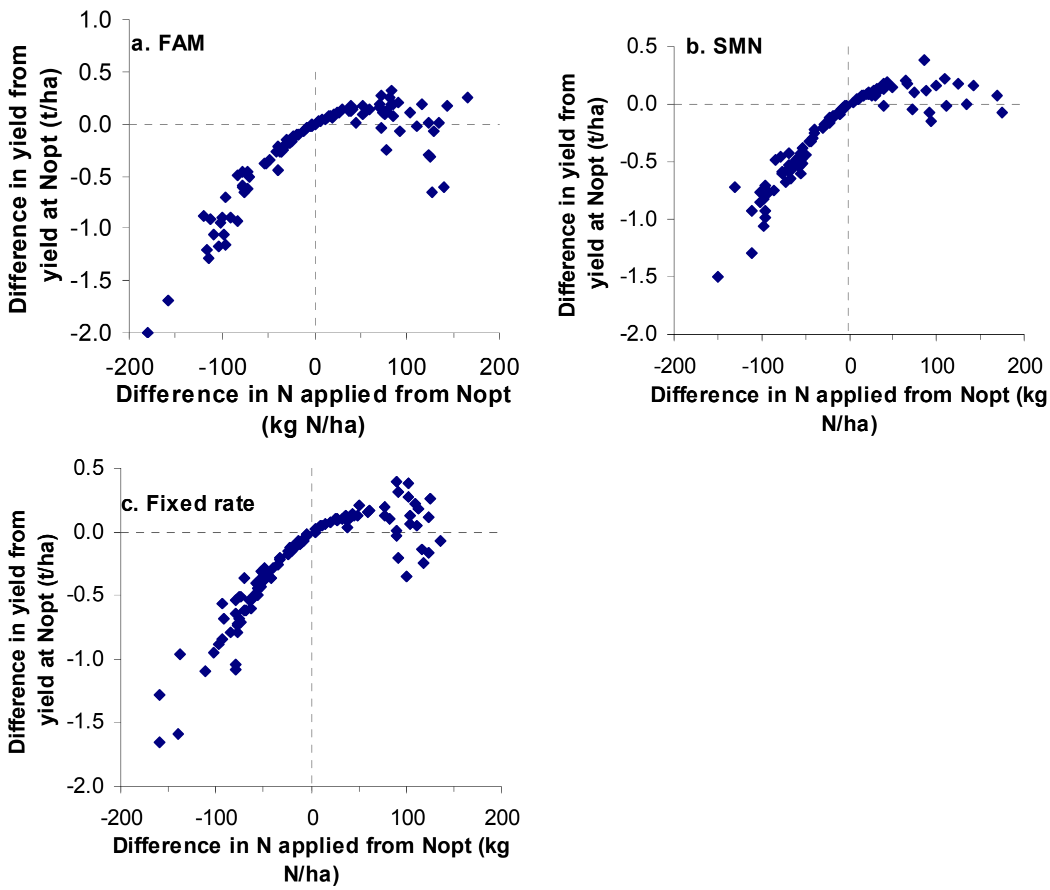

Figure 3. Effect of applying N rates different to the optimum N rate (Nopt) as a result of: a. RB209 field assessment method recommended (FAM); b. RB209 soil mineral N measurement method recommended (SMN); or c. a fixed rate of N (180 kg N/ha) on yield (t/ha at 15% moisture content) of winter wheat.

Although yields would increase slightly at recommended N rates higher than Nopt (Table 3, Figure 3), the economic margins over N costs were generally found to decrease whether recommendations led to under- or over-fertilisation (Figure 3). Under-fertilisation would lead to low yields and so lower margins over N costs, whereas although over-fertilisation would lead to slightly higher yields, the yield increases would not compensate for the extra N costs, and so margins again would decrease. The average reductions in the margin over N costs of applying a fixed N rate, FAM, or SMN recommendations compared to applying Nopt were £18, £21 and £15 /ha, respectively.

The graphs shown in Figure 3 are consistent with those shown in the N Management Guide (Sylvester-Bradley, 2009), with small economic loses where N recommendations were between -50 and + 50 kg N/ha from Nopt (Figure 4).

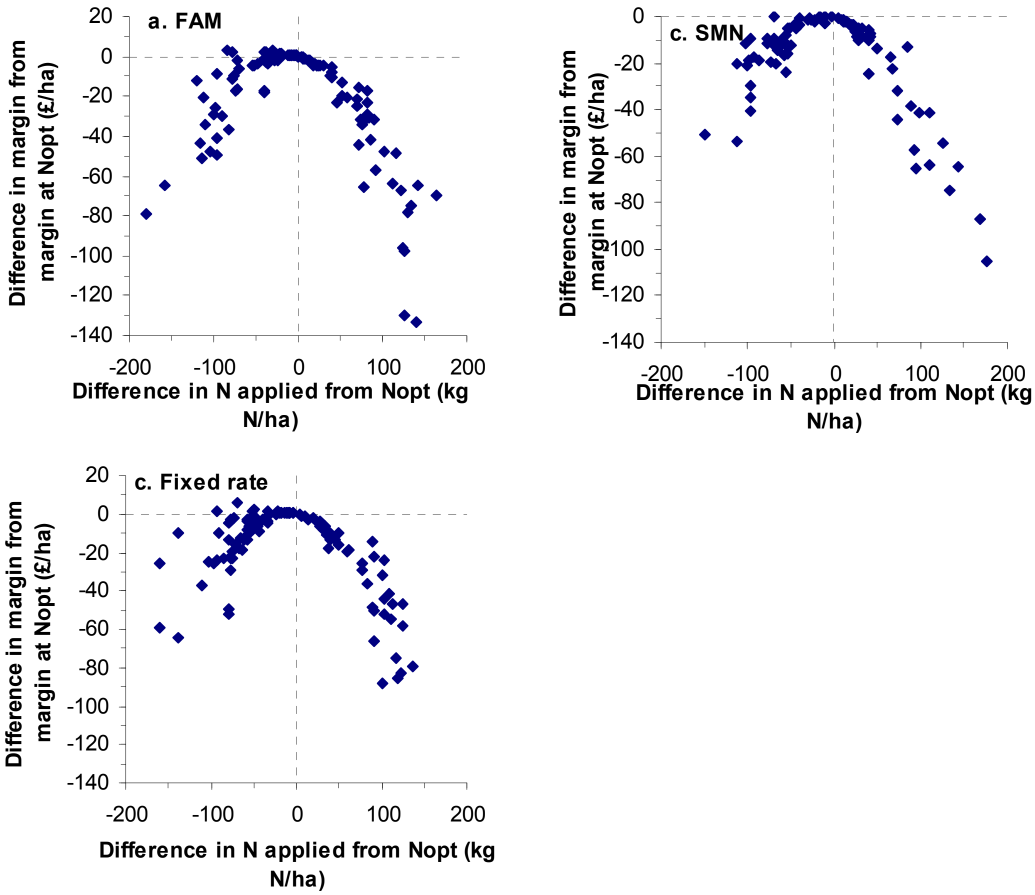

Figure 4. Effect of applying N rates different to the optimum N rate (Nopt) as a result of: a. RB209 field assessment method recommended (FAM); b. RB209 soil mineral N measurement method recommended (SMN); or c. a fixed rate of N (180 kg N/ha) on Margin over N costs (£/ha) of winter wheat.

