Developing and growing wheat for the biofuels market

R. SYLVESTER-BRADLEY & D.R. KINDRED

ADAS Boxworth, Cambridge, CB23 4NN

Summary

Wheat-based biofuels will be used to meet a substantial part of the targets now set for transport fuels in the EU. As currently grown and processed, wheat biofuel should save ~40% of the GHG emissions associated with petrol. Growers have many ways of achieving even greater reductions, particularly through maximising yields and manipulating fertiliser management, but adoption of these will depend on the availability of large premiums for GHG savings, of the order of £15/t grain or over £100/t CO_2equiv. Nine varieties are currently recommended for use in distilling but current testing and breeding criteria must be amended if future varieties are to sustain and improve GHG savings. As with most farm products, crop productivity remains crucial to the sustainability of biofuels, especially by minimising further destruction of virgin habitats and maintaining soil carbon stocks.

Introduction

Physical conditions in the UK and NW Europe are well suited to biofuel production, in that crops are high yielding with high energy content. The vision is that transport biofuels should ultimately be derived from 'ligno-cellulosic' biomass that has little value for alternative purposes and that may be produced as by-products, e.g. straw, or from land not suited to production of food or feed, e.g. forestry waste. Significant technological and commercial challenges underlie this vision of 'second generation' biofuels, so timescales for success are uncertain. Given the immediate and expanding global demand for transport biofuels and finite global capacity for feedstock production, there will undoubtedly be a significant period when 'first generation' biofuels (from starch, sugar and oils) hold sway. Current projections indicate that the UK stands to contribute significantly to its own requirements for 'first generation' biofuels, and exports of biofuels or their feedstocks are possible.

Use of potential foodstuffs as feedstocks for biofuels has raised concerns about exacerbating the global food shortages already arising through population growth, dietary improvement and climatic change. Certainly grain prices have increased, and are likely to remain high unless a production response proves easy. Persistent high prices will encourage attention to production, but this will necessarily be hampered, at least for biofuel feedstocks, by the need to minimise carbon emissions from cropping.

So there is now a big challenge to produce more food and fuel whilst emitting less carbon. The major elements of this challenge are in minimising the use of (i) inputs, mainly nitrogen, and (ii) land. Whatever the intended market, if production on currently productive land can be increased without significantly increasing greenhouse gas (GHG) emissions the amount of virgin land converted to agriculture can be minimised, with consequent large savings in GHG emissions and biodiversity.

Biofuels are economically more expensive than fossil fuels, even with current high fossil fuel prices, so success in the global biofuel market will depend on minimising both economic and environmental costs of production. The government's intention from 2010 is to reward biofuel use under the RTFO according to the levels of carbon saved (Defra 2007). Thus biofuel production from home-produced cereals now urgently depends on showing how far the cost per unit of carbon saved can be minimised.

A specification for wheat as a biofuel feedstock has been suggested and general principles for its production and processing have been devised using existing knowledge and recent data (Smith *et al.* 2006). Further HGCA-funded research is ongoing. Whilst in many ways, the principles behind this work are similar to cereal production for the feed or distilling markets, there are clear distinctions arising from the heightened importance of environmental costs, and the less exacting protocols for processing fuel-alcohol, compared to potable alcohol. This paper addresses the challenges and opportunities that the UK wheat industry faces, particularly wheat growers and breeders, as a UK biofuel industry establishes and evolves.

The ideal biofuel wheat

The primary role of biofuels in the EU is to reduce GHG emissions. Woods describes the main GHG costs of crop production elsewhere at this conference. Taking an average wheat crop yielding 7.9 t/ha grain (Defra statistics) and with 192 kg/ha fertiliser N applied (Goodlass & Welch 2007), the total GHG costs of producing average current UK wheat crops as a biofuel feedstock (Fig. 1) are dominated by fertiliser nitrogen, through both its manufacture (38%, half due to fossil fuel use, and half due to nitrous oxide emissions) and its use in-field (another 38%, all due to nitrous oxide emissions).

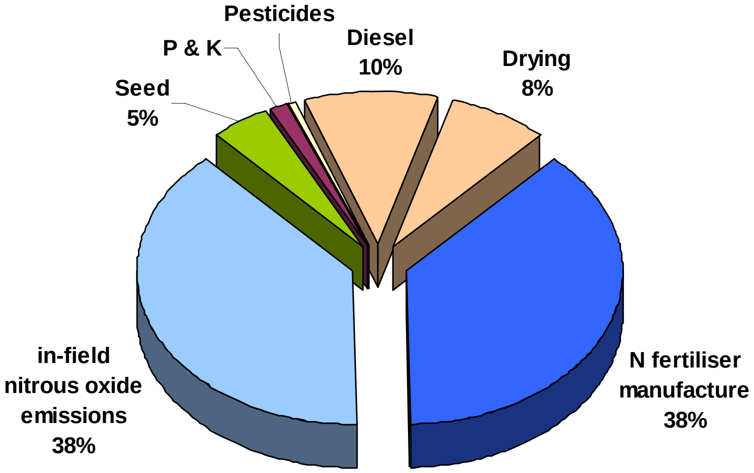

Fig. 1 Contributions to the greenhouse gas emissions arising from growing an average crop of winter wheat, estimated using the HGCA GHG calculator (Woods et al. 2005). Total emissions were 54 kg CO_2 equivalent per GJ fuel energy (compared to 86 kg CO_2e per GJ from petrol).

