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Optimising nitrogen applications for wheat grown for the biofuels market

by

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Acknowledgements

This study is drawn from data from ongoing HGCA project 3084 “Optimising N for Modern Wheat Varieties”, HGCA Project Report 400 “Managing Nitrogen Applications to New Group 1 and 2 Wheat Varieties” and from work package 1, crop responses of the Defra funded project NT2605 (available on the Defra website).

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Abstract

Previous HGCA-funded work has shown that the alcohol yield from wheat is inversely related to its protein content. It seems likely therefore that growing wheat for bioethanol production might require lower nitrogen (N) rates to maximise alcohol yield per ha. This report presents a re-analysis of over 100 sets of wheat N response data, to investigate the extent to which the optimum N rate for bioethanol production differs from that for grain production for the feed market. In addition, for one typical N response, the implications of N fertiliser use on the greenhouse gas (GHG) and energy balance of the resulting biofuel is examined.

Response experiments were chosen where alcohol yield could be estimated from recorded grain protein data, using a previously established relationship showing alcohol yield to increase by 7.2 litres alcohol / tonne for every 1% reduction in grain protein. The response data sets were chosen to represent a range of varieties, soil types, fertiliser types and seasons, so that the results would be as broadly applicable as possible.

Assuming a scenario whereby the bioethanol processor is also growing the crop, the analysis indicated that the optimum N rate for alcohol production per ha was on average 12% lower than the economic optimum for grain production. There was no evidence that this difference in optimum varied significantly between varieties, soil types, fertiliser types or season. However, whilst a reduction in N rate of around 12% would be required to optimise alcohol yield per ha rather than grain yield overall, the adjustment to normal rates that should ultimately be adopted by a grower will depend entirely on the price structure being offered by the grain buyer. If no premium is being offered for low protein, high starch or high alcohol yield grain, then financially the grower will remain better off using the established optima for feed grain production. Where premiums are a possibility, it will be increasingly more important for growers to ensure that N rates above the optimum are avoided.

Analysis of the N rate needed to maximise the energy savings from bioethanol per ha of crop showed that the rate of N required was close to that needed to optimise the alcohol yield per ha. N fertiliser represents a greater proportion of the GHG costs of producing a wheat crop than it does the energy costs, due to the N_2O emissions associated with its manufacture and use. To maximise the GHG savings per ha from bioethanol production therefore required a significantly lower N rate than that needed to optimise the alcohol production, about 100 kg N/ha compared to around 180 kg N/ha respectively. Whilst the best available information has been used to examine

energy and GHG consequences, results should be regarded as provisional as considerable debate continues in the scientific community surrounding the calculation of such GHG and energy costs.

Abbreviations

AN	Ammonium nitrate
CHP	Combined heat and power
CO2	Carbon dioxide
DDGS	Dried distillers grains with solubles
GHG	Greenhouse gas
ha	Hectare
LEXP	Linear plus exponential
N	Nitrogen
N_2O	Nitrous Oxide
NABIM	National Association of British and Irish Millers
NIR	Near Infra Red
Nmax-alcohol	N rate that gives maximum alcohol yield per ha
Nmax-grain	N rate that gives maximum grain yield per ha
Nopt-alcohol	Optimum N rate for alcohol yield per ha
Nopt-grain	Optimum N rate for grain yield per ha
RTFO	Renewable Transport Fuels Obligation
RL	Recommended List
t	Tonnes
Yopt	Yield at the optimum N rate

1.0 Introduction

The production of fuel alcohol from wheat in the UK is expected to begin in 2008 and, if current plans are realised, by 2010 will provide a market for approximately 3.5 million tonnes (t) of grain per annum, in addition to the 0.7 million t already required by the UK potable alcohol industry. UK wheat is already exported to supply fuel alcohol production facilities overseas.

Fertiliser N is a very important input for wheat crops, being one of the largest variable costs and having a determining role on grain yield and grain quality. The increase in grain yield and grain protein content in response to N fertiliser has been well documented (Sylvester-Bradley *et al.*, 1990). Due to the general inverse relationship between protein and starch, increasing grain protein is known to give decreasing alcohol yields (Riffkin 1990; Swanston *et al.* 2005; Smith *et al.* 2006; Kindred *et al*. 2007). Experience from the potable alcohol industry indicates that there is a decrease of 7.2 litres of alcohol per 1% increase in grain protein (Smith *et al*., 2006) as shown in Figure 1. Grains with low protein contents therefore give higher alcohol yields and are therefore more valuable to processors. As well as giving higher alcohol yields, lower protein grain may also be of greater value to processors due to the reduced quantities of residual materials that need to be processed, potentially giving savings in energy costs.

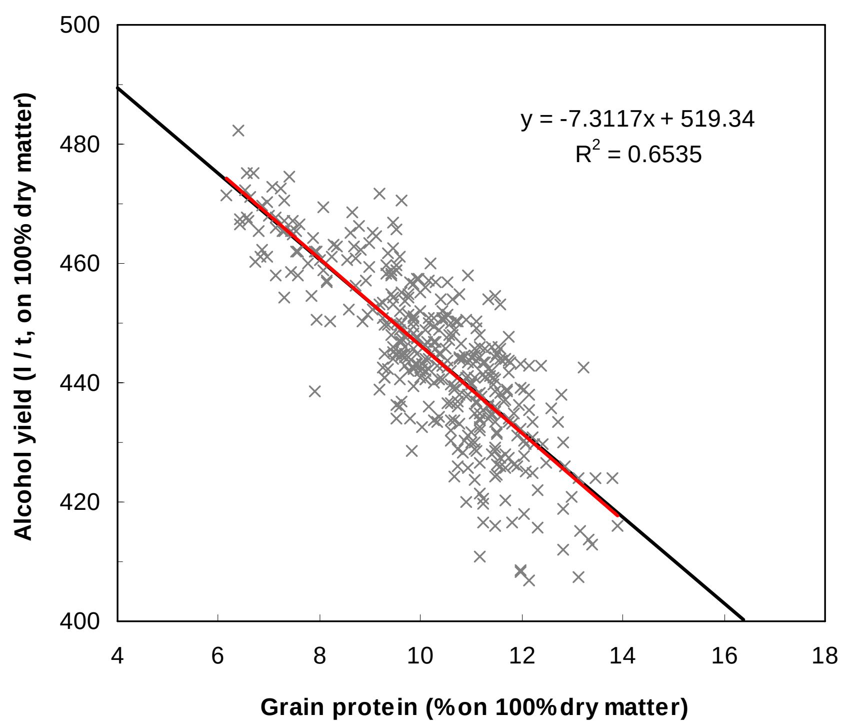

Figure 1 – Alcohol yields of grain samples from RL variety trials against crude protein content. Alcohol yields were measured by the Scotch Whisky Research Institute (SWRI) from many sites, harvested from 2003-2005 and from the GREEN grain project in 2005. The slope of the line represents direct replacement of starch by protein and complete conversion of starch to alcohol.

The point on a N response curve where the financial returns from extra grain production are equal to expense of extra fertiliser N is known as the economic breakeven point or N optimum, and is dependent upon the relative prices of grain and fertiliser i.e. the breakeven ratio (amount of grain with equivalent value to an amount of fertiliser N). Defra fertiliser recommendations, RB209 (MAFF, 2000), set out the optimum N rates (those which maximise financial returns to the farmer) at one breakeven ratio (3 kg grain per kg N), for different soil types and different crops, with different soil N supplies. It is used to support fertiliser decisions made by farmers. The RB209 recommendations however, do not provide any indication of the optimum N rate for maximising alcohol yield from a biofuel crop, nor maximising its energy or greenhouse gas (GHG) savings. These variables will become increasingly important considerations with the development of wheat for the UK bioethanol market in the UK over the next few years. If these are considered, the optimum N rate may vary considerably from the current recommendations for grain yield.

Fertiliser N use also has significant environmental consequences. Not only is it associated with losses of nitrate in water and ammonia to the atmosphere but fertiliser N makes up a large share of the energy costs of growing wheat and is associated with a large majority of the GHG emissions from cropping. The manufacture of fertiliser N requires large amounts of energy (40.6 MJ/kg N), uses large amounts of fossil fuels, and can result in significant nitrous oxide (N_2O) emissions from the use of nitric acid (Wood and Cowie, 2004). Nitrous oxide is around 300 times more potent as a GHG than CO_2,, consequently manufacture of N fertiliser results in large GHG emissions (6.69kg CO_2 eq. per kg N) (LowCVP, 2004). N fertiliser is also associated with increased emissions of N_2O from the soil (Webb *et al.*, 2004) which, using IPCC methodology (De Klein *et al.*, 2006), equates to 6.2kg CO_2 eq. per kg N (HGCA Project MD0607-0003: “Facilitating carbon accreditation schemes for biofuel production”). At N rates commonly used in the UK, fertiliser N manufacture and use can therefore account for 65% of the total GHG emissions from a wheat derived biofuel (Woods *et al.*, 2005, (HGCA GHG Calculator)).

Carbon accreditation schemes, which are due to be introduced as part of the Renewable Transport Fuels Obligation (RTFO) from 2010 will require some level of carbon reporting. Minimising GHG emissions per unit of biofuel is likely to become increasingly important. It is possible in time that premia may be available (or an absolute requirement may be put in place) for ‘low carbon’ grain that produces biofuels with advantageous GHG and energy balances. Hence optimising fertiliser N use for biofuel crops to maximise GHG savings may be substantially different to optimising fertiliser N use for yield.

Growers aiming to provide grain for alcohol production may therefore need to change their fertiliser practice from that which optimises grain yield to that which optimises grain value to the processor and (in the future) minimises carbon costs per unit of output. The optimum N rate for grain for bioethanol, or for any market, will always be a function of the cost of fertiliser relative to output (grain or alcohol) (the break-even ratio), together with the shape of the response curve of crop output to N input. This report provides information to growers and processors in the wheat for alcohol industry on how the optimum N rates to maximise returns from alcohol production compare to those used conventionally for grain production, and to assess how this is affected by variety, growing conditions, and economic scenarios.

The specific objectives of this report were to –

- Collate data and fit curves for the responses to fertiliser N of grain yield, grain protein, alcohol processing yield and alcohol production per hectare (ha) covering different varieties, regions, soil types and seasons.
- Determine economically optimum N rates and outputs for grain yield and alcohol production at a suitable range of prices for grain, N fertiliser and ethanol.
- Assess how economically optimum N rates differ for grain yield and alcohol production, and how these differences vary with variety and growing conditions.
- Consider optimising N applications in terms of overall energy and carbon balance
- Suggest appropriate strategies for fertiliser N use on wheat in spring 2007 and subsequent seasons, and identify gaps in information that need to be addressed by future research.

2.0 Optimising N rates for alcohol production

2.1 Methods employed

2.1.1 Data collection

This project makes use of grain yield and grain N data from 3 projects; HGCA Project 2700 which investigated the optimum N rate for modern bread making (group 1 and 2) varieties (Dampney *et al.* 2006a), HGCA Project 3084 which is currently investigating the optimum N of modern high yielding feed wheat and barley varieties compared to data for older varieties that underpins the current RB209 recommendations (MAFF 2000), and part of the Defra funded project NT2605 which compared fertiliser types (Dampney *et al.,* 2006b), although only data for the ammonium nitrate (AN) and urea treatments were utilised. Grain yield and grain N data were collected from a total of 38 N response experiments, giving a total of 146 treatment datasets (site, season, variety or fertiliser type) for which N response curves were fitted (details given in section 2.5). These experiments were carried out between 2002 and 2006 at 12 sites throughout England and Scotland, representing 25 different varieties on 4 different soil types and 2 fertiliser types. Detailed information on the agronomic regimes used in the production of the data used in this report can be found by referring to the original reports from which the data were derived, or, for project 3084, by request to J. Blake, ADAS Rosemaund.

2.1.2 Experimental data

To allow comparisons between responses, the wheat varieties represented in the dataset were classified on the basis of whether they were a milling (National Association of British and Irish Millers (NABIM) groups 1 or 2) or feed variety (NABIM groups 3 or 4) or a new (first added to the HGCA RL after 1990) or an old variety (first added to the HGCA Recommended List (RL) before 1990). Soil types were based on RB209 classifications. Data from the NT2605 experiments were used for determination of whether fertiliser type (urea or AN) had an effect on the change in optimum N rate.

