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Managing nitrogen applications to new Group 1 and 2 wheat varieties

by

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Contents

1. Abstract

- Using full nitrogen (N) response curves (7 N rates), the N requirements of selected modern high yielding Group 1 and 2 varieties (e.g. Einstein, Malacca, Xi19) was examined at 9 experimental sites (2002-2005), and compared to those of older and lower yielding varieties (e.g. Avalon and Mercia) that represent the dataset used to underpin the current recommendations in Defra's 'Fertiliser Recommendations (RB209)' publication (7th edition, 2000). Chopin Alveograph analyses were done at selected sites. At a further 9 sites, alternative strategies for applying extra late N for protein were examined, including combinations of late solid and foliar urea spray applications. It is anticipated that these results will be considered in any future revision of RB209.
- As expected, the average yield of the modern varieties was about 1t/ha higher than the older varieties (9.09t/ha compared to 8.09t/ha). Using a linear plus exponential curve fitting procedure, economic optimum N rates (Nopt) were derived for each variety tested, and at different economic breakeven ratios. Nopt values for yield (3:1 ratio) ranged from zero to over 340kg/ha N and there was a significant relationship ($p<0.05$) that showed that the higher yielding varieties had higher Nopt values by an average of 17.3kg N/t grain yield. At these N rates, the grain protein contents were mostly between 12.5-13.5% and averaged 12.76% - this is close to the current critical level in RB209 for breadmaking wheat. It was not possible to show any consistent differences in the N uptake efficiency of different varieties.
- Overall, the fitted Nopt values for yield (3:1 ratio) for the modern varieties were higher than the current RB209 recommendations. When each recommendation was adjusted for the grain N (protein) content of the experimental crop (as recommended in RB209), the Nopt was 29kg/ha higher on average than the recommended rate. The adjusted RB209 recommendations were usually higher than the unadjusted recommendation. Thus, both the current unadjusted and adjusted RB209 recommendations were generally under-estimating the Nopt for modern varieties at these sites. If the Nopt values were based on a breakeven ratio of 6:1 (equivalent to ammonium nitrate at £145/t and grain at £70/t) rather than 3:1 (as in RB209), the average Nopt reduced by 29kg/ha N, yield at the Nopt (Yopt) reduced by 0.13t/ha and grain protein at the Nopt reduced by 0.32%.
- For the modern variety crops, 6 out of 16 (38%) needed more than 280kg/ha N to achieve 13% protein, and 4 out of 16 (25%) needed more than 300kg/ha N. The highest unadjusted recommendation in the current RB209 is 280kg/ha N. At N rates needed to achieve 13% protein, the the extra margin over N cost (above that from achieving Yopt alone) was around £100/ha, assuming a £13/t premium and a 100% success rate of crops grown for the premium. At lower premiums and success rates (e.g. £5/t and 1 in 3 success rate), the margin did not generally justify growing milling compared to feed wheats.

- Late N applications increased protein contents but foliar urea was generally more effective than solid ammonium nitrate (0.66% and 0.34% protein from 40kg/ha late N respectively). Effects of late N on yield were uncommon and small, though small yield reductions were observed due to leaf scorch from late foliar urea application.

2. Summary

2.1 Project objectives

The overall aim of the project was 'To develop optimum nitrogen fertiliser application practices for realising the high yield potential of modern Group 1 and 2 wheat varieties whilst also meeting the grain protein and Alveograph quality requirements set by both home and export markets'. Specific objectives were:

1. To test if modern high yielding varieties have different nitrogen requirements for achieving their yield potential, compared to older lower yielding varieties which form the scientific underpinning basis of current national standard fertiliser recommendations (RB209).
2. To identify optimal methods for applying extra N in addition to that required for yield in order to achieve large increases in grain protein content.
3. To investigate the effect of different nitrogen management approaches on grain Alveograph values.

2.2 Background

There are several important issues and developments that provide the background to this project.