Based on this analysis it is clear that the 'ideal' biofuel wheat would be high yielding, thereby reducing land requirements, it would require little or no fertiliser nitrogen, could be established with minimal cultivations and harvested in a sufficiently dry state that it would not need subsequent drying. In addition, it should have a large straw yield, this straw either being incorporated into the soil, thereby sequestering significant carbon, or being burned as fuel, thereby replacing fossil carbon. The grain of the ideal wheat will have a high content of fermentable substrates, starch and sugar, hence conversely minimal protein, low non-starch polysaccharides (NSPs), oil and ash. Low NSPs are doubly important because of the viscosity they cause in the biofuel processing plant (Smith *et al.* 2006). Lastly, the ideal biofuel wheat will enable easy accreditation: as many as possible of its key attributes, as mentioned above, will be easily demonstrable at each step in the grain-chain, up to delivery for processing, so that the fuel provider can verify the GHG value of biofuel inclusion.

This paper now addresses the extent to which growers might match these ideals with current technology. It then addresses the scope for plant breeders to improve on the performance of current varieties in biofuel production.

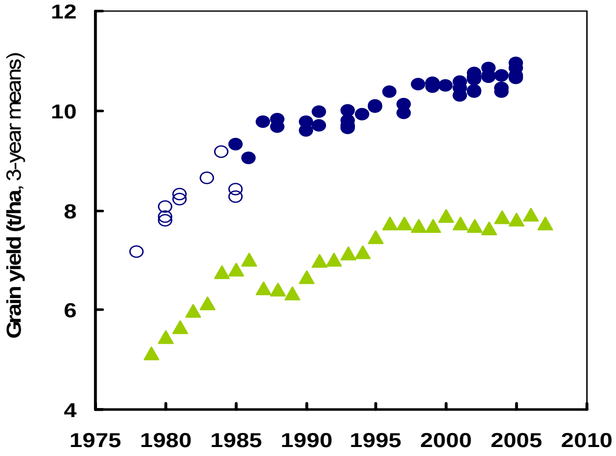

Fig. 2 Trends in grain yield (3 year moving averages) for the past thirty years as derived from Recommended Lists (newly recommended Group 3 & 4 varieties, circles) and census of whole-farm performance (triangles). Prior to 1985 (open symbols) RL yields are from plots untreated with fungicides.

Growing wheat for the biofuel market

High grain yield, hence low land requirement

Minimising the impact of biofuels on land requirements depends on achieving higher yields of all crops, whether for food, feed or fuel. Raising yields is a familiar challenge to the wheat industry (Paveley *et al.* provide an example at this conference), so little further might be said here. However, it is important to note that recent yield advances have been poor compared to those of the 1970s and 1980s (Fig. 2). Physiological analysis shows much scope for further improvement: the probable whole-farm yield-ceiling for UK wheat is about 50% beyond current yields (Sylvester-Bradley *et al.* 2004). The slow-down could have many causes, climatic, technological and economic: more extreme weather, slower discovery of new chemicals and development of chemical resistances, compromises forced by environmental targets (e.g. straw burning, reduced pollution), reduced funding for production-related research, or public aversion to GM technology. Low grain prices since the mid 1990s may also be blamed for stalling any on-farm yield improvement over the past decade. Certainly there appears to be pent-up potential for higher on-farm yields. If rising prices release this potential, and can be attributed at least in part to the impending biofuels market, then biofuels may not have the negative impacts on land requirements that some protagonists predict (Friends of the Earth, 2007). Indeed, it is possible that the whole of the UK's requirement for bioethanol under the RTFO (3 Mt) could be provided for by increased productivity, rather than increased wheat cropping.