2.1.1 Information on sites used in this study

Location	County	RB209 Soil Type
Boxworth	Cambridgeshire	Clay
Edlington	South Yorkshire	Shallow over chalk
Forgandenny	Perth and Kinross	Clay
High Mowthorpe	North Yorkshire	Shallow over chalk
Masstock Barnston	Merseyside	Clay
Masstock Fowlmere	Cambridgeshire	Shallow over chalk
Rosemaund	Herefordshire	Deep silty, clay
Rothamsted	Hertfordshire	Clay
SAC	Lothian	Sandy
SAC Bush	Lothian	Sandy
Sutton Bonington	Leicestershire	Other mineral
Terrington	Norfolk	Deep silty

2.1.2 Varieties used in this study

Group 1 and 2 wheats	Group 3 and 4 wheats
Avalon	Access
Einstein	Alchemy
Hereward	Ambrosia
Malacca	Consort
Mercia	Deben
Option	Dickson
Solstice	Gladiator
Xi19	*Hobbit*
	Hustler
	Istabraq
	Longbow
	Napier
	Norman
	Riband
	Robigus
	Slejpner
	Virtue

Varieties in italics were classified as old varieties and those in normal type were classified as new varieties.

2.1.3 N rates

For experiments derived from HGCA research projects 2700 and 3084, a series of 6 N rates was used. For experiments based on NT2605 experiments, 7 N rates were used. Soil N supply was assessed by soil mineral N sampling in spring and crop N content.

2.1.4 Calculating alcohol yields

Grain yield data and grain N% data for each experiment was taken at the plot level (3 replicates). Grain N% data were used to calculate grain protein by multiplying by a conversion factor of 5.7.

Grain protein (% at 100% DM) = Grain N (%) x 5.7

Alcohol processing yield per t was calculated as below, which is the regression relationship between measured alcohol yield and protein content of over 400 individual laboratory alcohol yield determinations carried out by the SWRI samples from Recommended List variety trials and the GREEN grain project (Smith *et al.*, 2006). Alcohol yield per ha was then calculated by multiplying grain yield adjusted to 100% DM with alcohol yield per dry tonne.

Alcohol yield (litres per dry tonne) = 520 – (7.2 x protein % DM)

2.1.5 Fitting N response curves

N response curves were fitted for grain yield, grain N%, alcohol yield per tonne and alcohol yield per ha. The grain yield and alcohol yield per ha curves were then used to determine optimum N rates for given economic scenarios. The method adopted to fit response curves for grain yield and to derive optimum N rates was broadly similar to that used to develop the current RB209 recommendations, as described in Dampney *et al.* (2006a).

The method considers that yield increases due to fertiliser N diminish successively as the N rate increases. Following a comparison of curves by George (1984), the linear plus exponential (LEXP) function has been used as the standard method of fitting for fertiliser recommendations, and this was used for fitting data from the experiments reported here. The function is:

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

where y is the yield in t/ha, N is the total applied fertiliser N in kg/ha and a, b, c and r are parameters determined by statistical fitting. These parameters have no distinct meaning and can be correlated with each other e.g. fitting sometimes gives large positive values of ‘a’ with large negative values of b. However, if interdependence between the parameters is appreciated, it is often useful to recognise the main features of responses with which each parameter tends to be associated.

These are as follows:

a: 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 the maximum curvature. Where large N rates cause significant yield loss (e.g. due to lodging), this parameter value tends to be more 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).

For the purposes of comparisons here an ‘individual curve’ approach was taken; response curves were fitted independently to the data for each variety using the LEXP function with floating r, and no consideration was given as to whether a ‘parallel curve’ approach was statistically more justifiable within subsets of the data.

The response curve for alcohol yield per ha was fitted using the LEXP function in the same manner as for grain yield.

To fit responses for grain N%, a Normal Type Curve with Depletion (Murray and Nunn, 1987) was generally used:

$$\text{Grain N\%} = D+C*\exp(-A*(N-B)^{2}$$

If there was no evidence of curvature, a straight line was fitted:

$$\text{Grain N\%} = A+B*N$$

The response of alcohol processing yield per t was calculated from fitted grain N% data using the equations in Section 2.1.4. As alcohol processing yield per tonne is simply a ‘reflection’ of grain N%, it was not necessary to independently fit curves to alcohol processing yield by regression.

2.1.6 Estimating N optima

Estimates of the optimal N rate (Nopt) were derived from the fitted parameters for the LEXP curves as follows:

$$\text{Nopt} = [\ln(k-c)-\ln(b(\ln(r)))]/\ln(r)$$

Where k is the break-even ratio of N (p/kg) to grain (p/kg) or alcohol (litres per kg). The breakeven ratios studied for grain ranged from 3 to 7 (kg grain per kg N). Standard errors of each Nopt value were determined. The grain yield and alcohol yield at Nopt (optimum yield (Yopt)) could be calculated from the fitted parameters.

Optimum N amounts were determined for alcohol yield in exactly the same way as for grain yield. A range of ethanol prices were assumed to give breakeven ratios that ranged from 0.7 to 2.2 (l ethanol per kg N).

The fitted response curves for grain yield and alcohol yields per ha were graphed against the experimental data points to investigate the goodness of fit. Of the original 146 individual N response datasets, 102 were used for the final analysis. Datasets were excluded where there was a poor fit between fitted and original data, where the response was poor or unstable, where grain N% data were missing or where the calculated optimum N rate at 3:1 breakeven ratio was excessively above the maximum N rate for the experiment.

2.1.7 Appropriate breakeven ratios and differing economic scenarios

The breakeven ratio is the quantity of grain or alcohol needed to pay for a kg of N. The optimum N rate is the application rate that gives the economic maximum return from crop production and represents the point on a N response curve where the cost of using more N would not be covered by the value of the extra crop produced. The N recommendations given in RB209 (7^{th} edition, 2000) are based on a breakeven ratio of 3:1 (3kg of grain required to pay for 1 kg of fertiliser N). However, fertiliser N prices have increased since the publication of RB209so higher breakeven ratios are more appropriate at present. Therefore breakeven ratios of 5:1 and 7:1 have also been considered in this report.

It is difficult at the current time to predict what the wholesale ethanol price will be from UK bioethanol facilities. Currently, wholesale prices for ethanol in the UK, imported from abroad are approximately 45p/l. Using the market ethanol price in calculations is potentially misleading as it assumes that there are no other costs involved to the processor except for the grain itself, whereas in reality transport, processing and storage will make up a significant proportion of the producers costs. Therefore, given the current uncertainties of the price at which UK bioethanol will settle and the “true” value of the grain to the processor, we have arbitrarily investigated prices at 20p/l; 40p/l and 60p/l of ethanol. In reality, the value of grain for ethanol may vary significantly from these figures and thus these values are used to examine the sensitivity of optimum N rates to ethanol price.

2.1.8 Comparing optimum N rates

In order to assess the difference in optimum N rates between growing wheat for grain and for alcohol, linear regressions were performed in Microsoft Excel between the optimum N rate for alcohol per ha against the optimum N rate for grain yield. Regressions were performed twice; one set restricted the line of best fit through the origin and another set allowed a Y intercept. Since the precision of the fit did not vary significantly between the two analyses, and the intercept was generally not significantly different to zero; the data presented here are derived from regressions with the line of best fit through the origin.

Regressions between the optimum N rate for grain and for alcohol were carried out at a range of breakeven ratios and ethanol prices for the whole dataset, and also with the data restricted to individual soil types, fertiliser types and variety types.

The b coefficient from the regressions represents the slope of the line of best fit between Nopt for alcohol and for grain under a specified set of conditions (breakeven ratio for grain, ethanol price, variety, soil type, and fertiliser type). It indicates the Nopt for alcohol as a proportion of the Nopt for grain (as shown in Figure 1). The coefficient multiplied by 100 gives the percentage that optimum for alcohol per ha is of the optimum for grain yield, and this is recorded in the results. The confidence interval given represents the t statistic (derived from the degrees of freedom at the 5% confidence limit) multiplied by the standard error of the slope from the regression analysis, also expressed as a percentage.

2.2 Results and discussion

2.2.1 N responses – example case.

Figure 2 shows typical response curves for grain yield, grain protein, alcohol yield per tonne and alcohol yield per ha, using data from the soft wheat variety Istabraq grown at ADAS High Mowthorpe, Yorkshire in harvest 2005. The effect of fertiliser N on grain yield is well documented (Sylvester-Bradley *et al.* 1990). Initial increases in fertiliser N result in large increases in grain yield, but the increases in grain yield become smaller as fertiliser N inputs increase, until a plateau is reached (Figure 2a). Beyond this point, increased fertiliser N applications do not affect grain yields, or yields decline. The application of fertiliser increases grain N and hence grain protein concentration, typically in a sigmoidal pattern as shown in Figure 2b. Using the previously established relationship between grain protein and alcohol yield of 7.2 litres alcohol/dry tonne decrease per 1% increase in grain protein (Smith *et al.* 2006), the response of alcohol processing yield to N fertiliser mirrors inversely that of grain protein. Multiplying the alcohol processing yield per t (Figure 2c) by the grain yield (adjusted to 100% dry matter) gives the alcohol yield per ha (Figure 2d). The response of alcohol yield to N fertiliser is similar to that for grain yield, as grain yield is the principal driver. However, because of the influence of increasing fertiliser decreasing alcohol processing yields per t, the maximum alcohol yield per ha is commonly reached at a lower N rate than that for grain yield. In addition, where increases in N fertiliser (above the yield optimum) continue to increase grain protein and reduce alcohol processing yields, the decline in alcohol yield per ha at high N rates is likely to be greater than any decline in grain yield.

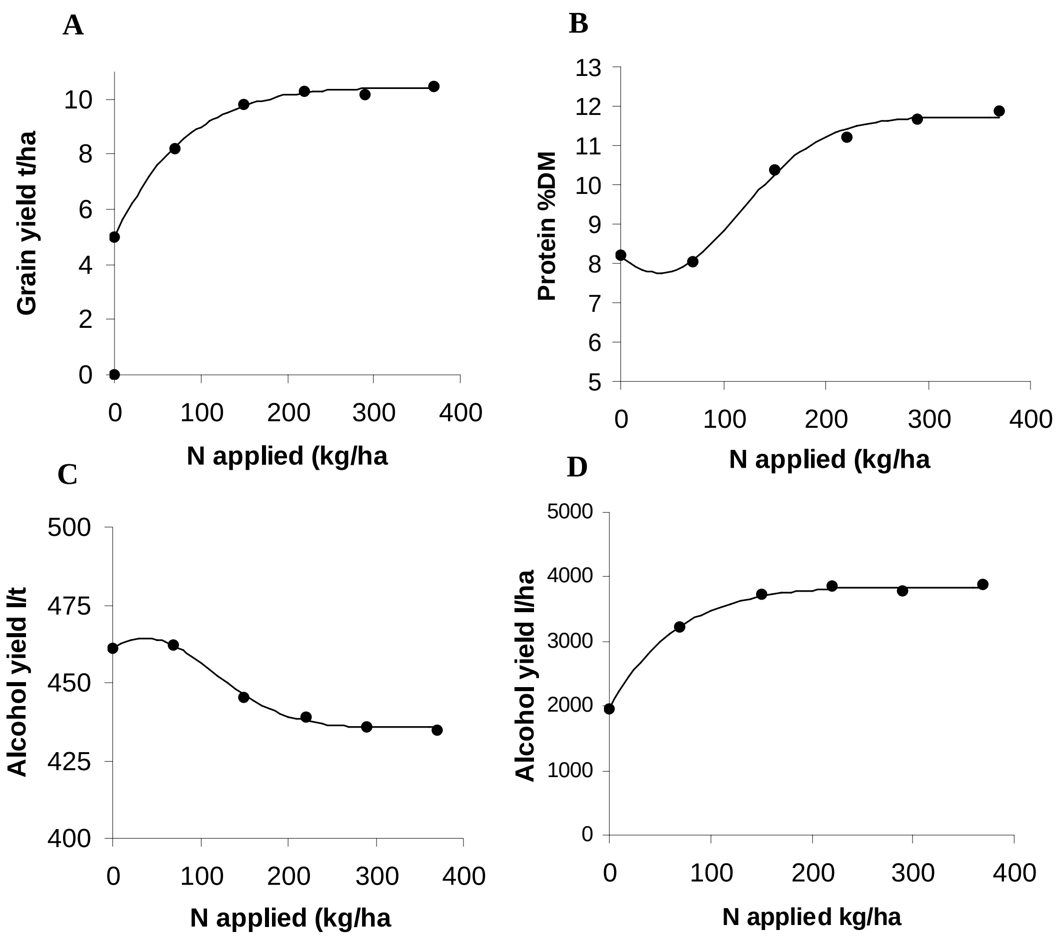

Figure 2 - Response of grain yield (a), grain protein (b), alcohol yield per tonne (c) and alcohol yield per ha (d) to N fertiliser. Data is for Istabraq grown at High Mowthorpe in 2004. See text for curves fitted.