1. There is uncertainty about the nitrogen requirements of modern Group 1 and 2 wheat varieties which are high yielding, and where a high grain protein concentration may also be needed. Around 30% of the UK wheat area is typically now sown to these varieties.
2. Fertiliser N prices have increased substantially in recent years due to increasing energy prices. This will increase the 'breakeven ratio' (kg grain needed to pay for 1kg of N) and reduce economic optimum N rates. This in turn will make it more difficult to achieve both high yields and high protein contents.
3. Nitrate Vulnerable Zones (NVZ) have been designated for large areas of the UK arable area. For land inside an NVZ, farmers must comply with the NVZ Action Programme (NVZ-AP) rules. Complying with the NVZ-AP rules is a cross compliance Statutory Management Requirement (SMR), and failure to comply can result in a reduction in the Single Farm Payment (SFP). The recommendations contained in Defra's 'Fertiliser Recommendations (RB209)' publication (7^{th} edition, 2000) are the recognised industry standard, and are used by the Environment Agency (EA) as the preferred basis for judging compliance. It is important therefore, that these recommendations are maintained fully up to date and relevant to modern growing conditions. The current RB209 recommendations for N use on wheat are based on over 280 experiments, but are now being questioned since these experiments were mostly carried out between 1981 and 1994, and on varieties with a significantly lower yield potential than modern varieties.

2.3 Experimental designs

There were 2 distinct experimental designs within the project, with 9 replicated small plot experimental sites of each design between harvests 2002 and 2005, commonly co-located at each site.

Design 1. Investigating the optimum N requirements of old and 'modern Group 1 or 2' varieties for yield.
At each experiment, there were 2 old varieties (from Avalon, Mercia and Riband), reflecting varieties of relatively low yield potential and typical of those used in the experiments that underpin RB209, and 2 modern varieties (from Einstein, Hereward, Malacca, Option, Solstice and Xi19) with a high yield potential. At each site, 7 N rates were tested for each variety – the N rates ranged from zero up to 300 or 340kg/ha N depending on the site, applied as 40kg/ha (late February/early March) and the balance split 50:50 between GS31 (1^{st} node stage) and early May. Response curves were fitted to all data and information obtained from the fitted curves.

The linear plus exponential (LEXP) function was used to fit yield response curves and to derive economic optimum N rates (Nopt) for each variety at each experimental site. The LEXP function assumes that yield increases due to fertiliser N diminish successively as the N rate increases up to the optimum. This function has been used as the standard method for fitting N response data and as the basis for setting recommended N rates in the current and earlier editions of RB209. It is recognised that further consideration of alternative response functions may be appropriate as part of any revision of RB209, but any such study will need to be carried out on a larger dataset than is available from this project. The yield at each Nopt rate (Yopt) was calculated.

Design 2. Investigating the optimum strategy for applying late N for protein
At each experiment, the following late N treatments were applied to a single Group 1 or 2 variety.

- Control (no extra N)
- 40, 80, 120kg/ha total N as 'extra' to the base dressing, applied
- all as ammonium nitrate (AN) prills at GS39-61 (flag leaf emerged to flowering)
- all as foliar applied urea spray (10% N) at GS69-75 (watery to milky ripe)
- all as foliar applied urea spray (20% N) at GS69-75 (watery to milky ripe)
- half as AN prills at GS39-61, half as foliar urea (10% N)
- half as AN prills at GS39-61, half as foliar urea (20% N)

2.4 Results and discussion

2.4.1 Nopt for yield

Good yield responses to applied N were obtained at most sites. At all sites, the modern varieties out-yielded the old varieties reflecting their anticipated higher yield potential. Overall, the mean Yopt for the modern varieties was 9.09t/ha and 8.09t/ha for the old varieties, a difference of 1.0t/ha. However, differences in the Yopt between individual modern and old varieties ranged up to nearly 3t/ha. At most sites, the higher yielding varieties had a higher Nopt. Typical examples are shown in Figure 2.1.