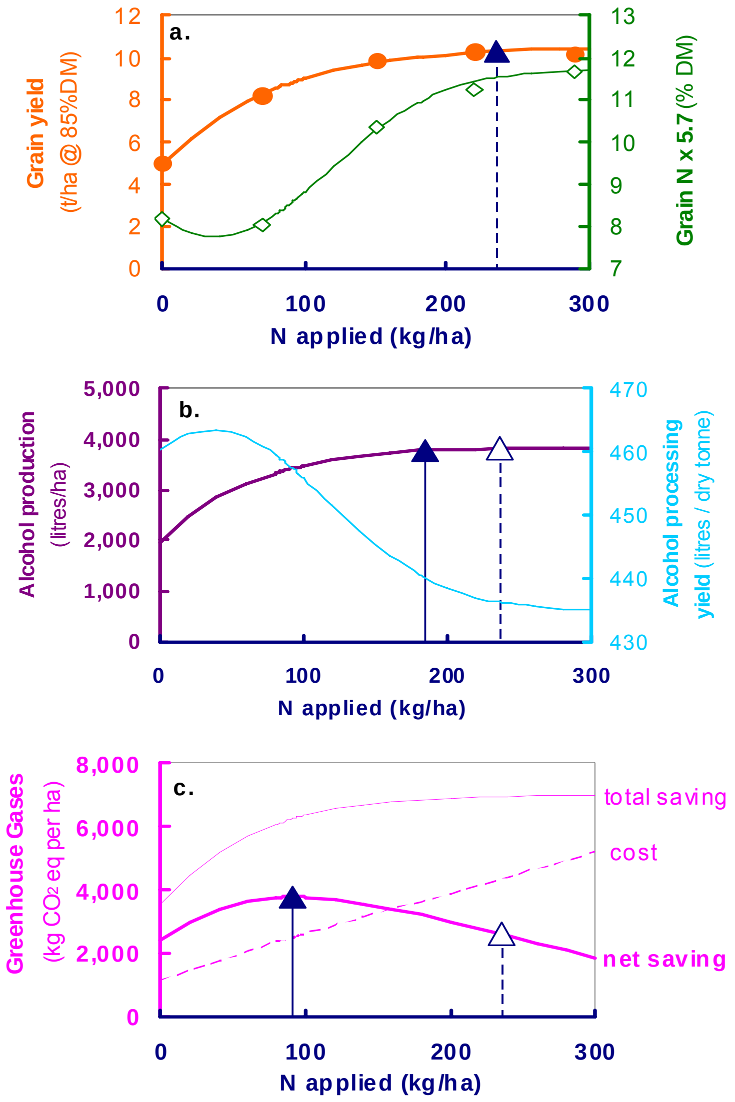

Fig. 3 Fitted responses to (lines) and optimum amounts of (triangles) fertiliser N for cv. Istabraq at ADAS High Mowthorpe in 2005: (a) grain yield, optimum 236 kg/ha N, and grain protein (N% x 5.7), (b) alcohol processing yield, predicted from grain protein, and alcohol production, optimum 184 kg/ha N, and (c) GHG cost, with total and net GHG saved per GJ biofuel energy, maximising at 91 kg/ha N (details in Kindred et al. 2007).

Low use of fertiliser N

The grower can seek to minimise N use by (a) maximising N supplies from non-fertiliser sources – from the soil, previous crops, animal manures, etc., (b) choosing a variety with low N demand, and (c) avoiding over-fertilisation. Considering (c) first, N fertiliser rates are generally set according to economic criteria – to just avoid the cost of extra fertiliser exceeding the likely extra value of grain produced.

As the UK biofuels market develops, it appears that there will be three successive stages in valuing wheat as a feedstock:

(i) as at present, based on feed wheat criteria, mainly the moisture-adjusted weight,

(ii) from 2008 or 2009, when processing plants will adjust prices according to the yield of alcohol (or starch content) predicted from grain analysis (by NIR), and

(iii) after 2010, when the government intends that rewards for biofuel use will relate to the GHG that they save (Defra 2007), causing feedstocks to be valued in the same way, under an accreditation scheme.

Optimisation of fertiliser N for feed wheat and for alcohol yield has been compared for recent N response trials, with alcohol yields being estimated from grain protein contents (Kindred *et al.* 2007). The assumed relationship between protein content (P) and alcohol processing yield (A) was A=520-7.2xP, where P=grain N% x 5.7; it accounted for 66% of variation in recent alcohol determinations by the Scotch Whisky Research Institute (Smith *et al.* 2006). Development under the GREEN grain project shows that direct NIR prediction of alcohol processing yield can now account for ~80% of variation, which should be adequate for use in trade. Optimising for alcohol yield rather than grain weight gave 12-22% lower optimum N amounts, the adjustment being consistent across sites and varieties but depending on the relative prices of fertiliser, grain and alcohol.

The same HGCA report (Kindred *et al.* 2007) also used the HGCA GHG Calculator (Woods *et al.* 2005) to consider optimisation of fertiliser N for GHG savings in one example case (Istabraq grown at ADAS High Mowthorpe in 2005). Given the consistent shape of the response curves for yield and protein to fertiliser N, it is reasonable to take this case as indicative. Assuming values of ammonium nitrate fertiliser at £150/t, feed grain at £145/t and alcohol at £0.27/litre, this case shows (Fig. 3) optimums of 236 kg/ha N for feed grain, 184 kg/ha N for alcohol production, and 91 kg/ha N for maximisation of GHG savings per GJ fuel energy. Given the same assumptions, the gross margin for growing wheat would be reduced by £12/ha for alcohol production and £131/ha for GHG saving, so the premium that would be required to exactly compensate growers for optimising alcohol production would be small (£1-£2 per tonne of grain), but for GHG saving would be very significant: £15 per tonne grain or greater than £100 per tonne CO_2 equivalent saved. It remains to be seen whether future accreditation arrangements and market mechanisms will support such large premiums; current carbon prices (per tonne CO_2 equivalent) are a mere tenth of the level estimated here. Clearly, if feedstock production is to be developed to maximise GHG saving, and optima are generally found to be 150 kg/ha (or 60%) less than for feed grain, the industry must develop a very different attitude to use of fertiliser N.