2.2.2 N rates to achieve maximum grain and alcohol yield

N rates needed to achieve *maximum* grain yield are compared to those needed for *maximum* alcohol yield in Figure 3 for 102 response curves. The majority of N responses had N rates for maximum alcohol yield per ha (Nmax-alcohol) that were less than the N rate for maximum grain yield (Nmax-grain). In several instances Nmax-alcohol was considerably less than Nmax-grain. On average the N rate to achieve maximum alcohol yield was 10% less than that to achieve maximum grain yield. Whilst it is apparent then that absolute N requirements for alcohol yield are less than for grain yield, it is also obvious that there is a good deal of scatter in the relationship between Nmax-grain and Nmax-alcohol. This stems from differences in the shapes and inter-relations of the N response curves for grain yield and alcohol processing yield for the range of experimental datasets. For example, where the response of protein (hence alcohol processing yield) to N fertiliser was relatively flat, the difference between maximum N-grain and maximum N-alcohol would be smaller than where N fertiliser had a large effect on alcohol processing yield. It might be expected that these differences would relate to environmental and management factors such as soil type, variety, yield potential etc. These factors are investigated further in Section 2.2.6.

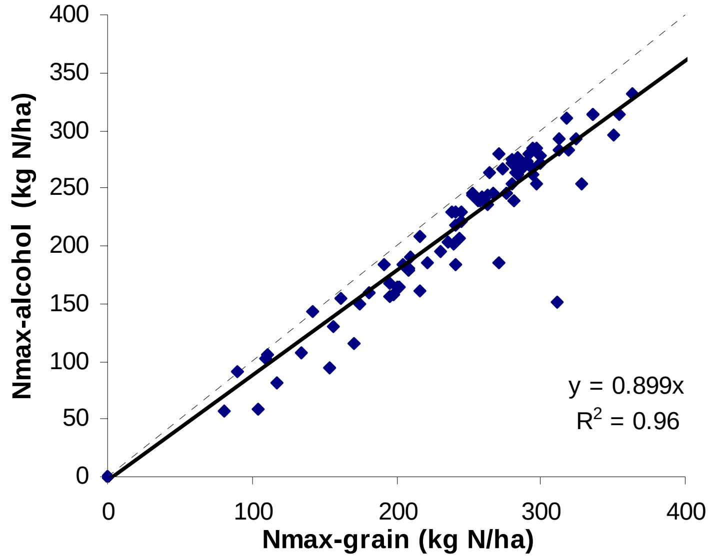

Figure 3 - Relationship between N rate that gives the maximum grain yield (Nmax-grain) and that giving the maximum alcohol yield (Nmax-alcohol) for the response experiments studied (excluding responses where maximum N was greater than 370kg N/ha). The dashed line shows 1:1 relationship and solid line is regression.

2.2.3 Optimum N rates for grain yield

In order to assess the differences between optima for grain yield and optima for alcohol, it is worthwhile first considering how optima for grain yield are determined in some detail. In particular, the effect of grain price and breakeven ratio on the optimum N-rate warrants consideration as the breakeven ratios used for grain and for alcohol can make up an important part of the difference in their optimums.

The optimum N rate for grain yield is the N rate that gives the maximum financial return to the grower per ha, in terms of grain output per ha (grain yield multiplied by grain price) minus fertiliser costs per ha (N rate multiplied by N price). The optimum is therefore dependent on the price of grain relative to the price of fertiliser - the breakeven ratio. Figure 4 shows breakeven ratios for a range of grain prices and AN fertiliser prices.

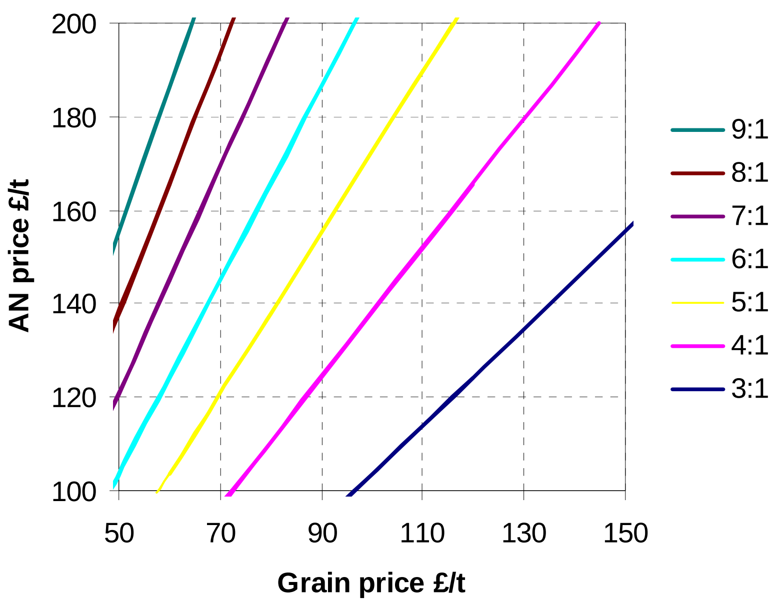

Figure 4 - Breakeven ratios for grain at varying grain prices and AN fertiliser prices.

The optimum N rate for grain yield occurs at the point on the yield response curve where the slope of the curve equals the breakeven ratio. At this point on the curve a 1kg increase in N fertiliser results in an increase of grain yield that equates to the breakeven ratio, so at the optimum N rate for a 5:1 breakeven ratio a 1kg/ha increase in fertiliser N would result in 5kg/ha extra grain yield. At N rates below the optimum, increasing the N rate by 1kg/ha will increase grain yield by *more* than 5kg/ha so it is economically worth applying more N. At N rates above the optimum, increasing the N rate by 1kg/ha will result in an increase in grain yield of *less* than 5kg/ha. In this case the added cost of fertiliser per ha exceeds the added value of grain per ha so it is not economic to apply more N. Maximum financial returns for grain yield, and hence the N optima, are always achieved at the N rate where the slope of the yield response to N equals the break-even ratio.

Increasing the breakeven ratio reduces the optimum N rate to an extent that is dependent upon the shape of the response curve; the ‘flatter’ the shape of the curve the greater the difference in the optima will be. The effect of changing from a 3:1 ratio to higher breakeven ratios (5:1 and 7:1) on the optimum N rate for grain yield for the set of ~100 yield responses (excluding responses where optima at 3:1 were greater than 400kg N/ha) is shown in Figure 5. General trends here show optimum N rates for grain yield (Nopt-grain) at a 5:1 breakeven ratio to be around 10% less than at a 3:1 ratio, and to be around 20% less for a 7:1 ratio. Again, these also show a fair degree of variation between responses in the amount to which an individual response curve is affected by the breakeven ratio. This stems from differences in the shapes of the responses, which may in turn be expected to differ with different environmental and management conditions.

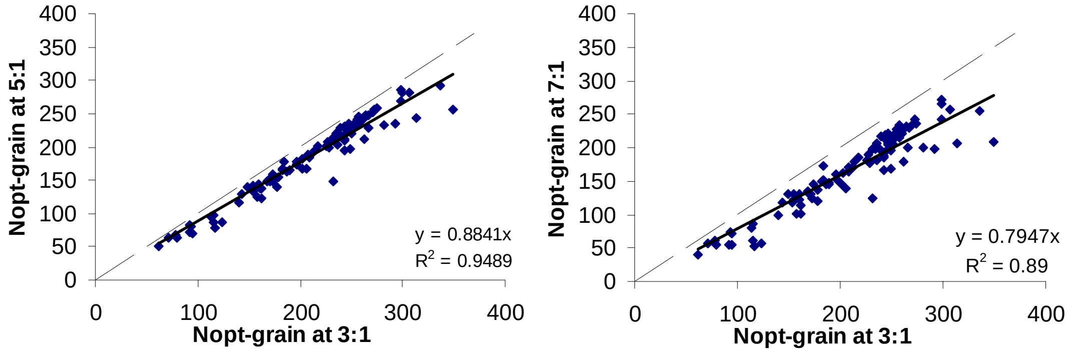

Figure 5 - The effect of changing the grain breakeven ratio on the optimum N rate for grain yield (Nopt-grain) from 3:1 to 5:1 and 7:1 for graphs a and b respectively. Each data point is for an individual response curve. The dashed line represents the 1:1 line and solid line is the regression line.

2.2.4 Optimum N rates for alcohol yield

Optimum N rates for alcohol production have not been explored previously. In order to determine optimum N rates for alcohol production there are a number of difficulties that need to be resolved. At the stage of reporting this work, exact details are not clear for how grain for bioethanol will be traded, whether growers will be rewarded for grain quality, and if so by how much. For this reason this work assumes a situation whereby the bioethanol processor is also growing the grain. In such a case, the bioethanol processor is not interested in how much grain is produced per ha, but rather how much alcohol can be produced per ha. Further, the processor would only be interested in applying N up to the point where extra N per ha provides sufficient extra alcohol per ha to cover its cost, that is the optimum N rate for alcohol yield (Nopt-alcohol) at the appropriate breakeven 'ratio' for ethanol. Analysis of this situation should be instructive in showing how N rates for biofuel crops should be revised to maximise the benefit for the whole industry, both the grower and the processor.

The assumed ethanol price is crucial to determining the optimum N rate for alcohol production. The current market price for ethanol is around 45p/l (F.O. Lichts, 2007). However, it may not be most appropriate to use such a market price in determining the optimum N rate for alcohol production; in this situation N fertiliser is not directly affecting ethanol production per ha in a manner whereby the ethanol is simply harvested from the land. Instead, N fertiliser effects on alcohol production per ha are mediated through grain production per ha. Converting to ethanol will involve additional costs. Therefore, the implied benefit of an extra kg of fertiliser N giving *x* extra litres of alcohol would not in reality give the processor the full value of that alcohol in extra profit, as extra money would also be spent on grain transport, storage and processing. Conversely extra alcohol yield per tonne of grain may be considered to give additional alcohol yield at little or no additional processing cost and perhaps at reduced cost if the cost of processing co products is reduced. Given the uncertainty about these costs, and about the market prices for biofuel alcohols into the future, we have analysed changes in optimum N amounts for a broad range of alcohol prices, from 10p to 60p per litre, largely to indicate the sensitivity of N adjustments to alcohol prices.

2.2.5 Comparing N optima for grain and alcohol

Optimum N rates for grain and alcohol at a range of breakeven ratios and ethanol prices respectively are shown in Figure 6 for the ‘typical’ response curve of Istabraq at High Mowthorpe, 2005, as used previously. The optimums for alcohol yield (Nopt-alcohol) are calculated for a range of ethanol prices assuming a constant fertiliser price of £150/t. Assuming a grain break-even ratio of 3:1 the optimum N rate for grain yield (Nopt-grain) gives alcohol yields per ha very close to the maximum. Therefore, the Nopt-alcohol is less than Nopt-grain at a 3:1 ratio even at very high ethanol prices. However, at a currently more realistic grain breakeven ratio of 5:1 it can be seen that Nopt-grain is very similar to that for Nopt-alcohol using an ethanol price of 40p/l. At lower ethanol prices Nopt-alcohol becomes increasingly lower than Nopt-grain.