GHG emissions were initially calculated on a per hectare basis without taking account of indirect effects of LUC. Since standard figures had been used for emissions associated with field operations and pesticide use etc., there was a near linear relationship between the difference in N applied from Nopt and GHGs per hectare (data not shown). The only emissions which scaled with yield were the N2O emissions associated with crop residues and emissions due to grain drying. With every kg N increase over the Nopt, GHGs increased by 17 kg CO_2e/ha and *vice versa*.

Where GHGs were estimated on a per tonne basis and took account of LUC, average increases in emissions compared to those at Nopt were 16, 28 and 10 kg CO_2e/t associated with a fixed N rate, FAM and SMN recommendations, respectively (Table 3).

The effects of under- and over-fertilising on GHGs differed (Figure 5). Where N recommendations or the fixed N rate were higher than Nopt, GHG emissions per tonne of grain increased significantly. The maximum increases in GHGs compared to those at Nopt were 245, 289 and 314 kg CO_2e/t with a fixed N rate, FAM and SMN recommendations, respectively (Table 3). This is because N, the biggest contributor to emissions, is increasing with little associated increase in yield. The small increase in yield above the Nopt means there is little or no effect of LUC. At N levels below Nopt, GHG emissions tended to decrease slightly and level off (Figure 5). Here, although N is decreasing, the yield foregone by using lower N levels means that more land would have to be converted to make up the shortfall in production, resulting in further GHG emissions.

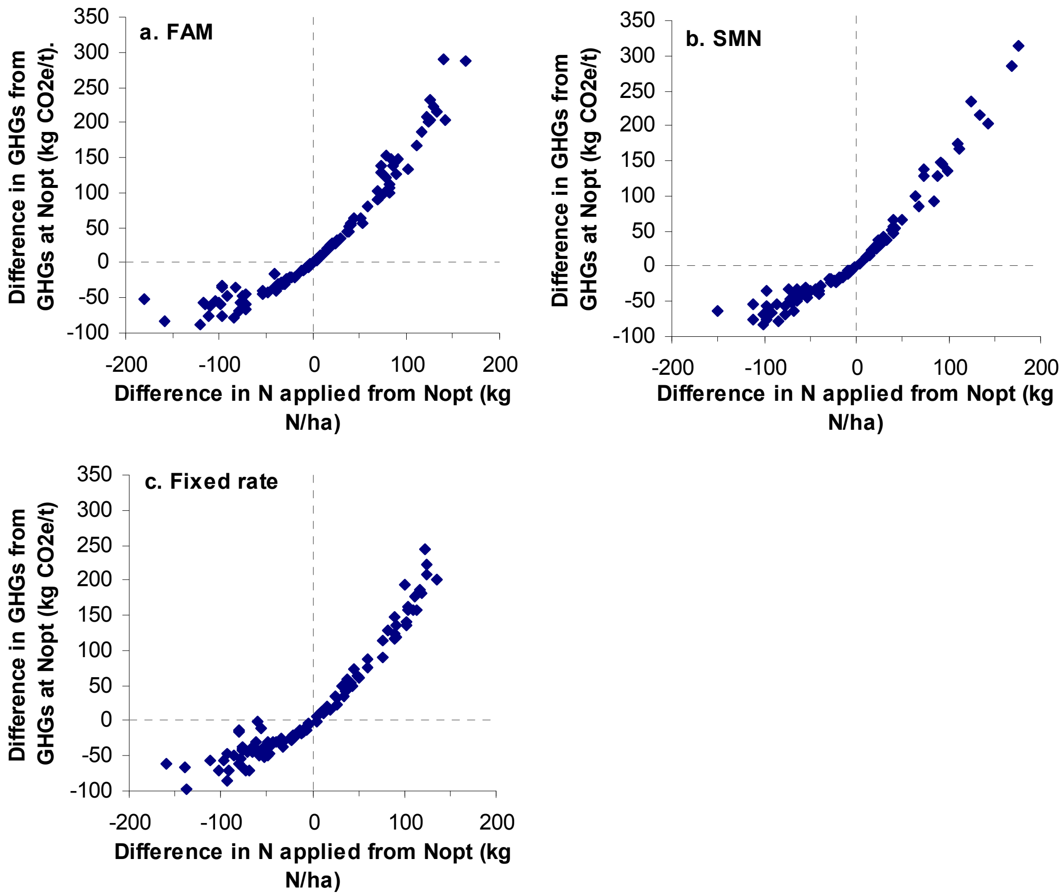

Figure 5. Effect of applying N rates different to the optimum N rate (Nopt) as a result of: a. RB209 field assessment method recommended (FAM); b. RB209 soil mineral N measurement method recommended (SMN); or c. a fixed rate of N (180 kg N/ha) on Greenhouse Gas emissions (kg CO_2e/t) of winter wheat taking account of effects of indirect land use change.

Oilseed rape

Over the 48 oilseed rape experiments examined, the average Nopt was 204 kg N/ha, associated with a yield of 4.36 t/ha (at 91% DM; Table 3). The average N rates recommended by RB209 FAM and SMN measurement were lower at 183 and 171 kg N/ha, respectively (Table 4).

Table 4. Winter oilseed rape: Comparison of N recommendation systems (fixed at 192 kg N/ha, RB209 with FAM and RB209 with SMN) with the optimum N rate (Nopt). Data from 48 N response experiments.

	Units	Max.	Min.	Median	Mean
Nopt at BER 2.5:1	*kg/ha*	354	54	221	204
Grain yield at Nopt	*t/ha*	5.35	3.01	4.32	4.36
Fixed N rate	*kg/ha*	192	192	192	192
N recommended by FAM	*kg/ha*	220	160	190	183
N recommended by SMN	*kg/ha*	220	80	190	171
N difference at 192 kg N/ha	*kg/ha*	138	-162	-29	55*
N difference at Nrec by FAM	*kg/ha*	106	-185	-12	60*
N difference at Nrec by SMN	*kg/ha*	63	-164	-33	40*
Yield change at 192 kg N/ha	*t/ha*	0.15	-0.72	-0.09	-0.11
Yield change at Nrec by FAM	*t/ha*	0.11	-0.96	-0.03	-0.15
Yield change at Nrec by SMN	*t/ha*	0.09	-0.73	-0.11	-0.14
Margin change at 192 kg N/ha	*£/ha*	0.26	-89.60	-13.34	-20.89
Margin change at Nrec by FAM	*£/ha*	0.30	-131.98	-15.71	-25.17
Margin change at Nrec by SMN	*£/ha*	0.30	-91.98	-9.99	-15.51
GHGs change at 192 kg N/ha	*kg CO_2 eq/t*	676	-245	-53	35
GHGs change at Nrec by FAM	*kg CO_2 eq/t*	500	-247	-21	22
GHGs change at Nrec by SMN	*kg CO_2 eq/t*	179	-247	-56	-39

* Means of N difference calculated with all differences as positive

As with the wheat, the ranges of the RB209 recommendations were significantly smaller than the range of the actual Nopts (a range of 300 kg N/ha; Table 4). The recommendations generated by RB209 with FAM only varied between 160 and 220 kg N/ha, a range of 60 kg N/ha (Table 4). Also as with the wheat, there was no relationship between the RB209 with FAM recommendations for OSR and the actual Nopts (Figure 6a). However, there was a significant relationship between the recommendations from the RB209 with SMN and actual Nopts (R^2 = 0.564; Figure 6b). It seems likely that the accuracy of the RB209 with SMN measurement was due to a combination of measuring both SMN and crop N in early spring. Crop N can vary significantly in oilseed rape and is therefore an important factor to consider when estimating the SNS. The average amount the SMN N recommendation deviated from the actual Nopts was lower than the other two options at 40 kg N/ha, compared to 55 and 60 kg N/ha for the fixed rate (192 kg N/ha) and FAM recommendation, respectively. The median of the N differences (Table 4) showed that RB209 recommendations and the fixed N rate tended to underestimate crop N requirements.