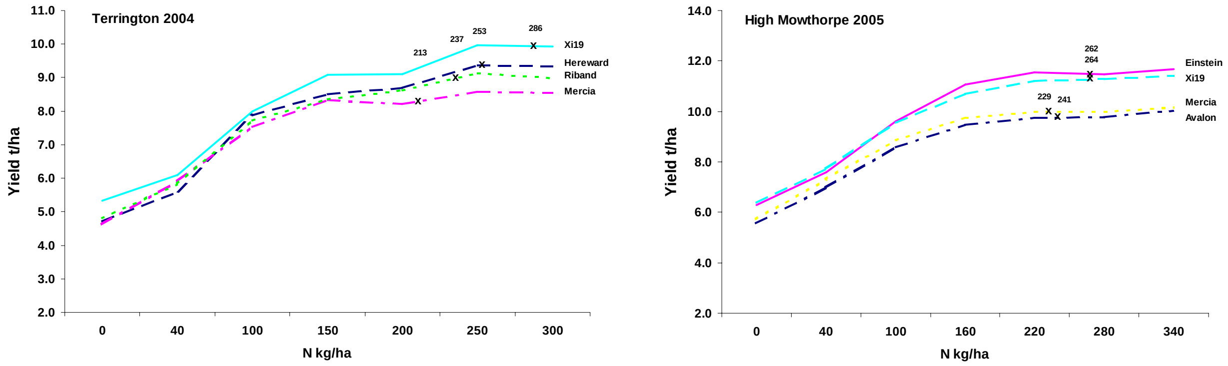


Figure 2.1 Grain yield response curves to rate of applied fertiliser-N. Fitted Nopt values (3:1 ratio) are shown for each variety

Figure 2.2 shows this relationship by plotting the differences in Nopt and Yopt (both at 3:1 ratio) for each variety compared to the lowest yielding variety at each site. Data for Boxworth 2004 (Nopt above maximum N rate tested), High Mowthorpe 2004 (low yields due to take-all) and Essex 2005 (no response to N) are excluded from this relationship. The fitted line (R^2=0.24, $p<0.05$) shows that the Nopt increased by an average of 17.3kg/ha N per tonne of higher yield.

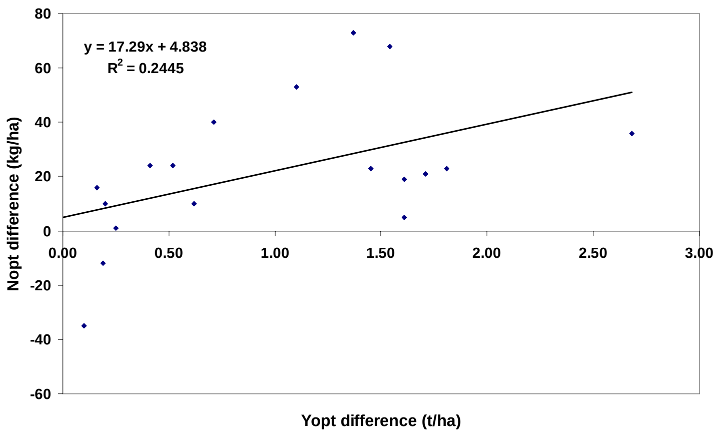


Figure 2.2 Relationship between differences in Nopt and Yopt (both at 3:1 ratio) between individual varieties and the lowest yielding variety at each site

The relationship between the Nopt for yield (3:1 ratio) and the protein content at this Nopt was examined. For the milling varieties, the grain protein content at the Nopt rate for yield (3:1 ratio) ranged from 10.27% to 14.23%, but averaged 12.76% (2.24% N). This is similar though slightly higher than the current critical level in RB209 for breadmaking wheat (2.2% N or 12.5% protein). For 18 of the 36 crops (50%), the protein at Nopt was between 12.5 and 13.5% (2.20-2.37% N) – see Figure 2.3. For 15 crops (42%), application of the fitted Nopt rate (3:1 ratio) resulted in a grain protein content of over 13%, and for 23 crops (64%) of crops it gave a grain protein content of over 12.5%.