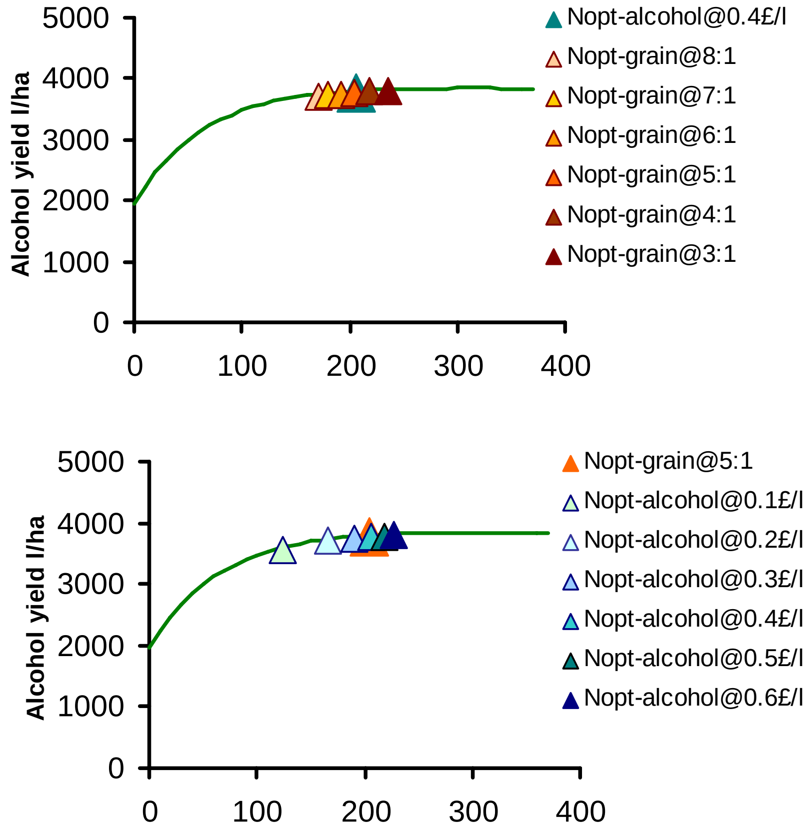

Figure 6 - The effect of grain breakeven ratio and ethanol price on the optimum N rate, using Istabraq at High Mowthorpe 2005 as an example. Figure (a) shows the optimum N rate for grain yield for break-even ratios between 3:1 and 8:1, and that for alcohol yield with an ethanol price of 40p/l. Figure (b) shows the optimum N rate for alcohol for a range of ethanol prices from 10p/l to 60p/l, assuming a N fertiliser price of £150/t for AN, against the optimum for grain yield at a 5:1 break-even ratio.

The relationship between Nopt-grain and Nopt-alcohol for the set of individual N response curves analysed in this work can be seen in Figure 7, at a range of grain breakeven ratios and ethanol prices.

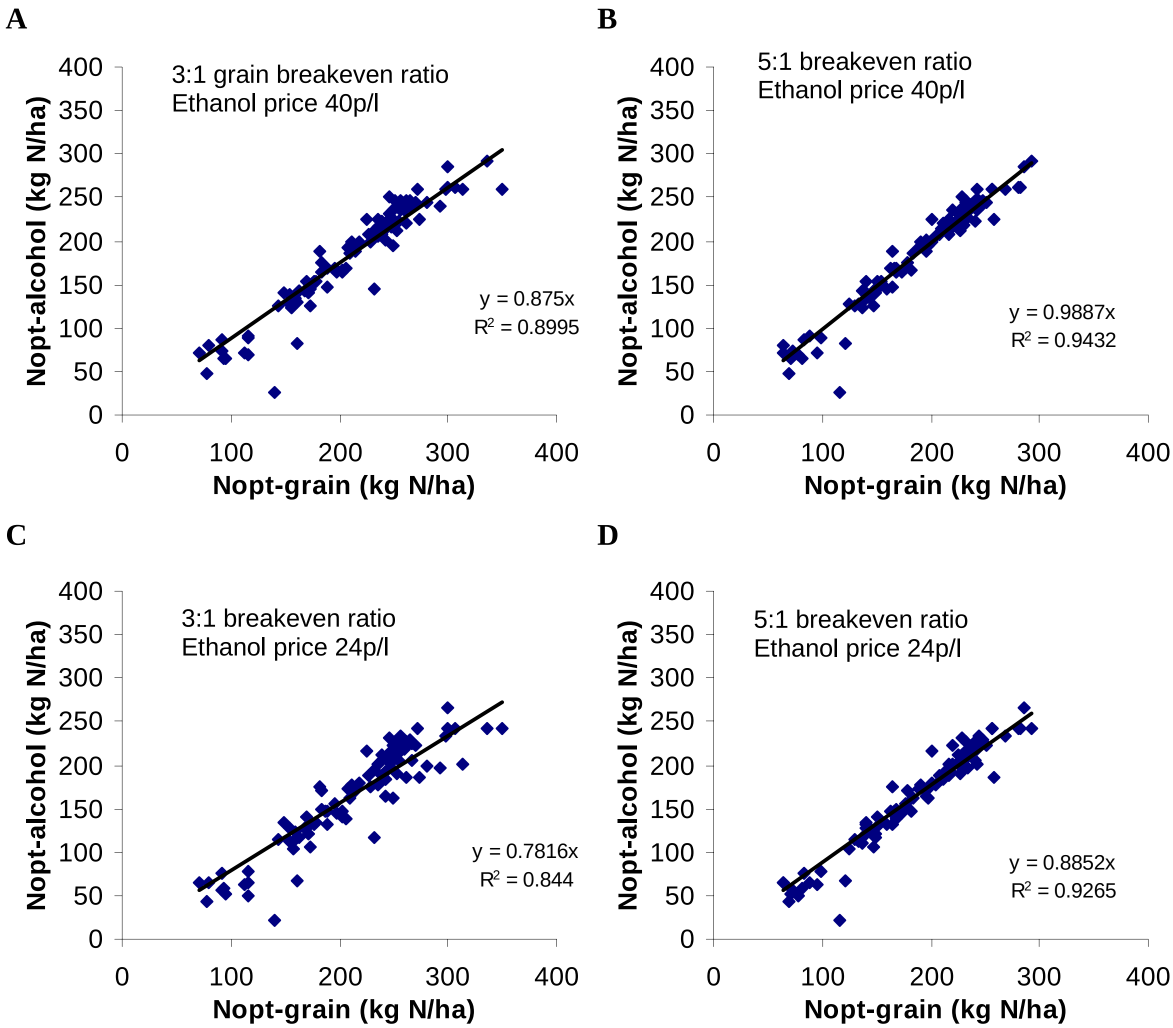

Figure 7 - Regression of optimum N rates for grain yield against optimum N rates for alcohol yield at a range of grain breakeven ratios and ethanol prices, assuming a constant fertiliser price of £150/t AN**.** The slope of the line given in the equation represents the relationship between the optimum N rate for alcohol yield and optimum N rate for grain yield. Graph A), for example, shows that at a 3:1 ratio for grain, 40p/l ethanol price, for the complete dataset, the optimum N rate for alcohol is 87% of that for grain.

In order to assess the effect of grain break-even ratio and ethanol price on the relationship between Nopt-alcohol and Nopt-grain the regressions shown in Figure 7 were repeated for a range of price scenarios for the whole dataset. The slope of the regression multiplied by 100, representing the percentage that Nopt-alcohol is of Nopt-grain, and the significance of this slope is given for a range of breakeven ratios and ethanol prices in Table 1.

Table 1 - Adjustment of fertiliser N required to optimise alcohol yield (litres per ha) as a percentage of that required to optimise grain yield (t per ha) at a range of break-even ratios and ethanol prices. The 95% confidence interval (CI), in percent, is shown beside each value.

Whole Dataset

		Ethanol price (pence per litre)									
		20	**CI**	**30**	**CI**	**40**	**CI**	**50**	**CI**	**60**	**CI**
Grain breakeven ratio	**3:1**	74	2.33	82	2.1	87	1.9	91	1.7	95	2.07
	4:1	79	1.96	88	1.7	94	1.6	98	1.6	102	2.60
	5:1	84	1.82	94	1.6	100	1.6	104	1.9	108	3.08
	6:1	89	1.79	99	1.7	105	1.9	109	2.3	114	3.55
	7:1	94	1.83	104	1.9	110	2.2	115	2.6	119	4.02

Df= 101, T statistic = 1.984

It is apparent from Table 1 that using different economic scenarios can result in Nopt-alcohol being less than Nopt-grain or more than Nopt-grain. The relevance of this to commercial practice is discussed further in Section 2.3.

2.2.6 Factors influencing the relationship between optima for grain and for alcohol

The graphs in Figure 7 (and also implicit in Figures 3 and 5) show a degree of variation in the relationship between Nopt-grain and Nopt-alcohol that is dependent on the shapes of the grain and alcohol response curves. Different environment and management factors that may influence the shapes of these curves, and thus the relationship between optima for grain and for alcohol, are investigated in this section.

2.2.6.1 Soil type

The optimum N rates for specific soil types have been studied extensively. The differences presented in RB209 (MAFF, 2000) generally arise through different retention of soil N supplies, or different efficiency of fertiliser N recovery. Whether optimum N rates for alcohol are influenced by soil type has not previously been investigated. Smith *et al.* (2006) speculated that organic and peaty soils with a high N supply could give high protein and low starch grains, whereas soils capable of high yields could give lower protein and higher starch grains.

The dataset collected for this study was split into soil types based on the current RB209 classification. The optimum N rate for alcohol as opposed to grain are presented for clay, shallow soils over chalk and deep silty soils, together with the 95% confidence interval (CI) (Table 2). There was no significant difference in the N rate adjustment for alcohol between the different soil types.

Table 2 - UK soil types – percentage adjustment of fertiliser N required for optimising alcohol yield (litres per ha) as a percentage of that required for optimising grain yield (t per ha) at a range of break-even ratios and ethanol price scenarios. The 95% confidence interval (CI), in percent, is shown beside each value.

Clay soils

		Ethanol price (pence per litre)					
		20	**CI**	**40**	**CI**	**60**	**CI**
Grain breakeven ratio	**3:1**	76%	4.5	88%	3.9	93%	3.9
	5:1	86%	4.0	100%	4.0	104%	4.5
	7:1	95%	3.9	110%	4.7	114%	5.7

Df=31, T statistic=2.039

Deep silty soils

		Ethanol price (pence per litre)					
		20	**CI**	**40**	**CI**	**60**	**CI**
Grain breakeven ratio	**3:1**	72%	4.4	87%	2.9	98%	4.3
	5:1	82%	2.6	100%	1.8	112%	8.3
	7:1	94%	2.1	112%	3.1	124%	10.7

Df= 26, T statistic= 2.055

Shallow over chalk soils

		Ethanol price (pence per litre)					
		20	**CI**	**40**	**CI**	**60**	**CI**
Grain breakeven ratio	**3:1**	73%	4.8	88%	3.9	95%	3.2
	5:1	83%	3.6	99%	3.0	107%	4.0
	7:1	92%	3.7	110%	4.4	119%	6.0

Df= 23, T statistic= 2.068

2.2.6.2 Variety

Milling v feed wheats

Varieties on the HGCA recommended list are classified into those suitable for milling (NABIM group 1 and 2 varieties) and those suitable for biscuit making and feed (NABIM group 3 and 4 varieties). Generally, the distinction between the two end-uses is based on protein content of the grain, with milling wheats having hard endosperms and greater protein contents than feed wheats.

Experience in the potable alcohol industry has shown that varieties differ in their alcohol processing yield and the ease of which they can be processed. Potable alcohol distillers prefer soft feed wheats owing to their higher starch content (which enhances alcohol processing yield), low protein content (which reduces the need to process distillers grains) and less common problems with viscosity. Consequently, little is known of alcohol yields from modern group 1 and 2 wheat varieties. Since fuel alcohol production can utilise a range of chemicals and enzymes forbidden in potable alcohol production, processing problems observed with potable alcohol production may be overcome for fuel alcohol production, enabling a wider range of varieties to be used. The quantity of feedstock required may make this a necessity.

The dataset was split into NABIM groups 1 and 2 varieties and NABIM group 3 and 4 varieties. Each dataset was analysed to determine the relationship between optimum N rate for alcohol compared to that for grain. As shown in Table 3 below, no significant difference was found in the adjustment to optimum N between group 1 and 2 and group 3 and 4 varieties. Prices of grain, fertiliser N and ethanol remain the primary influence on the relationship.