The average effects on yield of applying N at a fixed rate, or FAM or SMN recommended rates were -0.11, -0.15 and -0.14 t/ha, respectively (Table 4). Under-fertilisation led to greater yield reductions than over-fertilisation led to yield increases (Figure 7, Table 4) for the reasons given in the wheat section.

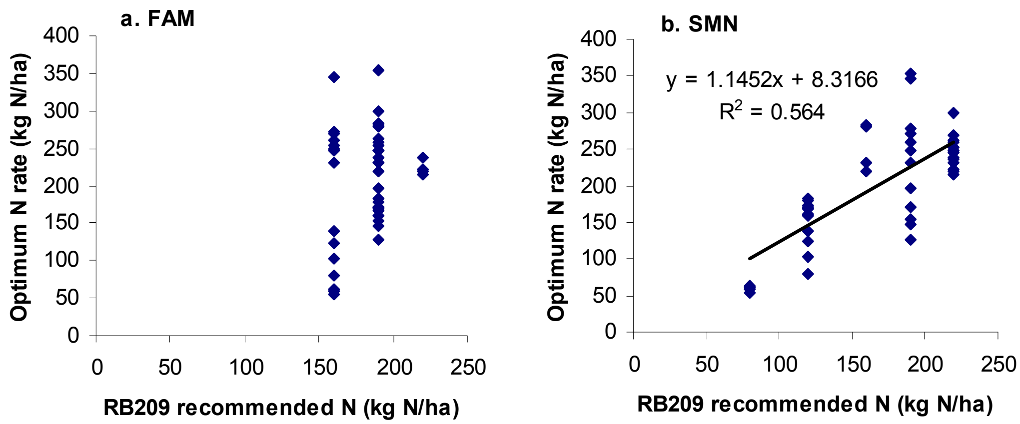

Figure 6. Relationships between the actual optimum N rate calculated of oilseed rape N response experiments and RB209 N rate recommendations generated using the: a. field assessment method (FAM); or b. Soil Mineral N measurement method (SMN).

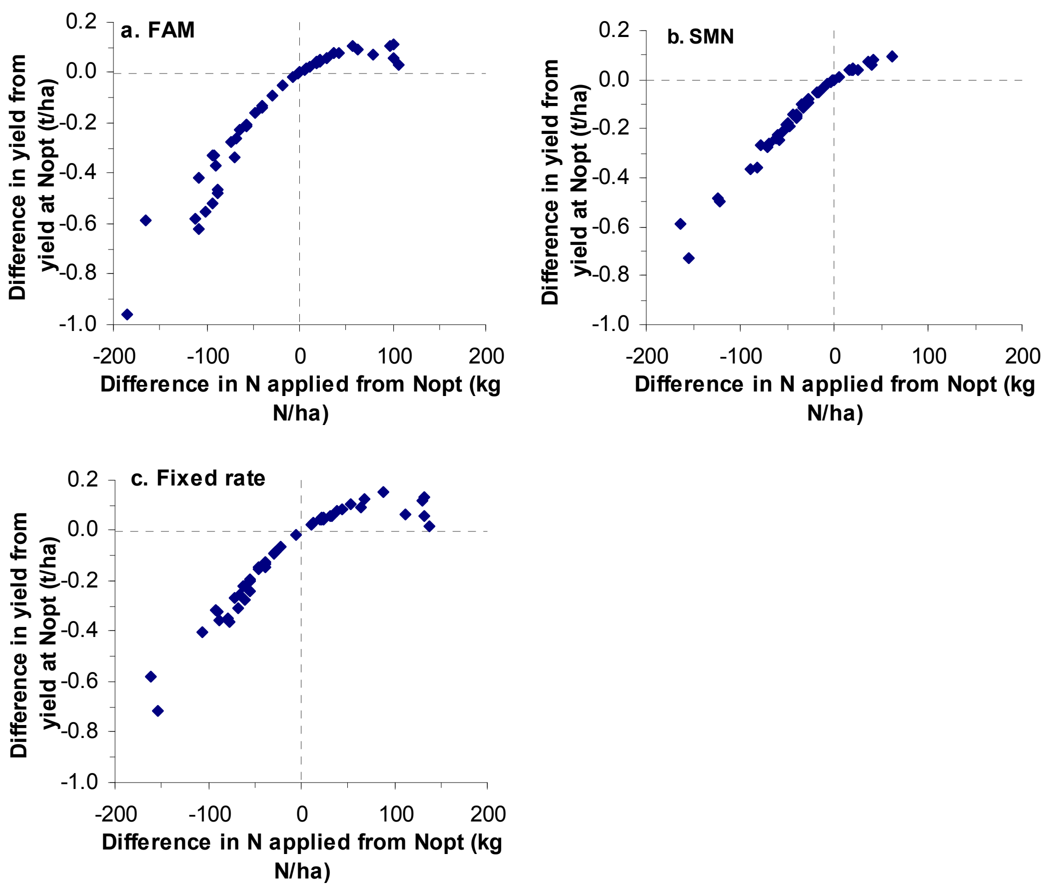

Figure 7. Effect of applying N rates different to the optimum N rate (Nopt) as a result of: a. RB209 field assessment method recommended (FAM); b. RB209 soil mineral N measurement method recommended (SMN); or c. a fixed rate of N (192 kg N/ha) on yield (t/ha at 15% moisture content) of oilseed rape.

The average differences in margin over N costs were -£21, -£25 and -£16 /ha for the fixed N rate, FAM and SMN recommendations, respectively (Table 4). Both under- and over-fertilising compared to Nopt led to reduced margins (Figure 8), although there was very little reduction in margin with over-fertilising by up to 50 kg N/ha compared to under-fertilising by the same amount (Figure 8).