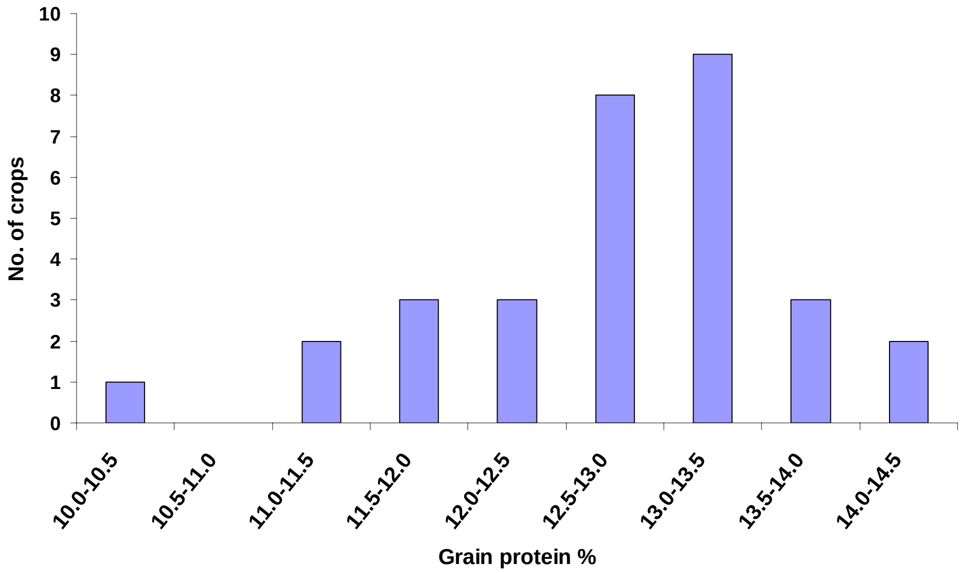


Figure 2.3 Distribution of grain protein content at Nopt

2.4.2 Comparison with current RB209 recommendations

Table 2.1 compares the RB209 recommended N rate for yield (Nrec) at each site, using both the Field Assessment Method (FAM) and the Soil Mineral Nitrogen (SMN) method (Anon 2000), with the mean fitted Nopt for yield (3:1 ratio) and the associated Yopt for the modern varieties. The FAM approach uses information on soil type, previous cropping and rainfall, whereas the SMN method uses soil mineral N analysis information (0-90cm). The RB209 recommendations are given with and without an adjustment for the grain N (protein) content - the adjusted recommendations were calculated using the fitted grain N value at the unadjusted RB209 recommended rate, then using an adjustment factor of 30kg/ha fertiliser-N per 0.1% grain N difference with the critical value of 2.2% grain N for breadmaking wheats (as in RB209).

At all sites apart from Essex 2005 and Rosemaund 2004, the fitted Nopt for yield was larger than the unadjusted Nrec from RB209 using either the FAM or SMN methods. The mean fitted Nopt for all sites (excluding Essex 2005) was 258kg/ha N – this was 65kg/ha N higher than the mean Nrec using the FAM (193kg/ha N), and 103kg/ha higher using the SMN method (144kg/ha N). At 6 of the 9 sites, the fitted Nopt was above 240kg/ha N, the highest unadjusted recommended N rate for yield in RB209. If the RB209 Nrec rates were adjusted for the grain N% achieved at harvest, most RB209 Nrec rates were increased. The average adjusted RB209 Nrec was 229kg/ha N, which was higher than the unadjusted Nrec using either the FAM or SMN methods. However, at 6 of the 9 sites, the adjusted RB209 Nrec was still less than the fitted Nopt. The mean Nopt across all sites was 29kg/ha N higher than the adjusted RB209 Nrec rate using either the FAM or SMN method, but up to nearly 100kg/ha N higher (Boxworth 2004).

Table 2.1 RB209 recommended N rates, fitted Nopt for yield and Yopt (3:1 ratio) for each site (mean of modern varieties only)

Site	**RB209 Nrec (unadjusted)**		**RB209 Nrec (adjusted)**		**Nopt (kg/ha N)**	**Yopt (t/ha)**
	FAM	**SMN**	**FAM**	**SMN**		
Boxworth 2003	180	100	146	160	211	7.12
Boxworth 2004	180	180	203	203	>300[a]	9.59
Terrington 2004	150	180	231	231	270	9.61
Rosemaund 2004	220	100	263	273	168	10.10
High Mowthorpe 2004	240	200	215	206	258	6.24
Terrington 2005	150	150	261	261	311	9.43
Rosemaund 2005	220	220	240	240	283	9.14
High Mowthorpe 2005	200	110	269	254	263	11.48
Essex 2005	100	40-80	100	40-80[b]	0	7.60
Mean [b]	**193**	**155**	**229**	**229**	**258**	**9.09**

a Taken as 300kg/ha for calculating the mean
b Essex 2005 excluded from the mean

2.4.3 N rate for yield and high grain protein content

Table 2.2 shows the N rate needed to achieve 13% protein for each variety at each site, compared to the unadjusted RB209 Nrec rate for yield. Excluding Essex 2005 (unresponsive to N), 38% of modern variety crops (6 out of 16) would have needed more than 280kg/ha N in order to achieve 13% protein, and 25% (4 out of 16) would have needed more than 300kg/ha N. The highest unadjusted recommendation in the current RB209 for yield and protein is 280kg/ha N. Excluding those sites where 13% protein was not achieved at the highest N rate tested, an average of 41kg/ha less N was needed to achieve a grain protein content of 12.5% rather than 13.0%. 50% of modern varieties (8 out of 16) would have needed more than 240kg/ha N to achieve a 12.5% protein target.