Scope for genetic reduction of crop N demand will be considered later, but there are enormous differences in fertiliser N requirements from field to field; official fertiliser recommendations vary from zero to 240 kg/ha or more (RB209). As yet it is unclear whether growers will be allowed to exploit this field to field variation when GHG costs are accredited; sense would say not, since the net effect would be a reduced GHG cost of growing for biofuels, but with an equivalent increase in GHG costs of growing for food and feed. Nevertheless, it seems possible that interim accreditation arrangements will only consider the biofuel crop, so biofuel crops should benefit significantly from being grown first after crops leaving high N residues, where soils are very retentive of N, or where organic manures can be applied. There may even be sufficient benefits to encourage greater use of legumes (which are not now deemed to cause significant nitrous oxide emission; Rochette & Janzen 2005) to enhance N supplies to biofuel crops.

Given that late N encourages high grain protein (%) in wheat and early N encourages low grain N% in barley, it is expected that early fertiliser N applications should be favoured for biofuel wheat. Initial HGCA-funded tests of N timing at five sites in 2007 failed to confirm this (Table 1), but the dry spring and wet summer of 2007 were atypical, and the N optimums were unexpectedly low, so further tests will be required.

Table 1. Alcohol yields in litres per hectare, estimated from grain yield and grain N analysis (see text), as affected by timing of N applications at five sites in 2007. Data are averages of 3 replicates and 3 N levels applied as 3-way splits (early March, GS31 and GS32). The 'Normal' treatment received 40 kg/ha in March (17% of the total on average). NS=not significant at P<0.05.

Site	*50% N in March*	*33% N in March*	*Normal N timing*	*F test; SED*
ADAS Boxworth	3,959	3,851	3,897	*NS; 70*
ADAS High Mowthorpe	3,676	3,639	3,578	*NS; 79*
ADAS Terrington	3,495	3,375	3,520	*NS; 109*
ADAS Rosemaund	4,372	4,358	4,367	*NS; 118*
Kent	3,835	3,870	3,929	*NS; 191*
Mean	**3,867**	**3,819**	**3,858**	

Managing other GHG impacts of growing wheat: fuel & straw

In relation to yield and nitrogen effects, GHG costs of pesticides and other fertilisers (P&K) are very small, but there are three further significant 'variable' GHG costs of growing wheat (Fig. 1): seed (5%), diesel for in-field operations (10%), and grain drying (8%). Additionally, growing operations can have significant impacts on the large amounts of carbon 'sequestered' in soil organic matter, and they can affect the GHG costs of processing grain for biofuels, through grain quality. Costs of transport to the processing plant are minor in GHG terms; however, processors will encourage production in their local region to keep financial transport costs low. The consequent issues arising for feedstock growers are variety choice, as it affects grain quality (considered in the section on breeding), seed production practices and seed rates, whether to adopt minimum tillage, and how to manage straw.

GHG costs of seed are derived almost entirely from the costs of growing the seed crop, and therefore arise largely from N fertiliser use. Seed growers will need to adopt similar strategies to feedstock growers in minimising N fertiliser use. Recent work on optimising plant densities (e.g. Spink *et al.* 2000a, b) indicated scope for less seed use than has been conventional, and it is likely that optimum rates will be similarly low for GHG savings, perhaps allowing a saving of 50 kg CO_2e/ha where rates are not already optimised.

A majority of the fuel used to grow and harvest wheat is for crop establishment, ploughing being the most expensive operation. The remainder is shared between applications and harvesting (P. Metcalf, personal communication). The main issue here is whether to plough because, as well as the fuel saving of about 59 kg/ha CO_2e from non-inversion tillage, there is also judged to be a benefit in soil carbon of 587 kg/ha/year CO_2e (Bhogal *et al.* 2007). It will be worth noting whether future accreditation schemes sanction this benefit; if so, they will also need to note that any reversion to ploughing would probably negate the benefit in soil-sequestered carbon.

Leaving aside vagaries of the weather, crop managers can adopt strategies to minimise fuel use in grain drying by advancing crop maturity (sowing early or choosing an early-maturing variety – the earliest maturing variety suitable for distilling is currently Zebedee), increasing harvesting capacity, reducing concerns over grain quality, and choosing a fuel-efficient drying system. If drying is consistently avoided the GHG saving is estimated to be 30 kg CO_2e per tonne grain (HGCA GHG Calculator; Woods *et al.* 2004).