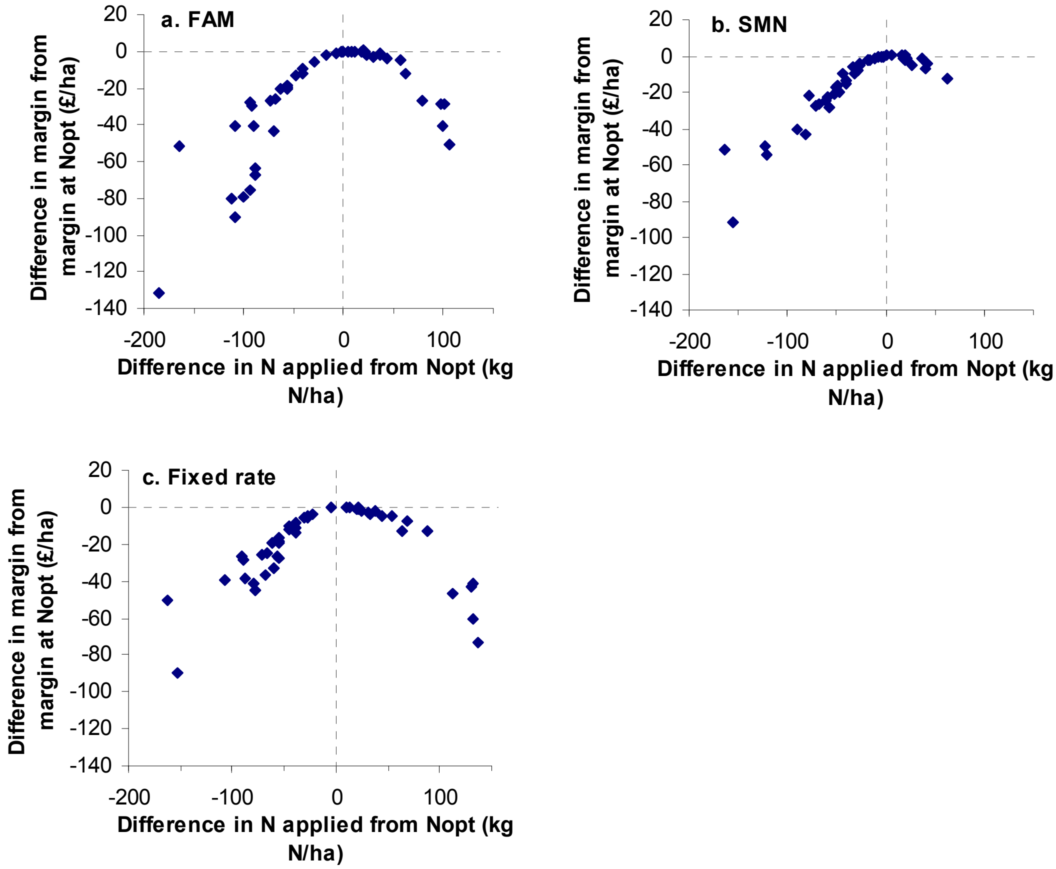

Figure 8. Effect of applying N rates different to the optimum N rate (Nopt) as a result of: a. RB209 field assessment method recommended (FAM); b. RB209 soil mineral N measurement method recommended (SMN); or c. a fixed rate of N (192 kg N/ha) on Margin over N costs (£/ha) of oilseed rape.

On average, GHG emissions were increased by applying a fixed N rate, or FAM recommendations, compared to those at Nopt. Average increases were 35 and 22 kg CO_2e/t for fixed rate and FAM recommended rates, respectively (Table 4). If SMN measurement recommendations were followed, however, GHGs were actually reduced compared to those at Nopt by 39 kg CO_2e/t on average (Table 4). This was because the majority of SMN recommendations were below Nopt (Figure 9), where GHGs were generally reduced compared to those at Nopt.

The shapes of the relationships between the difference in GHGs from Nopt and the difference in N applied from Nopt were similar to those found in the wheat where N applied was above Nopt (Figures 5 & 9). However, in the oilseed rape graphs for FAM recommendations and fixed rate N (Figure 9a & c), below a difference in N applied from Nopt of approximately -50kg N, GHGs increased, in Figure 8a to levels higher than at Nopt. At levels of N far below Nopt, LUC has a large effect on GHGs compared to the reduction in GHGs resulting from less N applied.

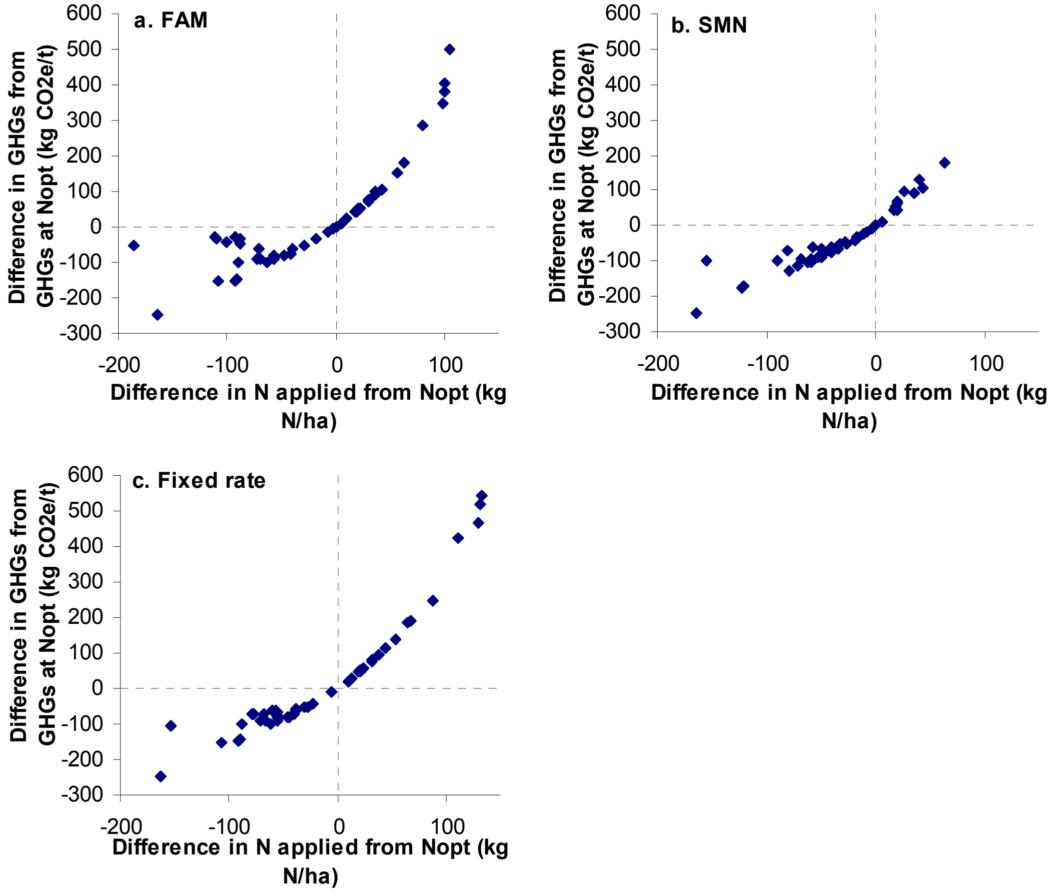

Figure 9. Effect of applying N rates different to the optimum N rate (Nopt) as a result of: a. RB209 field assessment method recommended (FAM); b. RB209 soil mineral N measurement method recommended (SMN); or c. a fixed rate of N (192 kg N/ha) on Greenhouse Gas emissions (kg CO_2e/t) of oilseed rape taking account of effects of indirect land use change.

Winter barley

Significantly fewer winter barley N response experiments were available to study than wheat or oilseed rape experiments. Only 10 have been included in the analysis. The average Nopt of these experiments was 213 kg N/ha, associated with a yield of 8.31 t/ha at 85% DM (Table 5).

The average Nopt was 41 and 23 kg N/ha higher than the average FAM and SMN RB209 recommendations, respectively, and 69 kg N/ha higher than the average N rate used on feed barley over the last three years (144 kg N/ha; Table 5). Indeed, the highest N rate recommended by the latest version of RB209 is 210 kg N/ha (Anon., 2010), which is lower than the actual Nopt in half of the experiments studied here. The average errors associated with applying N at a fixed rate, or at FAM and SMN recommended rates compared to Nopt were 72, 45 and 32 kg N/ha, respectively (Table 5).