Table 3 - Varieties – percentage adjustment of fertiliser N required for optimising alcohol yield (litres per ha) as a percentage of that required for optimising grain yield (t per ha) at a range of break-even ratios and ethanol price scenarios. The 95% confidence interval (CI), in percent, is shown beside each value.

Group 1 and 2 varieties

		Ethanol price (pence per litre)					
		20	**CI**	**40**	**CI**	**60**	**CI**
Grain breakeven ratio	**3:1**	74%	4.6	88%	3.4	98%	4.0
	5:1	85%	3.4	100%	2.9	111%	6.9
	7:1	95%	3.2	111%	3.6	122%	8.7

Df= 36, T stat=2.082

Group 3 and 4 varieties

		Ethanol price (pence per litre)					
		20	**CI**	**40**	**CI**	**60**	**CI**
Grain breakeven ratio	**3:1**	73%	2.5	86%	2.2	92%	2.1
	5:1	84%	2.1	99%	2.0	105%	2.4
	7:1	93%	2.3	110%	2.8	117%	3.5

Df=64, T stat=1.998

Old v new varieties

Better management practices and new varieties have resulted in on-farm grain yields from wheat increasing substantially, from an average of 6 t/ha in 1980s to a current average of 8 t/ha. Current RB209 recommendations are based on experiments largely carried out between 1981 and 1994. Hence they are not representative of modern high yielding varieties.

Table 4 below shows the optimum N rate for alcohol yield as opposed to grain yield for varieties used in the formulation of RB209 (varieties from 1980s and 1990s) classified as “old”, and modern varieties (available from the mid 1990s onwards) classified as “new”. No significant difference was found in the adjustment to optimum N rate between old and new varieties. Again the optimum N rate for alcohol was largely dictated by grain, fertiliser N and ethanol prices.

Table 4 - Old and new wheat varieties – percentage adjustment of fertiliser N required for optimising alcohol yield (litres per ha) as a percentage of that required for optimising grain yield (t per ha) at a range of break-even ratios and ethanol price scenarios. The 95% confidence interval (CI), in percent, is shown beside each value.

New varieties

		Ethanol price (pence per litre)					
		20	**CI**	**40**	**CI**	**60**	**CI**
Grain breakeven ratio	**3:1**	72%	4.0	86%	3.2	97%	3.8
	5:1	83%	2.9	99%	2.8	110%	6.4
	7:1	92%	2.7	110%	3.7	121%	8.3

Df= 43, T stat=2.0167

Old varieties

		Ethanol price (pence per litre)					
		20	**CI**	**40**	**CI**	**60**	**CI**
Grain breakeven ratio	**3:1**	73%	3.1	87%	2.4	94%	2.1
	5:1	83%	2.4	99%	2.1	107%	2.6
	7:1	93%	2.1	111%	2.8	119%	3.9

Df=37, T stat=2.026

2.2.6.3 Fertiliser type

Fertiliser choice may depend on price, ease of application and availability. In a two-year study in the mid 1980s Lloyd *et al.* (1997) showed that there was little effect on grain yield due to use of AN or urea fertiliser. Consequently the optimum N fertiliser level for grain was similar. However, more recently Dampney *et al.* (2006b) showed that using urea reduced grain yield by 0.3-0.4t/ha compared to AN. Both Dampney *et al.* (2006b) and Lloyd *et al.* (1997) showed that using urea fertiliser tended to result in lower grain protein contents.

It has been reported that urea fertilisers give less GHG emissions in their manufacture than AN (Wood and Cowie, 2004). This indicates that urea could possibly be favored in biofuel production (HGCA Project MD-0607-0033; Kindred *et al.* personal communication) but since use of urea results in high ammonia losses, the GHG benefits would need to be offset against other major environmental issues. Potentially also, reduced grain protein from urea could be beneficial.

Data from the recent Defra funded project NT2605 were used to investigate the effect of AN versus urea fertiliser on the change in optimum N rate for alcohol versus grain (Table 5). No significant difference was found between the fertiliser types, with grain, fertiliser and ethanol prices being the primary influence over N rates.

Table 5 - Different fertiliser N types – percentage adjustment of fertiliser N required for optimising alcohol yield (litres per ha) as a percentage of that required for optimising grain yield (t per ha) at a range of breakeven ratios and ethanol price scenarios. The 95% confidence interval (CI), in percent, is shown beside each value.

AN

		Ethanol price (pence per litre)					
		20	**CI**	**40**	**CI**	**60**	**CI**
Grain breakeven ratio	**3:1**	78%	8.2	87%	8.1	91%	8.2
	5:1	90%	6.5	101%	5.2	105%	4.8
	7:1	100%	8.4	112%	7.5	116%	7.3

Df=8, T stat= 2.306

Urea

		Ethanol price (pence per litre)					
		20	**CI**	**40**	**CI**	**60**	**CI**
Grain breakeven ratio	**3:1**	81%	13.7	92%	13.1	96%	12.6
	5:1	89%	13.2	101%	13.6	105%	13.9
	7:1	98%	14.4	110%	16.1	115%	17.1

Df=6, T stat= 2.446

2.2.6.4 Seasonal variation

The amount of N available in the soil varies considerably on a seasonal basis and is highly dependent upon previous cropping patterns and the quantity and distribution of rainfall. Soil N availability is known to vary from year to year and spatially between and within individual fields. Alcohol processing yields from varieties tested by SWRI in the RL testing system also show significant year on year variation as described in Smith *et al.* (2006). However, as shown in Table 6, there was no significant year on year difference in the adjustment to optimum N level for alcohol.

Table 6 - Seasonal variation – percentage adjustment of fertiliser N required for optimising alcohol yield (litres per ha) as a percentage of that required for optimising grain yield (t per ha) at a range of break-even ratios and ethanol price scenarios. The 95% confidence interval (CI), in percent, is shown beside each value.

2004

		Ethanol price (pence per litre)					
		20	**CI**	**40**	**CI**	**60**	**CI**
Grain breakeven ratio	**3:1**	71%	4.7	85%	3.2	93%	2.6
	5:1	82%	3.2	99%	2.2	108%	3.9
	7:1	93%	2.6	111%	3.7	121%	6.2

Df=23, T stat=2.069

2005

		Ethanol price (pence per litre)					
		20	**CI**	**40**	**CI**	**60**	**CI**
Grain breakeven ratio	**3:1**	75%	3.4	88%	3.1	94%	3.0
	5:1	84%	3.0	98%	3.0	104%	3.2
	7:1	92%	3.0	109%	3.5	115%	4.0

Df=43, T stat=2.017

2006

		Ethanol price (pence per litre)					
		20	**CI**	**40**	**CI**	**60**	**CI**
Grain breakeven ratio	**3:1**	70%	4.3	84%	4.3	90%	4.3
	5:1	78%	4.0	94%	4.3	101%	4.7
	7:1	88%	4.2	105%	5.1	112%	5.8

Df=29, T stat=2.045

2.3 Conclusions on economic N optima for alcohol.

The analyses comparing optimums for alcohol with optimums for grain clearly show that price has a very large influence on the relationship between these optimums, and appear to imply that, at high ethanol prices and high grain break-even ratios for grain, it is worth applying more N for alcohol than for grain. However, this clearly does not reflect reality, because increased N fertiliser does not result directly in increased alcohol production per ha, but increased *grain yield* per ha. An ethanol producer responding to higher ethanol prices who was growing a wheat crop would not spend more on fertiliser to increase grain yield per ha than the market value of the extra grain attained, rather he would buy grain on the open market. This implies a linkage between ethanol prices and grain prices.

As grain protein is relatively stable around the optimum N rate at around 11.5%, alcohol yield is also relatively stable at around 435 litres/t. At any grain price there is thus a minimum cost of the ethanol (i.e. grain price divided by alcohol yield/t), and conversely at any ethanol price there is a maximum value of grain (i.e. ethanol price multiplied by alcohol yield/t). Assuming fertiliser prices of £150t for ammonium nitrate, a grain breakeven ratio of 3:1 translates to a grain price of £145/t, which in turn implies an ‘equivalent’ ethanol price of 40p/l. A grain break-even ratio at 5:1 implies grain prices of £87/t and an equivalent ethanol price of 24p/l. Figure 8 shows that at *equivalent* grain and ethanol prices the optimum N rate for alcohol yield is, on average, around 87-88% of that for grain yield across increasing grain break-even ratios. This implies that generally N rates for alcohol production should be 12% less than for grain production, irrespective of prices.

It is therefore recommended that comparisons should be made at *equivalent* grain and ethanol prices, and future studies should use this principle of equivalence to determine optima for alcohol yield, so that effects caused by differences in grain and ethanol price are avoided. This also simplifies the question, as only the breakeven ratio for grain yield needs to be considered and that for ethanol can be deduced.

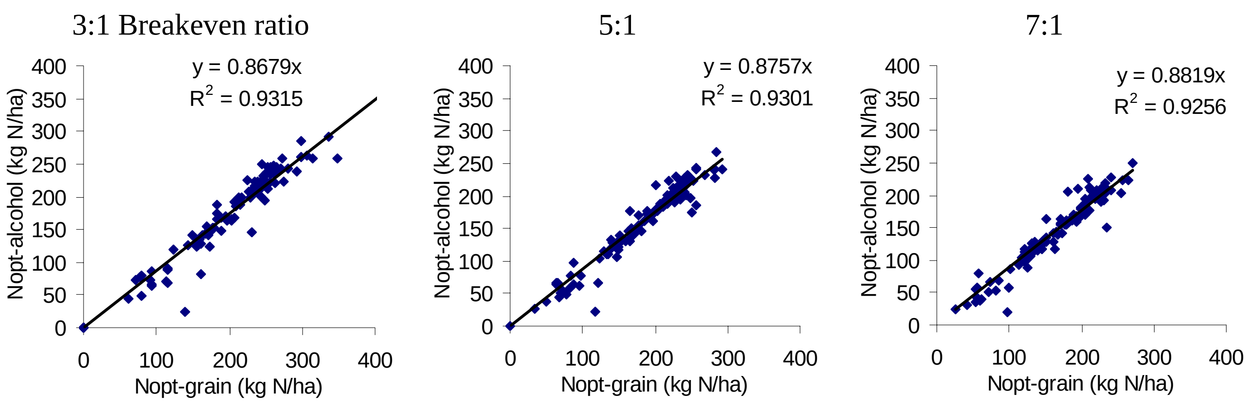

Figure 8 - Comparison of the optimum N rate for alcohol against that for grain at equivalent prices for grain and alcohol at a range of grain breakeven ratios.

2.3.1 Considering premia

The analysis thus far has been based on an artificial situation where the processor also grows the crop. Whilst this is instructive in showing theoretically how optimum N rates for alcohol yield should differ from those for grain yield in order to optimise financial returns across the industry, it does not reflect how growers will behave in practice. In the absence of any incentive to provide high alcohol yield (i.e. low protein) grain to processors, in practice growers should continue to fertilise wheat for optimum grain yield to maximise returns per ha.

In reality, processors are not interested in the grain yield or fertiliser use per ha (except in terms of GHG emissions discussed later). What processors are likely to be interested in is how much a tonne of grain is worth to them in terms of alcohol yield and processing efficiency. The relationship between alcohol yield and grain protein of 7.2 litres of ethanol per dry t grain per % protein in DM implies that, at an ethanol price of 40p/l, a 1% reduction in protein content is worth

(7.2 x 0.4 x 0.85 =) £2.88/t @85%dm in extra ethanol production to the processor. As the major costs and limitations of bioethanol production stem from the processing of grain and not from dealing with the resulting ethanol, this does represent a true economic benefit to the processor. Some minor additional costs might be incurred as more ethanol would need to be stored and transported etc, but as this extra ethanol is produced without extra grain required, no added processing costs associated with extra grain are incurred. In essence, using grain with higher alcohol yield should increase the ethanol production capacity of the whole facility. In addition to the extra value from greater ethanol production from using high alcohol grain, there may also be significant energy saving costs; grain with high alcohol yield gives less residual material, known as distillers dried grains with solubles (DDGS), after the starch in the grain has been converted to ethanol, so less energy is required in wetting, heating, cooling and drying the residue material. Using high alcohol grain may also allow less water to be used in the process overall, as grain that gives less residue material may be processed at higher dry matter contents. The total energy savings associated with high alcohol grain are less easy to quantify than the direct benefit of additional ethanol production, because they may be largely dependent on the integration of energy supplies within the individual facility. However, estimates conducted in the GREEN grain project (HGCA 2979) suggest these savings could be in the region of £1.50 per % protein reduction per t. It should be noted also however, that the reduced quantities of DDGS from low protein grain will mean less DDGS sold as an animal feed or energy source.