Much the most significant issue facing accreditation systems and thence growers, other than how to minimise N use, is how to consider and manage straw; the straw, chaff and stubble from a crop yielding 8 t/ha represent approximately 11 tonnes CO_2e per hectare! For GHG savings, the key choice here is between using the harvestable part of this straw as fuel, perhaps replacing some fossil fuel used in biofuel processing, or incorporating it in the soil, hence sequestering some of the straw carbon in stable soil organic matter. For a crop yielding 8 t/ha these GHG savings are estimated to be 1,980 and 690 kg/ha/year CO_2e respectively, based on estimates and assumptions described by Punter *et al.* (2004, p19) and Bhogal *et al.* (2007). Greater savings and possible financial advantages should encourage use of straw as fuel, but the substantial logistical repercussions of harvesting and transporting straw may persuade many growers that incorporation remains the better option.

Breeding wheat for the biofuel market

A new breeding objective

The existing distilling market ensures that breeders produce high-yielding varieties with grain suitable for alcohol processing – nine are currently recommended, yielding from 9.8 t/ha (Riband) to 11.0 t/ha (Glasgow) in HGCA RL trials. However, the current protocol for testing new wheat varieties (CEL 2006) uses N levels as recommended in RB209, and in first wheat trials intended for bread-making requires an additional 80 kg/ha N. The medium term success of biofuel-wheat in the EU, when prices are governed by GHG savings (Defra 2007), will depend crucially on varieties which also yield well with low N supplies, something that has received little explicit attention from variety testing agencies or wheat breeders hitherto. It is therefore important to consider how efficiency of N use has developed in wheat, and whether there may be untapped variation in UK wheat breeding programmes, or even amongst recommended varieties, that might enable rapid reductions in use of fertiliser N without affecting yield.

The two component targets in developing efficient N use are (i) N capture – N taken up per kg N available in the soil, and (ii) N utilisation – grain formed per kg N taken up. N capture concerns the root system, its depth and density, its interaction with soil processes, but capture also depends on the capacity of the crop to assimilate and incorporate N – the N ‘sink’. N utilisation on the other hand concerns many, more familiar, yield-determining processes, e.g. the N needed for canopy formation, the efficiency of photosynthesis, canopy survival, dry matter distribution to grain and grain storage capacity.

Testing for low N requirements

A difficulty arises in comparing varieties in simple yield trials because, on-farm, higher yielding varieties justify receiving more fertiliser N; thus, whilst high yielding varieties may appear more N-efficient in trials conducted with uniform N applications, this advantage may be reduced, or even negated, when the high yielding varieties are grown commercially. Data from trials where several varieties have been tested with nil and a range of other levels of applied N can be used to assess the extent of this effect: they enable each variety to be compared with its optimum amount of fertiliser N, and with nil or low N amounts. Such data are available from three sources: trials by Fisons and Levington Agriculture in the 1980s, (Foulkes *et al.* 1998), a trial from the WGIN Project in 2004 (data kindly provided by P Barraclough), and the recently completed HGCA Project 3084 (10 trials per year; harvests 2005 to 2007). These data indicate several consistent features of varietal variation in N response:

- There has been no detectable improvement over recent decades in performance without fertiliser N, either in grain yields (Fig. 4a) or N off-take (kg/ha). Yields without fertiliser N do not relate well to yields with optimum or large amounts of fertiliser N (Fig. 4b).
- As well as improving yields with optimum fertiliser N by approximately 1 t/ha/decade, breeding has brought an associated improvement in N capture. However, this improvement is apparently restricted to the recovery of fertiliser N, which is held in the topsoil during crop growth, not soil-derived N, which is distributed throughout the rooted zone (Sylvester-Bradley *et al.* 2004).
- Thus, although varieties with say 1 tonne/ha yield improvement justify use of 15-20 kg more fertiliser N, this increase in N requirement is less than if there had been no improvement in N capture.
- There is no association between grain N% of different varieties (with optimum N amounts) and optimum grain yield; breeding has brought no ‘dilution effect’, or other trend in grain N%, hence, unless N harvest index has improved (not measured in these studies), it appears that past wheat breeding has not improved N utilisation efficiency.