Table 5. Winter barley: Comparison of N recommendation systems (fixed at 144 kg N/ha, RB209 with FAM and RB209 with SMN) with the optimum N rate (Nopt). Data from 10 N response experiments.

	Units	Max.	Min.	Median	Mean
Nopt at BER 5:1	*kg/ha*	288	129	207	213
Grain yield at Nopt	*t/ha*	5.40	9.64	8.70	8.31
Fixed N rate	*kg/ha*	144	144	144	144
N recommended by FAM	*kg/ha*	190	150	170	172
N recommended by SMN	*kg/ha*	210	150	190	190
N difference at 144 kg N/ha	*kg/ha*	15	-144	-63	72*
N difference at Nrec by FAM	*kg/ha*	21	-102	-37	45*
N difference at Nrec by SMN	*kg/ha*	21	-82	-17	32*
Yield change at 144 kg N/ha	*t/ha*	0.06	-2.06	-0.66	-0.84
Yield change at Nrec by FAM	*t/ha*	0.08	-1.10	-0.30	-0.41
Yield change at Nrec by SMN	*t/ha*	0.08	-0.77	-0.11	-0.22
Margin change at 144 kg N/ha	*£/ha*	-1.35	-73.81	-14.75	-24.48
Margin change at Nrec by FAM	*£/ha*	1.38	-27.51	-5.75	-7.88
Margin change at Nrec by SMN	*£/ha*	1.66	-14.27	-2.73	-3.71
GHGs change at 144 kg N/ha	*kg CO_2 eq/t*	85	-46	-11	0
GHGs change at Nrec by FAM	*kg CO_2 eq/t*	37	-55	-16	-13
GHGs change at Nrec by SMN	*kg CO_2 eq/t*	37	-54	-10	-9

* Means of N difference calculated with all differences as positive

On average, yields were reduced by applying N at a fixed rate, or FAM or SMN recommendations compared to those at Nopt, by 0.84, 0.41 and 0.22 t/ha, respectively (Table 5; Figure 10). Yields were lower than at Nopt in the majority of experiments because N rates were generally below Nopt (Figure 10).

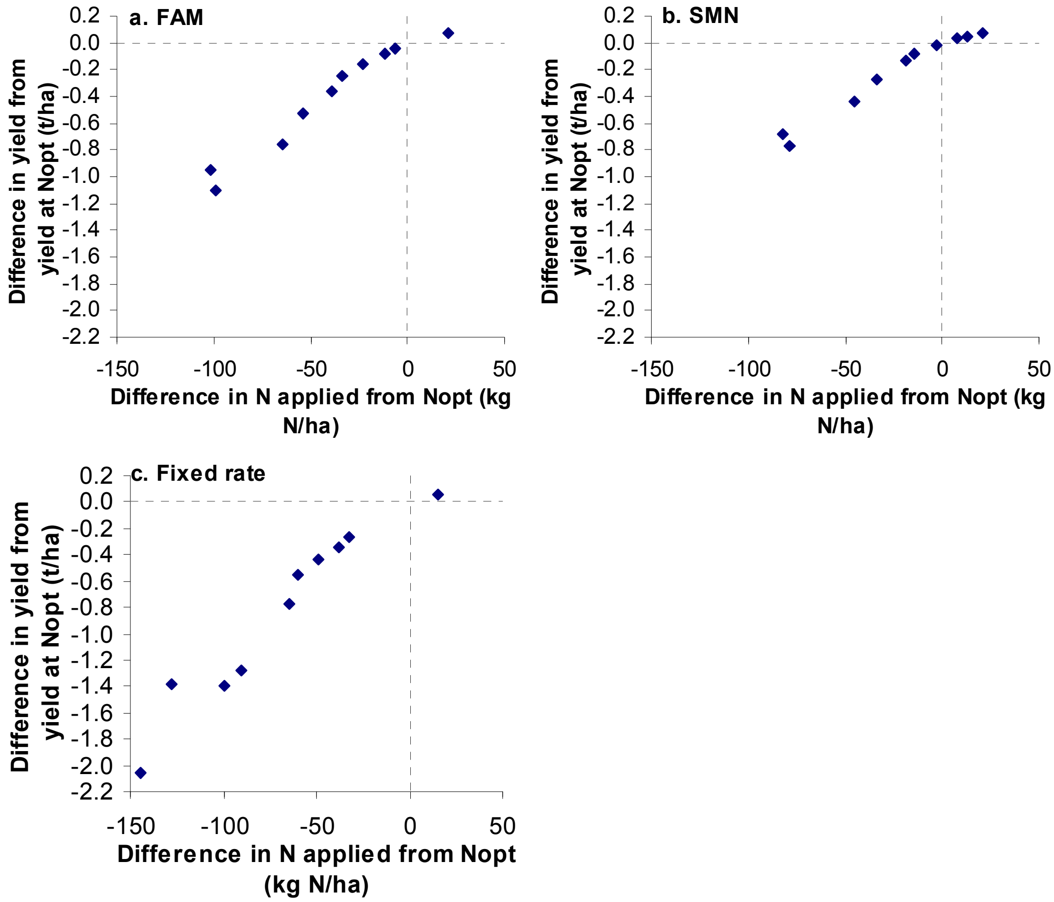

Figure 10. Effect of applying N rates different to the optimum N rate (Nopt) as a result of: a. RB209 field assessment method recommended (FAM); b. RB209 soil mineral N measurement method recommended (SMN); or c. a fixed rate of N (144 kg N/ha) on yield (t/ha at 15% moisture content) of winter barley.

The effects of using a fixed N rate, FAM or SMN recommendation on margins over N costs were -£24, -£8 and -£4/ha compared to applying Nopt (Table 5). Effects of under- and over-fertilising were similar to those found in wheat and oilseed rape, with reduced margins at N levels below and above Nopt (Figure 11).

Average GHG emissions were little changed by applying fixed N rates compared to Nopt (Table 5; Figure 12c). Applying a fixed N rate resulted in differences from Nopt of +15 to -144 kg N/ha, and as a result direct GHG emissions were often reduced compared to those at Nopt, but reduced yields caused some significant increases in GHG emissions due to LUC. This effect was less marked with RB209 recommendations (Figures 12a, b), as the yield reductions relative to Nopt were smaller (Table 5).