Note:- It must be recognised that these conclusions are based on all of the N being applied by early May, and that application of part of the total N rate as late N would probably achieve the same yield and a 13% protein content but with a slightly lower total N rate.

Analysis of the data also showed that in order too meet a 13% protein target, recommended N rates needed to increase by around 35kg N/t of yield increase (e.g. 35kg/ha more N needed for a 9t/ha crop compared to an 8t/ha crop in order to achieve 13% protein).

Table 2.2 N rate needed to achieve 13% grain protein

Site	**RB209 Nrec (FAM)**	**RB209 Nrec (SMN)**	**Avalon**	**Mercia**	**Riband**	**Einstein**	**Hereward**	**Malacca**	**Option**	**Solstice**	**Xi19**
Boxworth 2003	180	100		166	175			161			177
Boxworth 2004	180	180	126		>300			264		268	
Terrington 2004	150	180		>300	>300		>300				>300
Rosemaund 2004	220	100		226	>240	>240			>240		
H Mowthorpe 2004	240	200	183		285	231	242				
Terrington 2005	150	150	316	301				294		317	
Rosemaund 2005	220	220	216	238		298					278
H Mowthorpe 2005	200	110	>340	>340		>340					>340
Essex 2005	100	40-80	0	61				57		43	

The financial margin over the cost of fertiliser N for different N rates was calculated from each dataset for all Group 1 varieties and Solstice (i.e. those varieties that command the highest premiums). The cost of fertiliser-N was assumed to be 43 pence/kg (equivalent to £148 per tonne of ammonium nitrate) and feed wheat at £70/t (ratio of 6:1). Dockage of the premium was assumed to take place between 12.5 and 13.0% at the rate of £1/t for each 0.1% protein below 13.0%, with no premium payable below 12.5% protein. No account was taken of the yield difference between growing a milling variety compared to a higher yielding feed variety (typically around 0.15t/ha and worth about £12/ha). Table 2.3 shows the maximum extra margin that would be obtained for different premium/success rate scenarios (premiums of £13/t or £5/t, each with success rates of 1 in 1, 1in 3 and 1 in 5 crops). Figure 2.4 illustrates how the margin changes with N rate for each scenario for Solstice at Boxworth 2004 and Xi19 at High Mowthorpe 2005.

Table 2.3 Maximum extra margin (£/ha) over fertiliser-N cost for different premium and success rate scenarios

	Premium and success rate						
	No premium	**£13/t**	**£13/t**	**£13/t**	**£5/t**	**£5/t**	**£5/t**
	n/a	**1 in 1**	**1 in 3**	**1 in 5**	**1 in 1**	**1 in 3**	**1 in 5**
Hereward (HM2004)	305	+75	+24	+14	+28	+8	+4
Hereward (Tt2004)	545	+103	+31	+18	+29	+6	+3
Malacca (Bx2004)	526	+107	+29	+13	+35	+4	0
Malacca (Tt2004)	512	+108	+30	+16	+36	+6	+1
Solstice (Bx2004)	586	+126	+40	+22	+46	+13	+7
Solstice (Tt2004)	558	+123	+37	+20	+44	+11	+4
Xi19 (HM2005)	689	+61	0	0	0	0	0
Xi19 (Rs2005)	493	+118	+39	+24	+45	+15	+9
Xi19 (Tt2004)	>578	+91	+30	+18	+10	+3	+2
Mean	**533**	**+101**	**+29**	**+16**	**+30**	**+7**	**+3**