Given the economic benefits of low protein grain to the processor it is not unreasonable to expect processors to offer premiums for high alcohol processing yield grain. Indeed, this is the case for many bioethanol plants in Europe and elsewhere.

A full analysis of optimising N fertiliser to maximise financial returns from potential alcohol yield premiums is outside the scope of this study. However, the effect of a potential protein-based premium on optimum N rates for the Istabraq response at High Mowthorpe in 2005 is illustrated in Figure 9. This illustrates three hypothetical premium structures;

1. a premium based on whether or not grain is below a threshold protein content;
2. a premium giving payments on a sliding scale relative to protein content below (or alcohol yield above) a threshold protein content (or alcohol yield)
3. as with scenario 2 but also with penalties for protein content above (or alcohol yield below) a threshold.

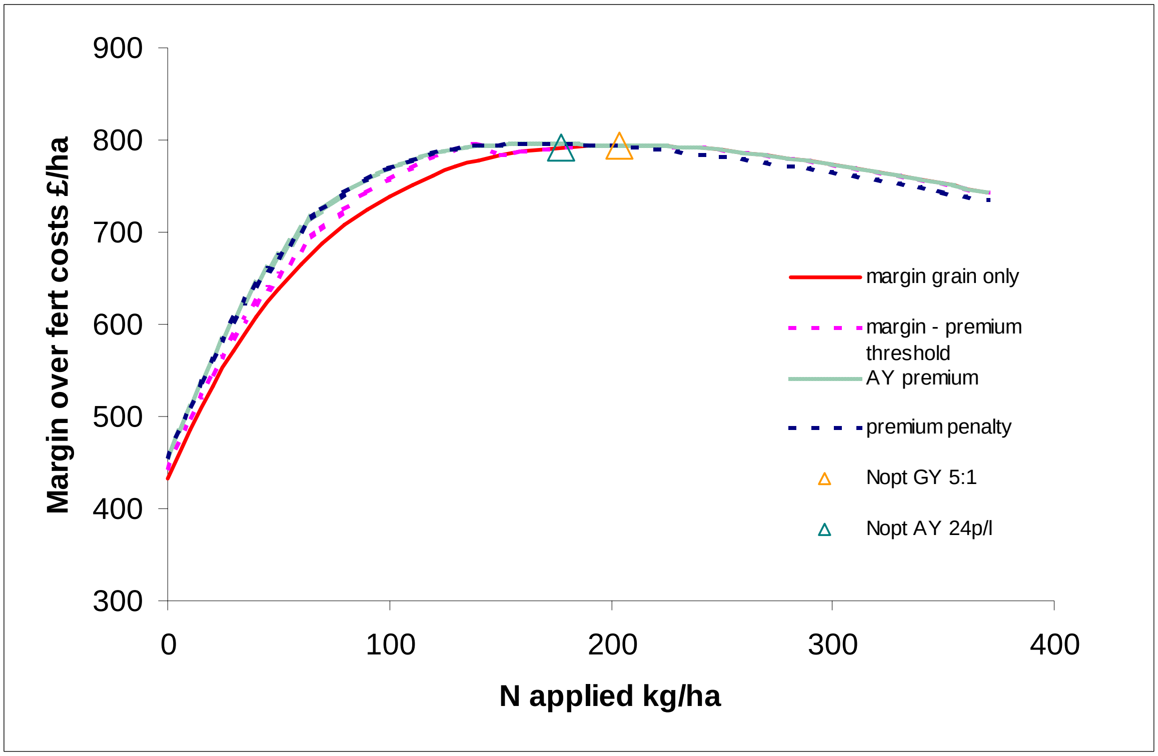

Figure 9 - Financial returns per ha (margin over fertiliser cost) for a range of premium scenarios, based on the response curves of Istabraq at High Mowthorpe 2005. The red line shows the margin from grain yield only, assuming a grain price of £87/t and fertiliser price of £150/t. The pink dashed line assumes a premium of £2/t for protein content less than 10% protein, the green dashed line assumes a premium of £1.44 per percent reduction in grain protein content (20p/l ethanol) below a protein content of 11.1% protein (440l alcohol/t). The blue dashed line assumes the same scenario as the green dashed line but assumes an equivalent penalty of £1.44 per percent protein above 11.1% protein. N optimums for grain yield (Nopt GY) at a 5:1 breakeven ratio and for alcohol yield (Nopt AY) at 24p/l ethanol and £150/t AN fertiliser are shown for comparison.

Initial indications suggest that appropriate farmer practices are very sensitive to the thresholds used, the size of the premium, and the grain and fertiliser prices. Further work is required to analyse a range of responses under a range of economic scenarios. However, it seems that relatively modest premiums for low protein could make it worthwhile growers reducing N applications significantly. Figure 9 shows that under a protein premium on a sliding scale, N rates could be reduced from around 200kg N/ha (the optimum for grain) to less than 150kg N/ha, without a reduction in financial returns per ha.

It would seem from the dataset analysed in this study that reductions in N fertiliser would be justified for a good number of the responses in this dataset, the proportion depending on the details of the premiums on offer. As growers have found with managing N to maximise premiums for milling wheat, a consideration of risks is required; there is a danger that reduced N applications could result in reduced grain yields but not sufficiently reduced grain protein to trigger a premium payment.

Clearly, further work will be required to advise growers on optimising N rates for alcohol yield premiums, whether based on starch, protein or indirect assessment of alcohol yield by NIR, if and when these premiums are offered.

3.0 Effects of fertiliser N on the GHG and energy balance

3.1 Methods employed

To investigate the influence of N fertiliser on the GHG emissions and energy cost of crops for biofuels, the total GHG/energy costs per GJ of biofuel and the GHG/energy savings per ha relative to fossil petrol were assessed across N rates using a 'typical' N response from the current dataset. Increasing N fertiliser applications affects the GHG and energy cost of biofuels in a number of ways:

- Costs per ha associated with the manufacture of fertiliser increase,
- Estimated N_2O emissions from the soil increase,
- With increasing grain protein the alcohol processing yield of the grain decreases,
- Processing efficiency decreases,
- Grain yield per ha is increased so non-fertiliser costs are reduced per unit of grain or biofuel.

Each of these influences was considered in the analysis. Standard figures for GHG and energy costs for wheat production and ethanol processing were taken from previous studies and from the on-going HGCA project "Facilitating carbon accreditation schemes for biofuel production", Mortimer *et al.* (2004) and the HGCA GHG calculator. The response of Istabraq at High Mowthorpe 2005 was used to model the effects of N as this was considered to give a typical N response.

Firstly, default figures for crop inputs and farm diesel were used to calculate crop costs per ha. Costs from manufacturing N fertiliser were calculated from previously used (HGCA GHG Calculator: Woods *et al.* 2005) emission factors for AN (6.69 kg CO_2 eq/kg N) for rates between 0 to 400 kg N/ha. Soil nitrous oxide (N_2O) emissions were assumed to have a baseline of 1.8kg N_2O/ha (relating to crop residues) and to increase with N application by 0.021 kg N_2O/kg N (De Klein *et al.*, 2006; HGCA Project "Facilitating carbon accreditation schemes for biofuel production" (MD-0607-0003)). N_2O was assumed to have a global warming potential of 296kg carbon dioxide (CO_2) eq/kg N_2O.

To convert costs per ha into costs per tonne of grain, total costs per ha were divided by grain yield at each N rate. Costs per tonne for grain drying, storage and transport were then added to the growing costs per tonne to give the total cost of grain to the ethanol processor.

Processing is assumed to occur using a combined heat and power (CHP) plant with technology that is thought most likely to be implemented (scenario b22; LowCVP, 2004). Primary energy costs were calculated assuming 1.11MJp/MJ of gas and 3.08MJp/MJ of electricity. Previous studies have calculated processing costs of biofuel production on the basis of each unit of ethanol produced. Given that, in reality, the amount of grain going through the plant is the limiting factor, rather than the amount of ethanol produced, and that processing costs per tonne of ethanol will be less where more ethanol is produced per tonne of grain, processing costs were converted to a per tonne of grain basis. The amount of grain required to produce a tonne of ethanol was calculated from the calculated alcohol yield per tonne at the range of N rates. This allowed differing processing costs per tonne of ethanol to be calculated on the basis of changes in alcohol processing yield. This approach allows some of the increased processing efficiency of high alcohol yield grain to be accounted for, but may underestimate the full benefits; grain with high starch contents that give high alcohol yields will result in less residual material in the plant that has to be wetted, heated, cooled and dried, and less water may be required, so energy costs could be reduced further than is estimated here.

From the calculated requirement of grain per tonne of ethanol the full costs of biofuel production from crop production at a range of N rates could now be expressed in terms of costs per kg or MJ of ethanol. However, 'credits' need to account for alternative land-use and for any co-products. These have each been calculated on a credit per unit of ethanol for each N rate to allow fair comparisons. If the biofuel crop was not grown and the land was in set-aside there would still be some emissions from diesel-use for mowing, and, potentially some N_2O emissions. In this case N_2O emissions from set-aside are assumed to be half the emissions for a crop receiving no applied N. The diesel and N_2O costs that would accrue from set-aside were calculated as credits per tonne of grain through to per tonne of ethanol. The production of bioethanol gives DDGS as a co-product; these can displace imported protein animal feeds such as soya meal. Grain with high starch giving high alcohol yields will give reduced quantities of DDGS per tonne of grain. In order to account for this, a theoretical relationship between grain protein and DDGS was used, assuming that protein replaces starch and that non-fermentable constituents (i.e. non-starch polysaccharides, ash, lipid, lignin (Smith *et al.* 2006)) make up 16.5% dry matter (Cottrill *et al.*, 2007). Credits were then calculated per tonne of grain and per unit of ethanol for each N rate. The use of CHP for bioethanol processing gives surplus electricity that displaces electricity from the national grid. This credit was calculated per tonne of grain processed and per unit of ethanol at each N rate. No credit was assumed for straw as a co-product of grain production.

Combining the total costs of biofuel production with the credits allows net costs to be calculated per GJ of biofuel across the range of N rates. Savings against petrol per GJ of ethanol can be calculated by subtracting the ethanol costs from the costs for petrol (85.8kg CO_2eq/GJ petrol, 1140MJp/GJ petrol). These savings can then be multiplied by the ethanol yield per ha to give total GHG and energy savings per ha across the range of N rates.

3.2 Results and discussion

Using Istabraq at High Mowthorpe 2005 as an illustrative example, the impact of increasing N fertiliser applications on the overall GHG and energy balance of the biofuel, and on the potential savings accruing per ha, can be seen in Figures 10, 11, 12 and 13. Given the developing and uncertain nature of many of the assumptions and data used in these calculations some caution is required in their interpretation (especially for N_2O emissions and DDGS credits). Results are particularly affected by assumptions about the source of energy and heat for the bioethanol plant.