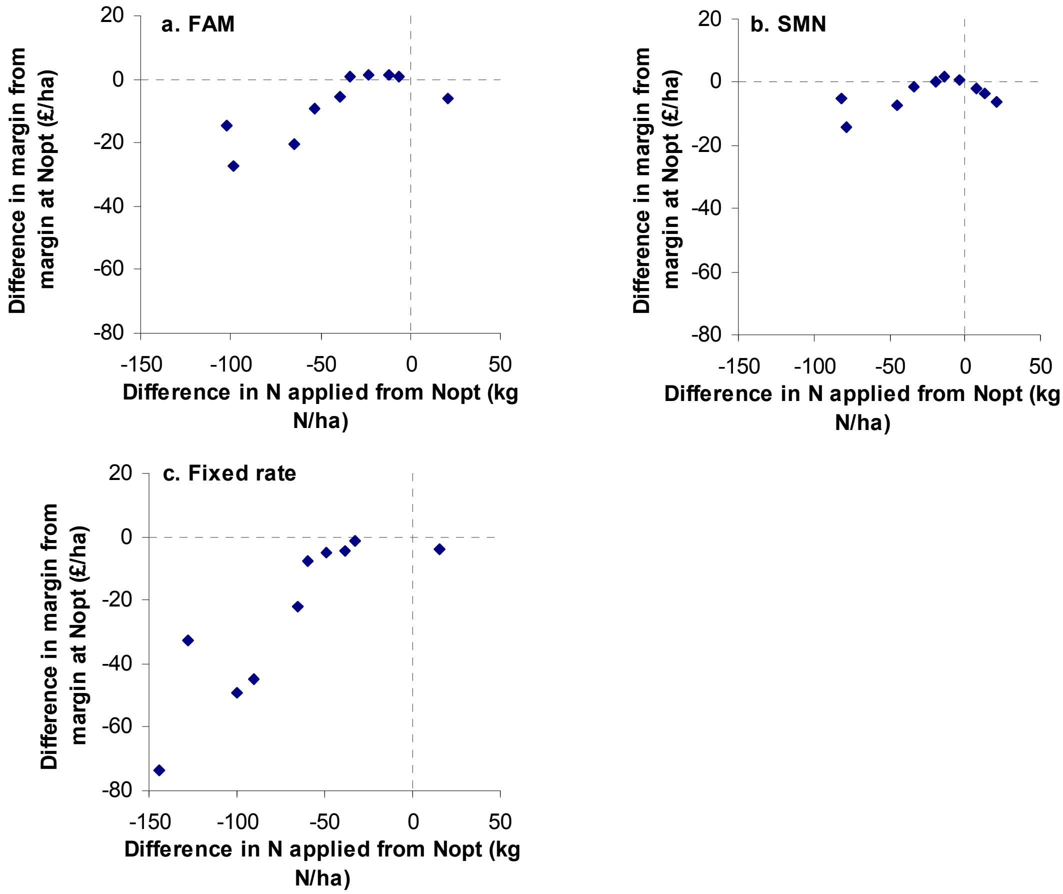

Figure 11. Effect of applying N rates different to the optimum N rate (Nopt) as a result of: a. RB209 field assessment method recommended (FAM); b. RB209 soil mineral N measurement method recommended (SMN); or c. a fixed rate of N (144 kg N/ha) on Margin over N costs (£/ha) of winter barley.

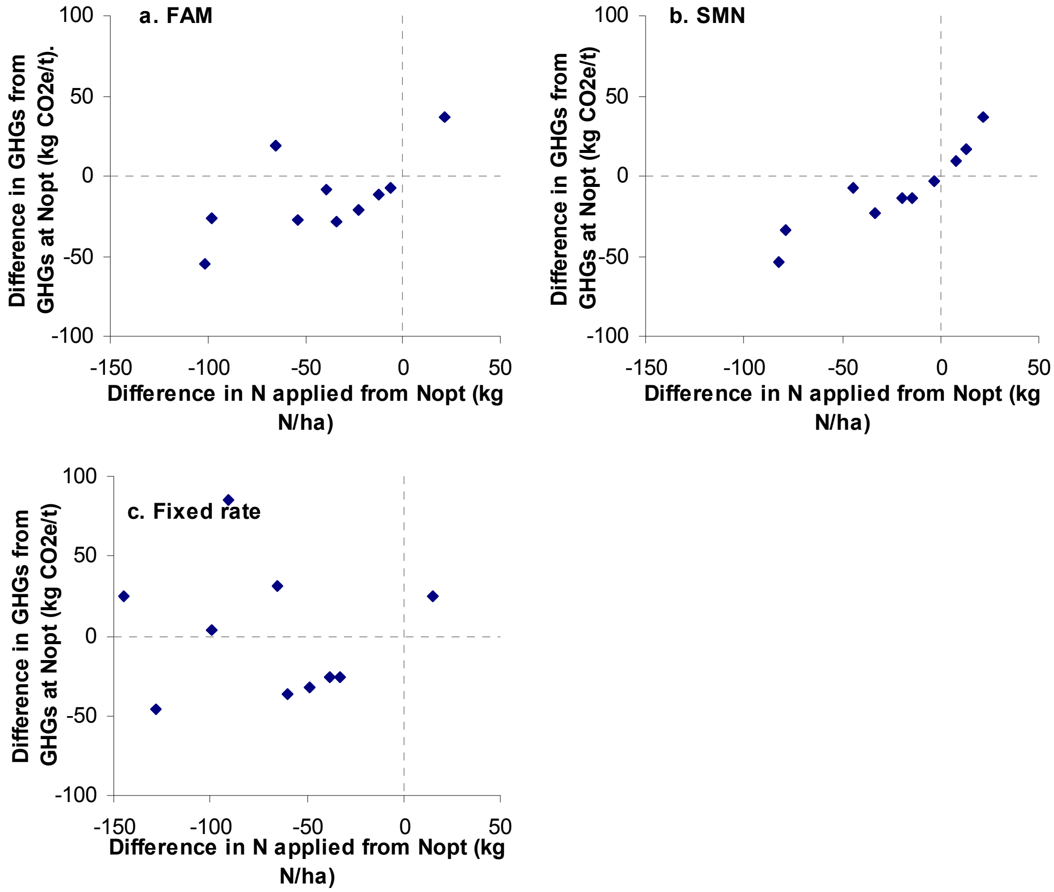

Figure 12. Effect of applying N rates different to the optimum N rate (Nopt) as a result of: a. RB209 field assessment method recommended (FAM); b. RB209 soil mineral N measurement method recommended (SMN); or c. a fixed rate of N (144 kg N/ha) on Greenhouse Gas emissions (kg CO_2e/t) of winter barley taking account of effects of indirect land use change.

Spring barley

The average Nopt of the 12 spring barley experiments was 126 kg N/ha, which was associated with a yield of 5.72 t/ha @ 85% DM (Table 6). The average RB209 recommended rates were similar to the Nopt average at 123 and 140 kg N/ha for the FAM and SMN measurement methods, respectively (Table 6). However, the range of actual Nopts (157 kg N/ha) was larger than those recommended by FAM (70 kg N/ha) and SMN (50 kg N/ha). The average N rate errors associated with applying fertiliser at a fixed rate or FAM or SMN recommended rates were 40, 37 and 40 kg N/ha, respectively.

Table 6. Spring barley: Comparison of N recommendation systems (fixed at 96 kg N/ha, RB209 with FAM and RB209 with SMN) with the optimum N rate (Nopt). Data from 12 N response experiments.