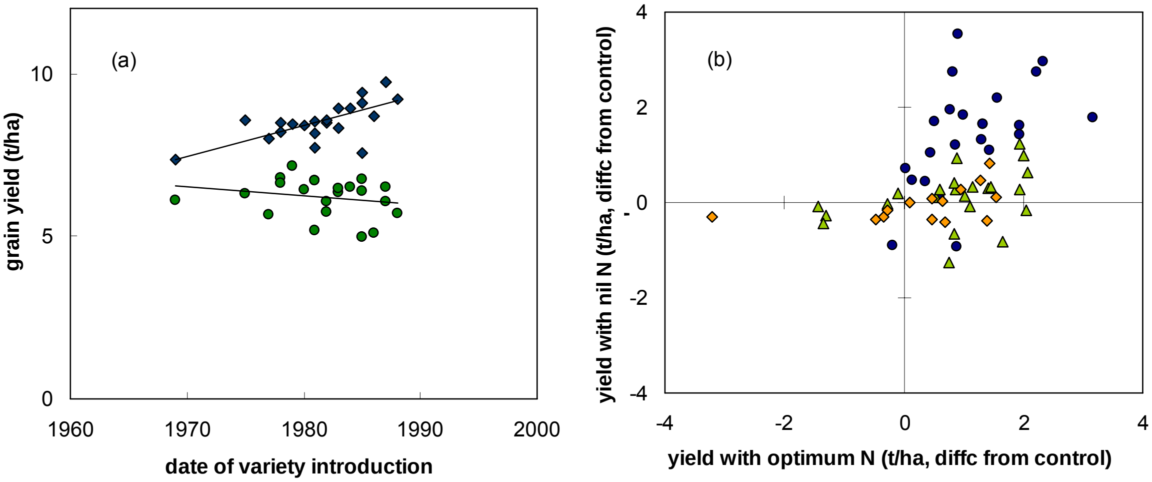

Fig. 4 (a) For 22 varieties introduced from 1969 to 1988, trends in grain yield with optimum N amounts (diamonds) and with nil N applied (circles). Data from Foulkes, Sylvester-Bradley & Scott (1998). (b) For 24 comparisons of 2 old (1^{st} on RL 1977-1987) and 2 new (1999-2005) varieties conducted in 2005 to 2007, yield differences with optimum N and with nil N. Data from HGCA Project 3084.

It must be concluded that breeding for a testing system which uses ample fertiliser N has brought little progress in yield with small, largely soil-derived, N supplies. To bring progress, it will be necessary to test new varieties with little fertiliser N, and possibly with nil, as well as with ample N levels (Fig. 5). There is an analogy with testing varieties with no fungicides or PGRs, except that low N testing has greater necessity because traits enhancing N use efficiency are much less obvious than disease and lodging resistances.

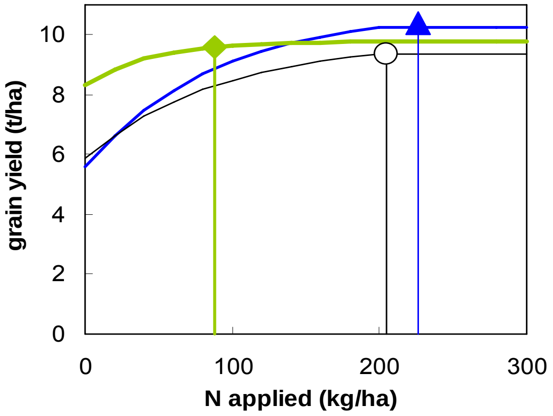

Fig. 5. Modelled N responses and optimum N amounts (symbols) for a control variety (circle), a variety bred for yield through 10% better photosynthetic efficiency but with worse recovery of soil N (triangle) and a variety bred for low N requirement through 10% better N recovery and 33% less canopy N, based on the 'steps' model of Sylvester-Bradley et al. (1990). The premium needed to compensate for loss of profit from growing the low N variety instead of the high photosynthesis variety is £1.67/tonne.

Progress towards breeding the ideal biofuel wheat

The GREEN grain project (LINK Project 0992 / HGCA Project 2979; Sylvester-Bradley 2007) was set up to explore the scope to breed wheat with low N requirements, as well as grain with maximum alcohol processing potential. Average recovery of fertiliser N by wheat is 60% (Bloom *et al.* 1998) and it has been increased by yield-breeding (Foulkes *et al.* 1998) so the project chose to focus primarily on N utilisation rather than on N capture traits. However, it is worth noting that there have been two recent innovations which may, in time, offer to bring substantial improvements in N capture.

- The first involves introgressing from a wild relative, the capacity to produce root exudates that inhibit conversion of ammonium to nitrate in soil (Subbarao *et al.* 2007). In combination with ammonium nutrition (from urea fertilisers, or in anaerobic soils), this has the potential to reduce leaching and denitrification losses of N. However, it remains to be seen whether this trait represents a significant advantage under field conditions, particularly in the relatively dry and aerobic soils on which wheat is normally grown.
- The second concerns a discovery by Good's group in Alberta (Good *et al.* 2004; Lea & Azevedo 2007) that promoting activity of the enzyme alanine aminotransferase enhances N assimilation in plants. This trait has been transferred successfully to oilseed rape in California, using GM technology, causing fertiliser N requirements to halve (Good *et al.* 2007), and it will now be transferred to rice, maize and wheat (Etter 2007; Arcadia Biosciences 2007) with the aspiration of bringing dramatic reductions in nitrous oxide emissions from all these extensively grown crops (Aldhous 2008).