3.2.1 GHG balance

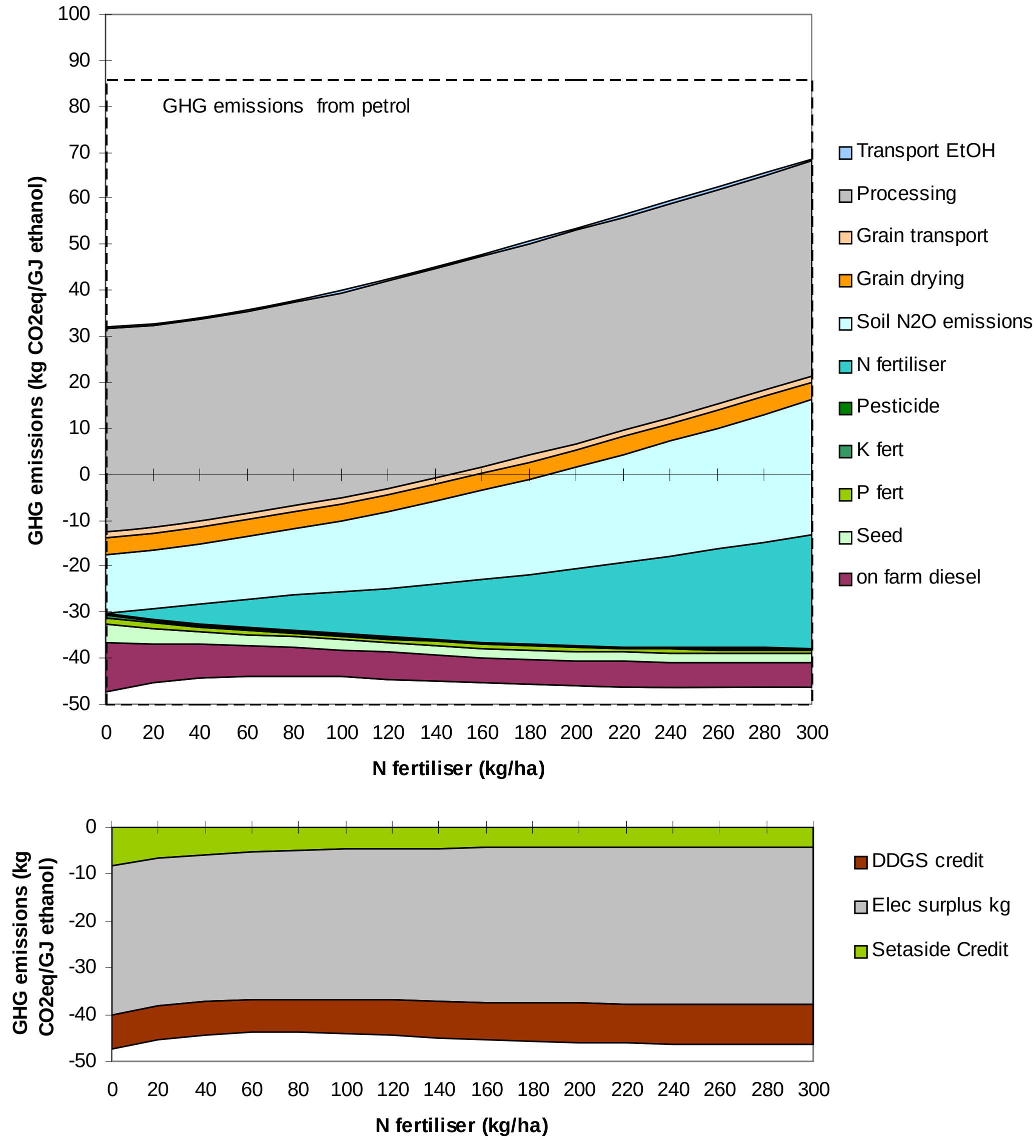

Figure 10 - The impact of N fertiliser on the GHG emissions in biofuel production. See text for details. Response based on Istabraq at High Mowthorpe 2005.

Figure 10 shows the cumulative greenhouse gas emissions from each part of the biofuel production system, and how these change as N fertiliser is applied. The graph starts with a negative baseline that accounts for the credits from set-aside, DDGS and electricity export (shown in the lower graph). Overall, it can be seen that around half of the total greenhouse gas (GHG) costs accrue from growing the crop, including grain drying, and the remainder from processing costs. Assuming that a reasonably sophisticated CHP plant is used, the majority of the processing costs are offset by the surplus electricity generated, so in fact, the majority of the GHG costs of the biofuel come from the production of the wheat crop. Initial applications of fertiliser reduce the emissions of other crop inputs as the grain yield increases. Grain drying, transport and processing costs apply to each tonne of grain, regardless of yield per ha, and these costs increase marginally with increasing

N fertiliser as grain protein increases and alcohol processing yield decreases. It can be argued that the full effects of increasing grain protein on processing costs are not accounted for in this analysis as no benefit is included for the reduced heating and drying costs of dealing with a reduced quantity of DDGS (Smith *et al.*, 2006). The overwhelming impact however of increasing fertiliser application is the increase in GHG costs of fertiliser manufacture and in-field N_2O emissions. For this scenario, net GHG emissions per GJ of biofuel increase from 32kg CO_2eq/GJ with no N to 68kg CO_2eq/GJ when 300kg N are applied. The increased efficiency of grain production with initial N applications means that overall emissions increase slowly with initial increases in N, but they increase rapidly after about 60kg N/ha. If petrol is taken to give emissions of 86kg CO_2eq/GJ, then GHG savings change from 63% at zero N to 54% with 100kg N applied to 38% with 200kg N applied and 21% with 300kg N applied.

This analysis conceals an important consideration however; the low yields with low N applications would cause more land to be required for production elsewhere. If this resulted in extension of cultivation to new lands it could increase emissions significantly. A likely consequence of using crops for biofuels is that land will become limiting, given that food production will need to continue. In this case, the priority may not be to maximise savings per unit of biofuel but to maximise the savings from each ha of land.

By multiplying the GHG savings per unit of bioethanol at each N rate by the bioethanol yield per ha at each N rate the GHG savings per ha were assessed (Figure 11). This demonstrates that GHG savings per ha increase substantially with initial increases in N fertiliser as bioethanol yields per ha increase. However, the savings per ha peak well below the N rate that maximises bioethanol yield per ha. In this case maximum savings are achieved at around 100kg N/ha. Beyond the maximum, further increases in N fertiliser and the associated GHG emissions result in substantial decreases in the GHG savings per ha.

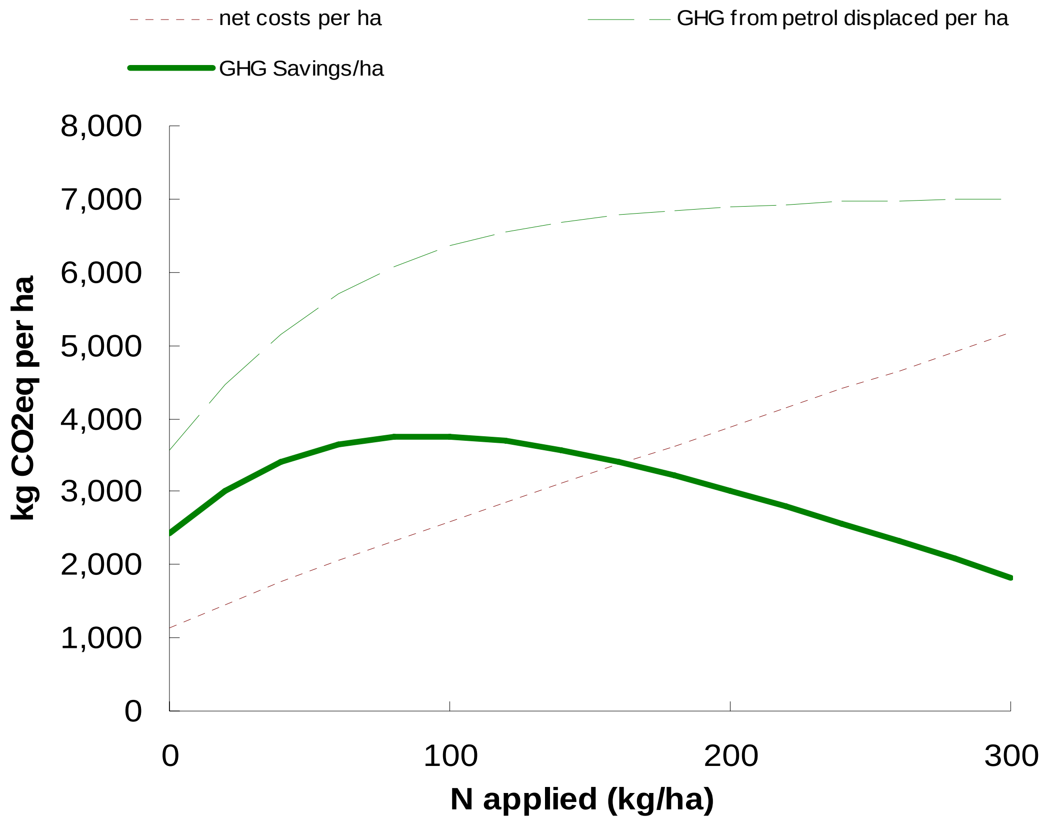

Figure 11 - The effect of N fertiliser on GHG costs and savings from bioethanol production. Responses based on Istabraq at High Mowthorpe 2005.

3.2.2 Energy balance

The responses to N of energy balance of biofuels, and the energy savings per ha are similar to the responses in GHG emissions. However, as fertiliser makes up a smaller proportion of the total energy costs of biofuel production than it does GHG costs (because of the additional N_2O emissions both in manufacture and in the field), the negative impacts of increasing fertiliser use are reduced. Figure 12 shows that the energy costs per unit of bioethanol actually decrease with initial applications of fertiliser for this scenario, and the subsequent increase in energy costs per unit of biofuel with further increases in N fertiliser is relatively minor, with net primary energy costs of 440MJp/GJ at 300kg N/ha only slightly greater than costs at zero-N of 413MJp/GJ.

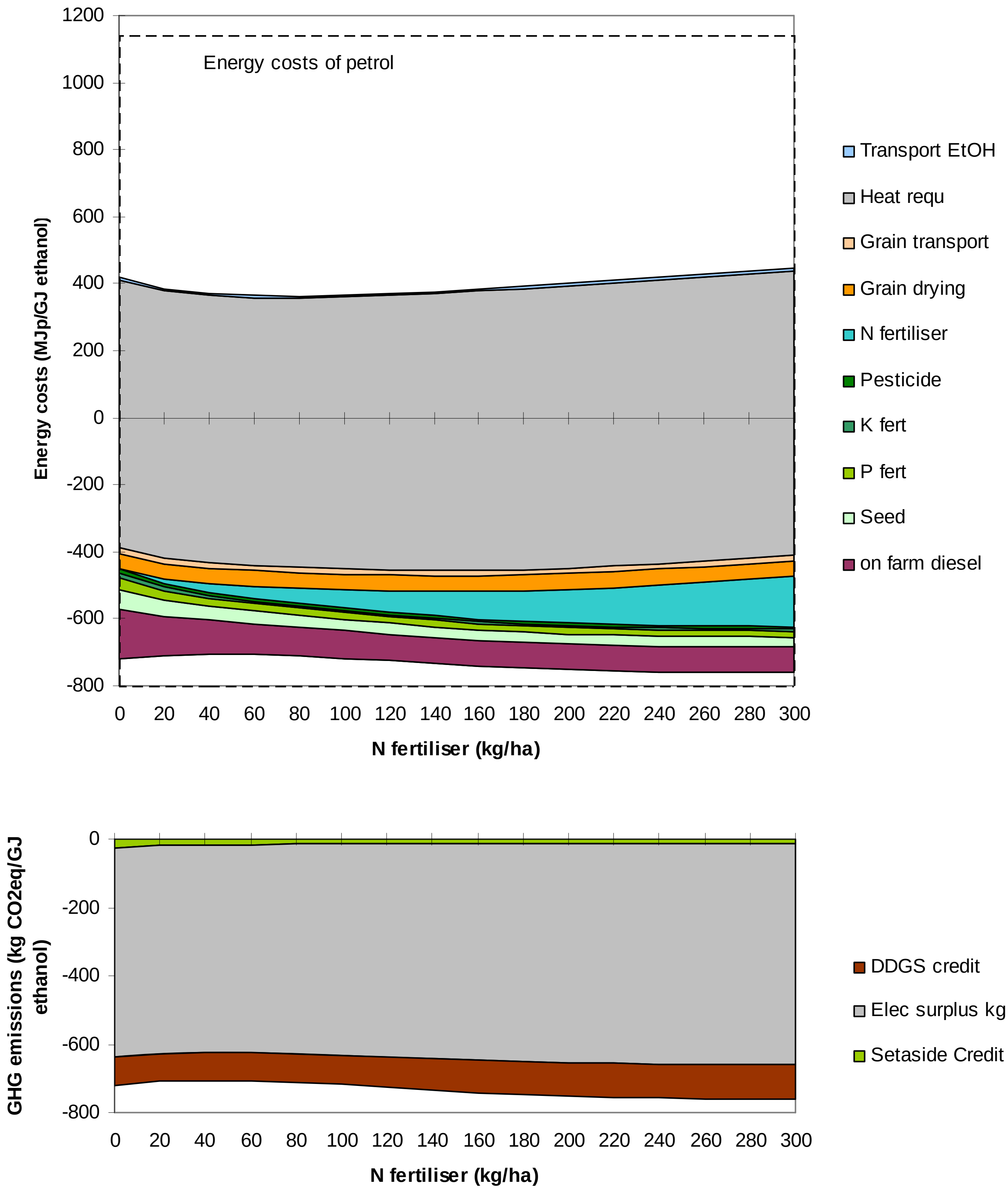

Figure 12 - The impact of N fertiliser on the energy costs of bioethanol production. See text for details. Response based on Istabraq at High Mowthorpe 2005.