	Units	Max.	Min.	Median	Mean
Nopt at BER 5:1	*kg/ha*	220	63	115	126
Grain yield at Nopt	*t/ha*	6.72	4	5.99	5.72
Fixed N rate	*kg/ha*	96	96	96	96
N recommended by FAM	*kg/ha*	140	70	140	123
N recommended by SMN	*kg/ha*	160	110	150	140
N difference at 96 kg N/ha	*kg/ha*	33	-124	-19	40*
N difference at Nrec by FAM	*kg/ha*	77	-80	-6.98	37*
N difference at Nrec by SMN	*kg/ha*	97	-110	22	40*
Yield change at 96 kg N/ha	*t/ha*	0.07	-1.25	-0.12	-0.28
Yield change at Nrec by FAM	*t/ha*	0.14	-0.64	-0.07	-0.10
Yield change at Nrec by SMN	*t/ha*	0.18	-1.04	0.02	-0.08
Margin change at 96 kg N/ha	*£/ha*	2.07	-24.66	-0.23	-4.21
Margin change at Nrec by FAM	*£/ha*	4.18	-44.05	-2.69	-5.92
Margin change at Nrec by SMN	*£/ha*	1.83	-60	-11.00	-13.90
GHGs change at 96 kg N/ha	*kg CO_2 eq/t*	95	-59	-5	6
GHGs change at Nrec by FAM	*kg CO_2 eq/t*	314	-39	1	32
GHGs change at Nrec by SMN	*kg CO_2 eq/t*	435	-13	40	80

* Means of N difference calculated with all differences as positive

On average, applying a fixed rate of N or FAM or SMN recommendations led to yield reductions of 0.28, 0.10 and 0.08 t/ha, respectively (Table 6). As with the other crops, over-fertilisation would generally lead to small yield increases, whereas under-fertilisation would lead to large yield decreases whatever the N rate strategy (Figure 13). However, where N rates are significantly higher than Nopt, the shape of the LEXP curve means that there can be yield decreases compared to the Nopt (Figure 13 a & b). This can be due, for example, to high N rates causing significant lodging and so a reduction in yield.

As with the other crops, applying a fixed rate of N, or rates recommended by FAM and SMN generally had a negative effect on the margin over N costs compared to those at Nopt (Table 6; Figure 14).

GHG emissions were again found to be higher, on average, where a fixed N rate or FAM or SMN recommended rates were used compared to Nopt (6, 32 and 80 kg CO_2e/t higher, respectively; Table 6). As well as GHG increases with over-fertilisation, increases were again found with under-fertilisation due to LUC effects (Figure 15).

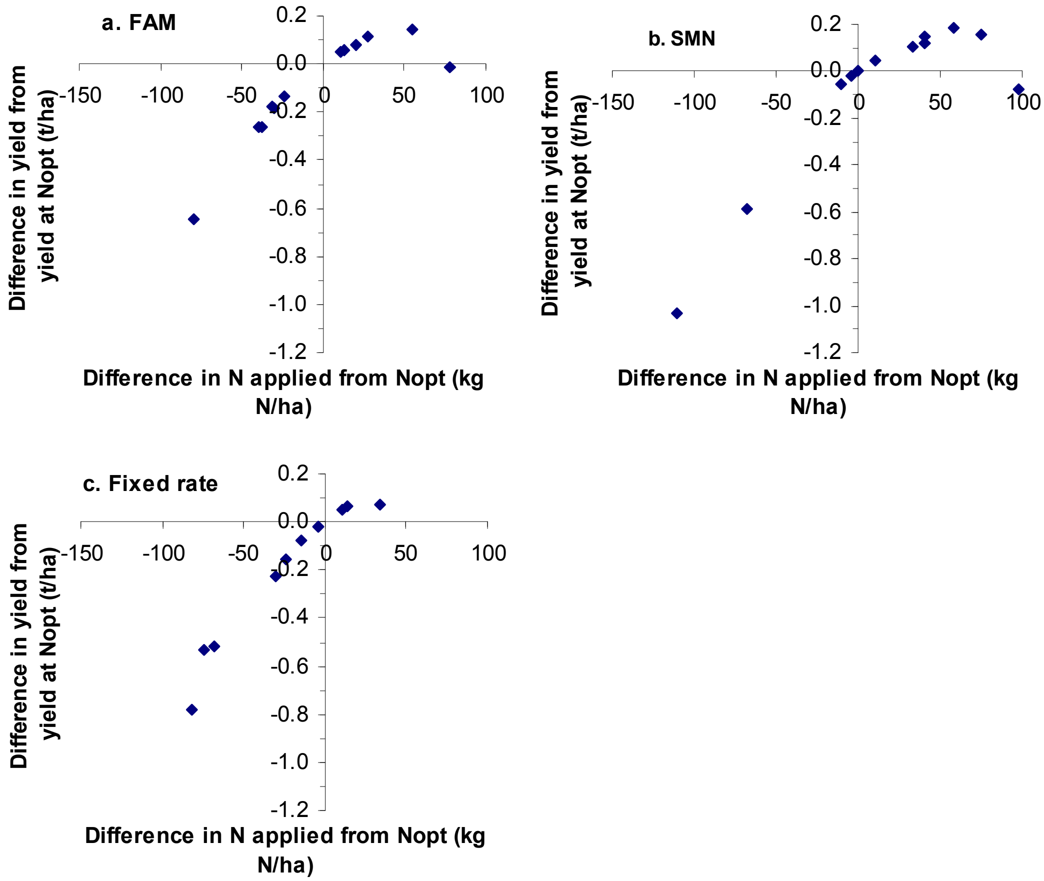

Figure 13. Effect of applying N rates different to the optimum N rate (Nopt) as a result of: a. RB209 field assessment method recommended (FAM); b. RB209 soil mineral N measurement method recommended (SMN); or c. a fixed rate of N (96 kg N/ha) on yield (t/ha at 15% moisture content) of spring barley.