Turning to N utilisation, the GREEN grain project identified that of the 180 kg/ha N held in wheat canopies at flowering, only about half is required for photosynthesis; if the remaining N is just stored for redistribution to grain, then this may well represent an inefficiency in N use, especially if high grain N storage is counter-productive to the end-user. Work has therefore focussed on the extent to which current wheat varieties store N, and has characterised N storage both in the canopy and the grain. Separation of the canopy into its component parts shows their roles to be rather complex: 20% N is stored in the true stem and 20% in sheath (Fig. 6), organs that appear to have little role in photosynthesis; leaf blades hold only 43% N at the optimum, and are more susceptible than stems and sheaths to losing N when N supplies are sub-optimal, but stems and lower leaves are most responsive to super-optimal N supplies.

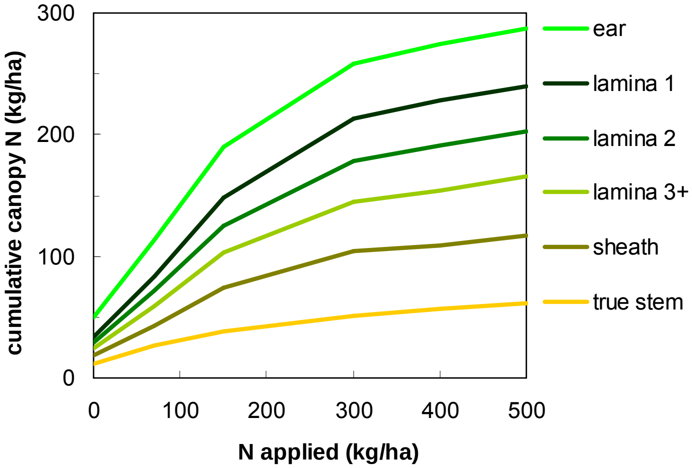

Fig. 6. Effect of applied N on N distribution in the canopy at flowering of Istabraq grown at Lincoln, New Zealand in 2006-7. The N optimum was 285 kg/ha, with a yield of 14.4 t/ha. (Data of A Pask, University of Nottingham & P Jamieson, NZ Institute for Crop & Food Research, through the GREEN grain Project).

The notion that stems store N therefore seems reasonable, but variation in stem plus sheath N amongst modern wheat germplasm is small: 68-78 kg/ha, and there are big interactions with environmental conditions so it will be difficult to select directly for low stem N storage. More heritable stem traits are height and wall width; some progress in reducing stem N may be possible by reducing these, as long as detrimental repercussions on soluble stem reserves, lodging or disease can be avoided.

In considering N storage in grain, we have confirmed that gliadins (alcohol-soluble proteins held in the endosperm) constitute ~40% of grain protein and, of all grain proteins, these are the most responsive to N supplies (Kindred, Verhoeven *et al.* 2007). Low gliadin is not detrimental to seed germination and it enhances alcohol processing yield, so gliadins can be considered to cause superfluous N storage in biofuel wheats. Amongst commercial varieties, gliadin storage varies from 37% (Glasgow) to 50% (Buchan) of grain protein at the same N level; it therefore has significant potential for direct selection in breeding programmes.

With regard to varieties with low N requirements, the best indication from trials with just 2 N levels is a low response to N. Of the subset of varieties now on the RL that have been tested in the GREEN grain project (Fig. 7), the highest yielding varieties gave the highest responses, but the lowest response was in Claire, not the lowest yielding variety. These results and those in Fig. 4 indicate that some nil or low N testing could help to minimise N requirements in high yielding varieties.

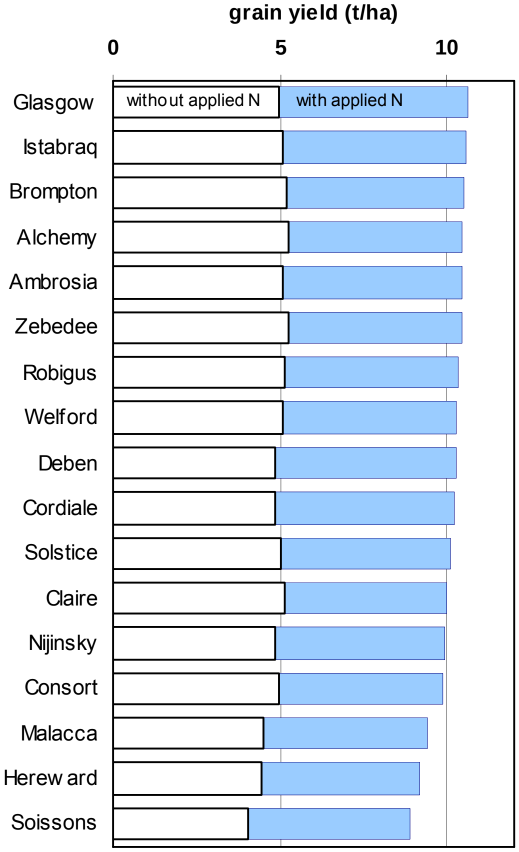

Fig.7. Grain yields of varieties from the HGCA Recommended List, and yields with nil N applied, calculated from measurements in 5 trials from the GREEN grain project.