This more limited impact of fertiliser on the overall energy balance means that when scaling up to the energy savings per ha, fertiliser continues to give an overall benefit in energy savings up until close to the N rate that generally gives optimum grain and alcohol yield per ha (i.e 200kg N/ha).

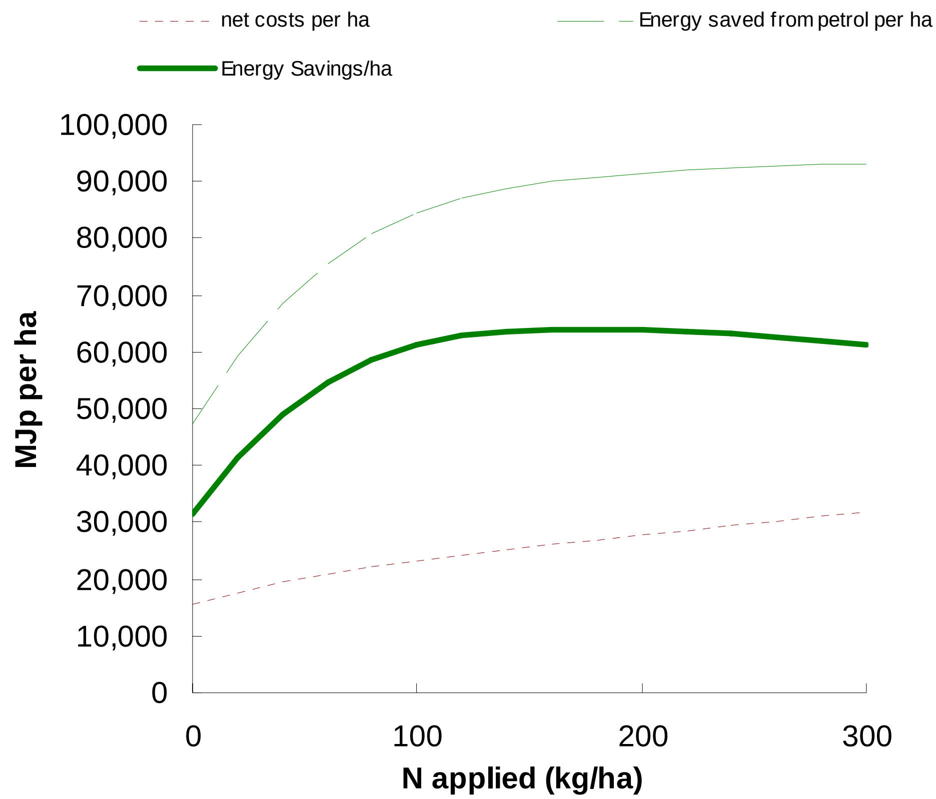

Figure 13 - The effect of N fertiliser on primary energy costs and savings from bioethanol production. Responses based on Istabraq at High Mowthorpe 2005.

A note of caution is needed when considering the detail of the N fertiliser response of GHG emissions and energy costs for crops or for biofuels, particularly with regard to the absolute costs/savings. The parameters, assumptions and approaches used in these calculations are not definitive and may change as methodologies improve. Considerable uncertainty surrounds the GHG costs of growing crops. Many of these issues are being dealt with in the current HGCA project "Facilitating carbon accreditation schemes: feedstock production" however, further work is needed, in particular to consider the effect of N fertilisers on N_2O emissions and on the neutralisation of lime, and impacts of rotations.

At present only one 'typical' N response has been examined. There is a need to analyse the response of energy and GHG balance over a range of N response datasets, for example with higher and lower N optima. In future work it should be possible to reconcile the GHG implications of N fertiliser with the economics of crop production in order to evaluate possible economic N optima to maximise GHG savings at a given 'carbon' price. Alternatively, the cost to a grower of fertilising to maximise GHG savings rather than to optimise grain yield could be assessed. This would be informative in seeing how large any potential premiums would need to be to change grower practice.

4.0 Overall conclusion and recommendations

Wheat is likely to become a major biofuel crop in the UK over the next few years with several plants in the UK planning to utilise wheat as their primary feedstock. HGCA Research Review No. 61 (Smith *et al.*, 2006) highlighted that both varietal choice and agronomic practices can have a significant influence over the suitability of grains for alcohol production. Fertiliser N is the most important single input into wheat for alcohol production; increasing grain yields and grain protein content at the expense of starch content (and hence alcohol processing yields) and increasing the GHG emissions and energy cost of the resulting biofuel.

This review has considered the joint benefits to grower and processor for optimising N fertiliser use and investigated whether the N management practices for alcohol production need to differ from those for feed wheat production. Analysis of a dataset of 102 individual N responses from different soil types, varieties, locations and years indicated that *maximum* alcohol yields per ha are achieved at N rates around 10% less than those to achieve *maximum* grain yields. Using the assumption that the processor is also growing the grain, the *optimum* N rate for alcohol production compared to that for grain was found to be sensitive to the grain break-even ratio and ethanol price. Despite considerable variation in the relationship between the optimum for grain and the optimum for alcohol between responses from different experiments, no significant effects of soil type, fertiliser type, variety or seasonal variation on this relationship were evident in this study.

Historically there has been no link between the price of grain and the value of ethanol as their prices are fixed by different commodity markets. The initial analysis in this report compares the N optima for alcohol (using a market ethanol price to determine the breakeven ratio) with optima for grain (using standard breakeven ratios). However in the future as bioethanol production increases on a world scale the two prices are likely to become increasingly linked, particularly if demand for grain for both food and fuel uses outstrips supply. In this scenario the price of ethanol will set a maximum value for grain for alcohol production, and conversely, the price of grain will set a minimum price for ethanol. To make fair comparisons of the optima for alcohol and for grain it is recommended that an *equivalent* price for alcohol is used, based on the grain price. Assuming *equivalent* prices for grain and for ethanol, it has been shown that *optimum* N rates for alcohol yield per ha are around 12% less than those for grain yield. It is suggested that the use of equivalent prices provides a useful and simple approach for future studies, as only the breakeven ratio for grain needs to be considered.

Assuming that the processor was also growing the grain, the analysis suggests that, on average, financial returns for the processor would be maximized at N rates 12% less than those that would maximize returns for feed wheat growers. Traditionally for feed markets the financial risk from over fertilising has only been small, as small increases in grain yield would almost cover the cost of over fertilizing, but there has been significant financial risk from under fertilising due to lost yield. For alcohol production, however, there will be decreasing alcohol processing yields per tonne with fertiliser applications above the optimum, it is therefore likely that the financial penalty of over-fertilising will be greater for alcohol production than for feed wheat production. Risk analyses are required to evaluate the financial costs of over- and under-fertilising, and to enable recommendations to be given as to whether it is best overall to aim for the optimum, or either side of the optimum.

In reality, farmers and bioethanol producers are different entities with differing requirements and motivations. In the absence of any incentives (economic or otherwise), farmers will aim to produce optimum grain yields to maximise returns, the quality of the grain for alcohol production being unimportant. The bioethanol processor on the other hand will seek to utilise wheat with a high starch content (hence low protein content) because this not only maximises alcohol yields per tonne of material processed but also reduces the costs associated with processing the co-products. Therefore, the situation analysed above must be considered as theoretical; eventually the market will determine the behaviour of both farmer and producer. Assuming an ethanol price of 40p/l, a change in grain protein of only 1% will be worth £2.80 per tonne to the processor or approximately 2% of the costs of purchasing the grain. Introduction of premiums for low protein (or high starch) grains and, in the future, an advantageous GHG balance, could act as a mechanism to compensate farmers for reduced yields which may be incurred as a result of producing a better quality grain for the bioethanol processor. As such mechanisms are introduced there will be a need to assess the best fertiliser strategies to maximize returns for the grower, considering both the economic optimum N rates and the risks of missing the optimum.

Overall, unless a premium for low protein grain is being offered to growers, it is not possible on economic grounds to recommend that growers reduce N rates from those that would be optimum for feed wheat.

4.1 Recommendations for growers

The primary recommendations for growers arising from this study are summarised below:

1. Where sale into the bioethanol market is only a possibility, growers should continue to fertilise wheat crops as for feed wheat, but taking care that the optimum is not being exceeded.

2. Where wheat is being grown under contract for bioethanol production, and a premium is being offered for starch (or alcohol processing yield), or for greenhouse gas savings, it is likely to be worth reducing N rates to less than those currently recommended for feed wheat. This will depend strongly on prices and premium mechanisms.

3. Where growers' returns will relate directly to the yield of ethanol, wheat crops should be fertilised at a rate about 10% lower than that which would be used for feed wheat.

4.2 Further research requirements

There are a number of areas where further research would be instructive.

– Further study optimising N rates for different premium structures, if and when these come in to place. This should consider the variation between crops, hence the risks of not acquiring the optima being targeted.

– This study has used grain protein content as an indirect measure for alcohol processing yield. This is justified because protein content has been shown to give a more accurate prediction of alcohol processing yield than grain starch content (Smith *et al.* 2006) and it allows the use of historic datasets for which no measured or predicted alcohol yields are available. However, there is considerable scatter in the relationship between alcohol yield and grain protein content (Figure 1), which in part relates to consistent differences between varieties, seasons etc. at the same protein content (Smith *et al.*, 2006). The use of real alcohol measurements (especially using a fuel-alcohol methodology) would allow a more accurate assessment of alcohol yield under different N rates, and could help understand whether there are differences in N requirement for alcohol yield per ha between different varieties (and other environment and management factors). Failing that, it is possible that prediction systems for alcohol processing yield could be useful, for instance the use of NIR, or perhaps using grain protein in combination with adjustments (based on prior knowledge) of the alcohol yield characteristics of the variety.

– Awareness of the GHG and energy costs of a biofuel will become increasingly important with the introduction of carbon assurance standards in 2010/2011. Whilst at first this may be achieved through simple checks on average amounts of energy used and GHGs resulting from the production of a fuel, it is likely that assurance standards will develop to ensure that all biofuels provide a net energy gain and lower GHG emissions than the petrol fuels that they replace. Using a ‘typical’ N response, the impact of N fertiliser on overall energy and GHG balance was demonstrated in this study. It seems that whilst the consequences of increasing N fertiliser on the *energy* balance of the resulting biofuel are small, N fertiliser has a major effect on the *GHG* balance of biofuels. Whilst initial applications of fertiliser had a limited impact on overall GHG savings per ha, because of the increased efficiency of crop production, increasing N fertiliser applications up to and beyond the optimum for grain yield resulted in substantial reductions in net GHG savings per ha. There is clearly a need for further work to investigate the implications of N fertiliser on GHG costs of cropping and of biofuels more thoroughly. In particular, an economic analysis is required to optimise N fertiliser for GHG savings.

– The work presented in this report should be considered as part of a whole approach to investigating the effects of N agronomy on grain quantity, quality and GHG (and energy) balances. The timing of N applications and N fertiliser type are also potentially important. The effect of N timing on the wheat for biofuels markets is currently being investigated in an extension to HGCA research project “optimising fertiliser nitrogen levels for modern cereal crops” entitled “timing nitrogen applications to optimise alcohol production from wheat”. Further investigation into the relative effects of using urea as opposed to using AN with regard to GHG and grain quality effects may be worthwhile. There may be merit in taking a holistic approach to growing crops for biofuels, integrating investigations into N forms, N timing and N rate with other agronomic regimes and varieties to ascertain the best strategies for growing grain for alcohol markets. Similar approaches will also be required to optimise N nutrition for oilseed rape crops destined for biodiesel markets and for sugar beet destined for bioethanol markets.

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