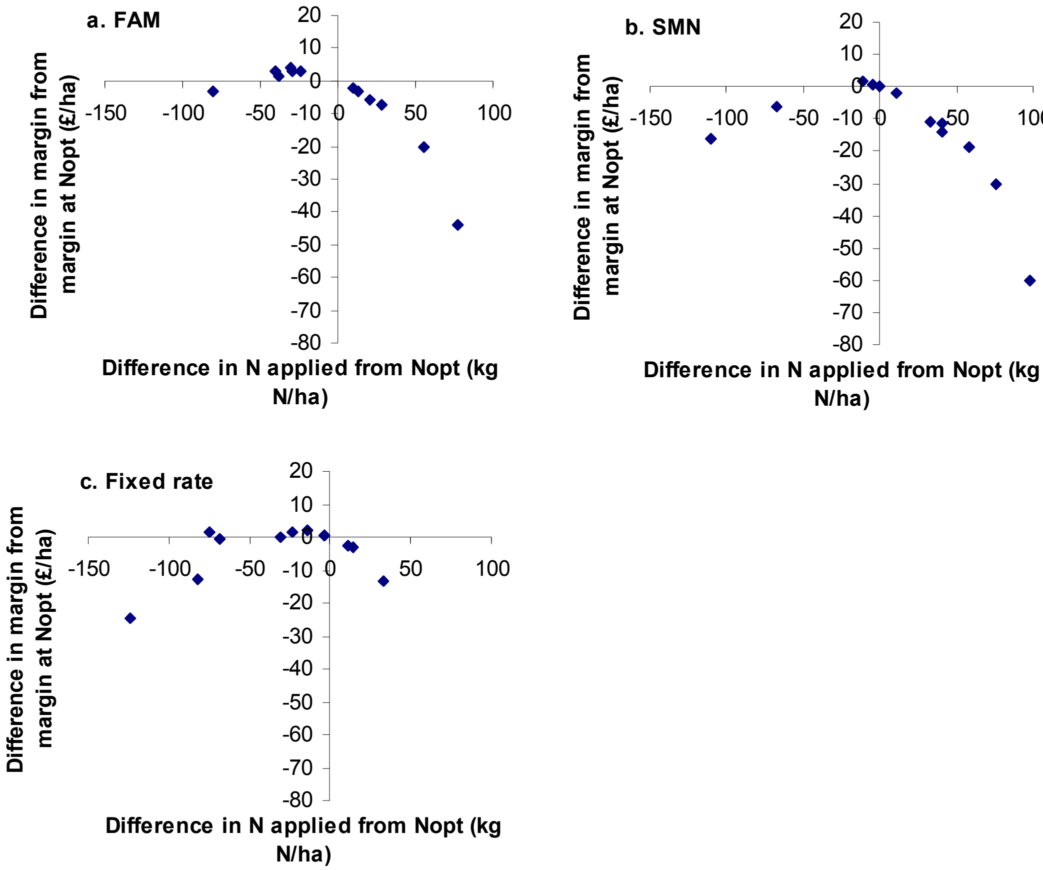

Figure 14. Effect of applying N rates different to the optimum N rate (Nopt) as a result of: a. RB209 field assessment method recommended (FAM); b. RB209 soil mineral N measurement method recommended (SMN); or c. a fixed rate of N (96 kg N/ha) on Margin over N costs (£/ha) of spring barley.

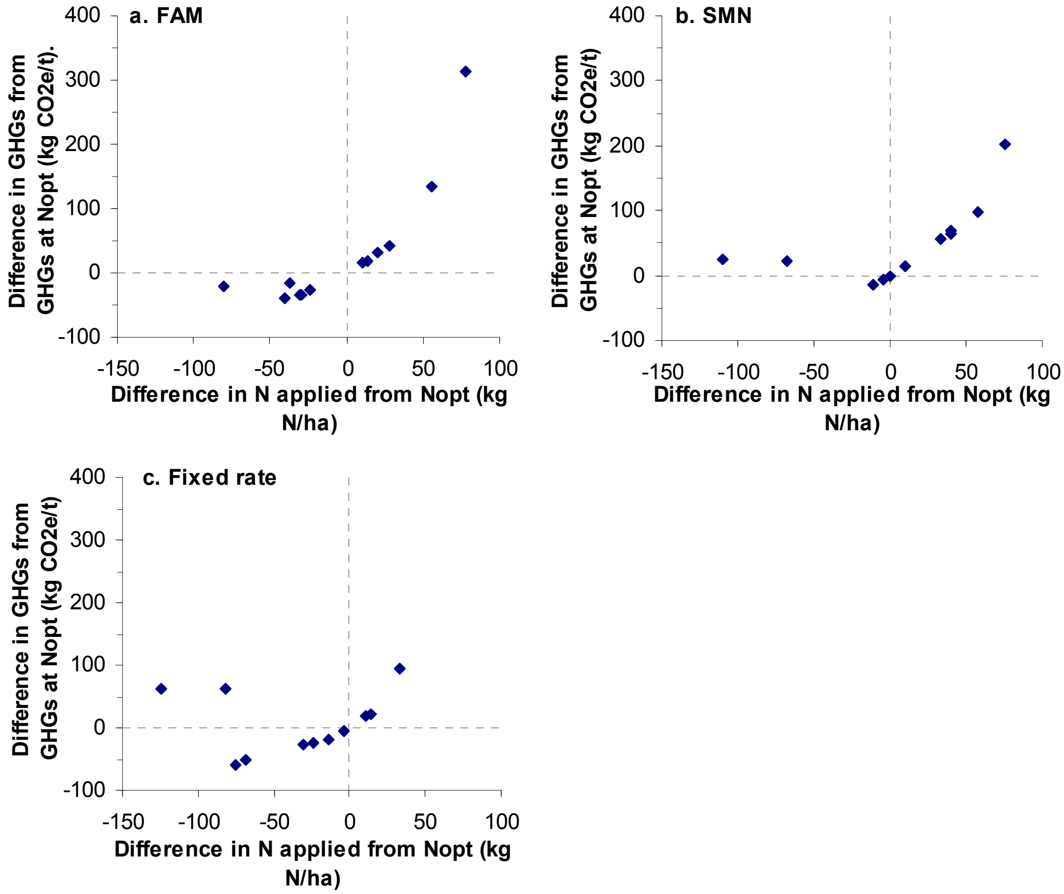

Figure 15. Effect of applying N rates different to the optimum N rate (Nopt) as a result of: a. RB209 field assessment method recommended (FAM); b. RB209 soil mineral N measurement method recommended (SMN); or c. a fixed rate of N (96 kg N/ha) on Greenhouse Gas emissions (kg CO_2e/t) of spring barley taking account of effects of indirect land use change.

Conclusions

This study aimed to estimate the level of imprecision in N fertiliser use and what effects this has on yield and GHG emissions. It assumed that a grower would use RB209 recommendations (using FAM or SMN measurement) to work out crop N requirements, or may otherwise apply a fixed rate to all crops.

The winter wheat and spring barley experiments studied showed that, on average, RB209 recommendations gave similar recommendations to the average optimum N rate. Oilseed rape N recommendations were, on average, 27 kg N/ha lower than the average Nopt, and winter barley N recommendations were, on average, 32 kg N/ha lower than the average Nopts. However, in all cases, ranges of actual Nopts were significantly larger than the range of recommendations that are possible from RB209.

With winter wheat and oilseed rape, where most data were available, no relationships between the amount of N recommended using RB209's FAM method and the calculated Nopts were found. There were, however, significant positive relationships between the amount of N recommended through the SMN measurement method, and the actual Nopt for both crops, and the relationship was particularly good for oilseed rape. The average error in the amount of N applied from using the RB209 SMN measurement method compared to the actual Nopt was also less than that associated with using the FAM in winter wheat, oilseed rape and winter barley, although average errors were still 54, 40 and 27 kg N/ha, respectively.

There is an error associated with fitting the Nopt. In this study, any experiments with large errors were removed. It can be concluded that using the RB209 SMN method is generally more precise that using the FAM.

Using the average N rate applied to a particular crop over the last three years gave different errors according to the crop. However, in all crops these 'fixed rates' were lower than the average actual Nopts. This was particularly noticeable in the winter and spring barley experiments, where the fixed rates were 69 and 30 kg N/ha, respectively, lower than the actual Nopts. However, only ten winter and twelve spring barley experiments were available for this study. Further experiments are needed to improve understanding of N responses in these crops.

The effects of the N rate errors on yields, margins over N costs and GHG emissions were similar for all crops. On average, yields were reduced, but it could be seen that although under-fertilisation led to dramatic decreases in yield, over-fertilisation generally led to very slight increases in yield. Both under- and over-fertilisation led to decreases in margins over N costs, although consistent with Sylvester-Bradley *et al.* (2008) decreases in margins were relatively small where N rate errors were in the range of +/- 50 kg N/ha. When N rates were higher than Nopt, the slight increases in yield coupled with increases in N rate associated with N fertilisation led to large increases in GHG emissions on a per tonne basis, and taking account of indirect land use change. Where N rates were slightly (up to 50 kg N/ha) below Nopt, GHGs were generally reduced slightly, but significant under-fertilisation led to increases in GHGs due to the significant amount of land that would need to be put into production to make up the yield foregone by using a low N rate.