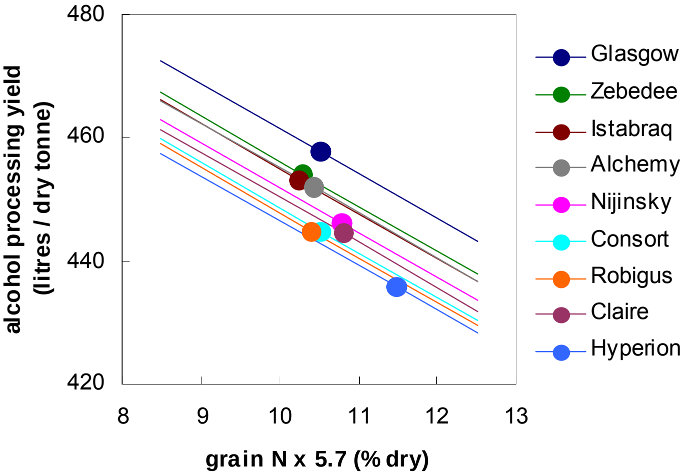

Fig. 8 Best fit lines (and mean values) for grain protein (N x 5.&) and alcohol processing yields for the varieties tested in 6 RL and GREEN grain project trials in 2005, grain analysed by SWRI (Smith et al. 2006). The key shows varieties in order of alcohol yield.

The qualities of wheat grain needed for alcohol processing are reviewed in HGCA Research Review 61 (Smith *et al.* 2006). Low grain protein is important but available data from the SWRI (Fig. 8) clearly show that there are other aspects to maximising alcohol yield per tonne of grain. Work is ongoing to identify what factors are most important but non-starch polysaccharides (NSPs) are implicated. These not only displace starch in the grain, but they are also responsible for causing undesirable levels of viscosity during processing which can seriously hamper efficient running of the processing plant.

There has been little time for wheat testing and breeding to adapt to a new biofuel market in the UK, and there is clearly much scope for progress. Whilst ongoing testing has been successful in maximising crop productivity and improving quality for distilling, the main aim of any new practices must be to minimise the requirements of UK wheats for fertiliser N. It is encouraging that progress in N capture has been allied to yield improvement, and there is hope that new innovations will bring further progress in the medium term, but there is a need to reduce the amount of N required to form an adequate canopy for photosynthesis, and to reduce the amount of N stored in wheat grain. It is worth noting that some triticale varieties perform well at reduced levels of fertiliser N (Aufhammer *et al.* 1996) as well as having suitable grain for processing (Rosenberger 2005). One route to progress may be through analysing and incorporating the traits giving rise to this advantage or even, in the meantime, considering triticale as a biofuel feedstock. Triticale is used in the Baltic region, and some initial HGCA-funded work is already in place.

GHG accreditation

Bringing accreditation to the farm

Given that government intends that rewards for biofuel use should relate to their GHG savings after 2010, the development of appropriate accreditation procedures has a high priority. The HGCA has led the way by developing the GHG Calculator (Woods *et al.* 2005 and this conference). However, a crucial concern in establishing biofuel production in the UK is that bureaucracy and 'red tape' should not be deterrents. Easy accreditation will be crucial, but ideal accreditation must measure and validate grain yield, N use, straw yield, grain drying and starch content (or potential alcohol yield) for each grain lot at several stages: as it is harvested, then stored, despatched, traded and eventually delivered for processing.

Using grain analysis to avoid bureaucracy

Part of the problem here is that grain is mixed and remixed at most stages from harvesting in the field through to processing, so it becomes a complex problem to amalgamate data from many origins. We suggest that grain analysis could provide a solution. The concentration of N in grain relates well to the extent to which use of fertiliser N differs from optimum (e.g. Fig. 3), NIR can be used to predict potential alcohol processing yield and, if necessary, varieties can be identified rapidly using grain analysis (Uthayakumaran *et al.* 2005). Furthermore, since low yielding crops generally concentrate N in their grain, rewards for low grain N% will have the combined effect of encouraging yield maximisation as well as low use of fertiliser N. It may well be worth overlooking the minor effects of grain drying and straw yield on GHG costs, to allow this major saving in bureaucracy.

Conclusions

With current wheat growing systems in the UK, wheat-biofuel can provide major savings in GHG costs of transport fuels. The key to reducing GHG costs is in minimising N fertiliser use. Significant financial premiums are needed to maximise GHG savings from wheat-biofuels. There is extensive scope to improve GHG savings from wheat-biofuels through changes in the ways that new varieties are tested and bred. But crop productivity remains the central focus of any endeavour to develop sustainable biofuel production; indeed it is crucial to improving the sustainability of all cropping systems, preventing further destruction of virgin habitats and preserving soil carbon stocks.

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