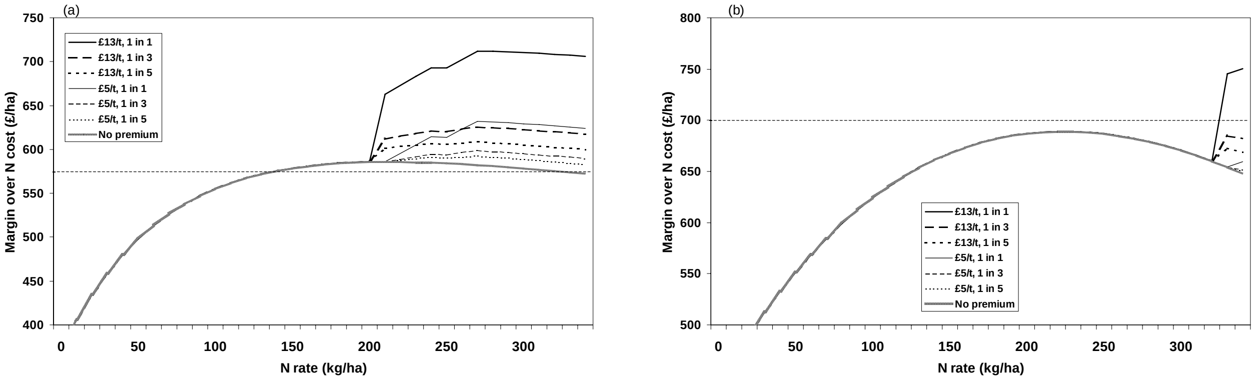


Figure 2.4 Change in margin over fertiliser-N cost for different premium and success rate scenarios for (a) Solstice at Boxworth 2004 and (b) Xi19 at High Mowthorpe 2005

Table 2.3 shows that a premium of £13/t with a perfect 1 in 1 success rate increased the margin over the cost of fertiliser N by £101/ha on average (above that from achieving Yopt only), and up to £126/ha. In recent years, premiums have been well over £20/t which would nearly double this extra margin. If the premium value or success rate was less, then the extra margin quickly reduced. For a £13/t premium, the average extra margin reduced from £101/ha for a 1 in 1 success rate, to £29/ha for a 1 in 3 success rate and only £16/ha for a 1 in 5 success rate. If the premium value was only £5/t, the respective extra margins were £30/ha, £7/ha and £3/ha. If the difference in yield potential between Group 1 and feed varieties is considered to be around 0.15t/ha (worth c.£12/ha), then growing milling rather than feed varieties would on average have been worthwhile where the premium was only £5/t provided the success rate was 1 in 1, or if the premium was £13/t even if the success rate was only 1 in 5. In most cases, it would not have been worthwhile growing a milling wheat compared to a feed wheat where the premium was £5/t and the success rate was 1 in 3 or worse.

Note:- These data are based on all of the N applied by early May. The target protein contents and maximum margins would probably be achieved at slightly lower total N rates if part of the total N rate was applied as late foliar urea, since this strategy will usually give a larger increase in protein.

The response of Xi19 at High Mowthorpe 2005 is noteworthy. Although 12.6% protein and 11.4t/ha yield was obtained from use of very high rates of N at this site (340kg/ha), this was only profitable under a scenario of £13/t premium and a perfect 1 in 1 success rate. This was because the Nopt for yield (6:1 ratio) was only 223kg/ha, so a large amount of additional N above this was needed (c.120kg/ha costing over £50/ha) before the premium could be obtained.

2.4.4 Varietal differences

One of the objectives of the project was to investigate if there were any inherent differences between varieties in their ability to recover soil or fertiliser N. Improving the ability of a crop to recover both soil and applied fertiliser N is important for both economic and environmental reasons. Examination of the data showed that, although there were some statistically significant differences between modern varieties at individual sites, no consistent effects could be found.

2.4.5 Effect of breakeven ratio on Nopt

The fitted response curves for grain yield and protein content were examined to identify the effects of changes to the breakeven ratio. Although, current RB209 recommendations are based on a ratio of 3:1, a breakeven ratio of 6:1 would be more appropriate where feed grain is valued at £70/t and ammonium nitrate costs £145/t (42p/kg N).

On average, changing the breakeven ratio from 3:1 to 6:1 for the modern varieties would reduce the Nopt by 29kg/ha N, reduce Yopt by 0.13t/ha, and reduce grain protein by 0.32%.

2.4.6 Specific weight and Chopin Alveograph responses

At all sites where there was a yield response to applied fertiliser N, there was also a small positive response of specific weight. However, the majority of the response was at N rates that were well below the Nopt rate for yield. Although there were significant ($p<0.05$) differences between some varieties at most sites, there were no consistent differences between individual varieties.

Chopin Alveograph information is required to meet the quality requirements of export markets, but not for the UK market. In essence, the Chopin Alveograph measures the quality of the wheat gluten that holds the loaf together. The key requirements for the ukp bread wheat standard (appropriate for Group 1 and 2 varieties) is for W>170, P/L<0.9 and protein 11-13%; for the uks soft wheat brand, the requirements are for W<120, P/L<0.55 and protein 10.5-11.5%. W is a measure of the baking strength of the dough, P the maximum pressure required to burst the dough bubble, L the extensibility of the dough and P/L the dough strength and extensibility (HGCA Chopin Alveograph Guide). Chopin Alveograph analyses were carried on samples from each replicate of all N rates for 11 modern varieties.

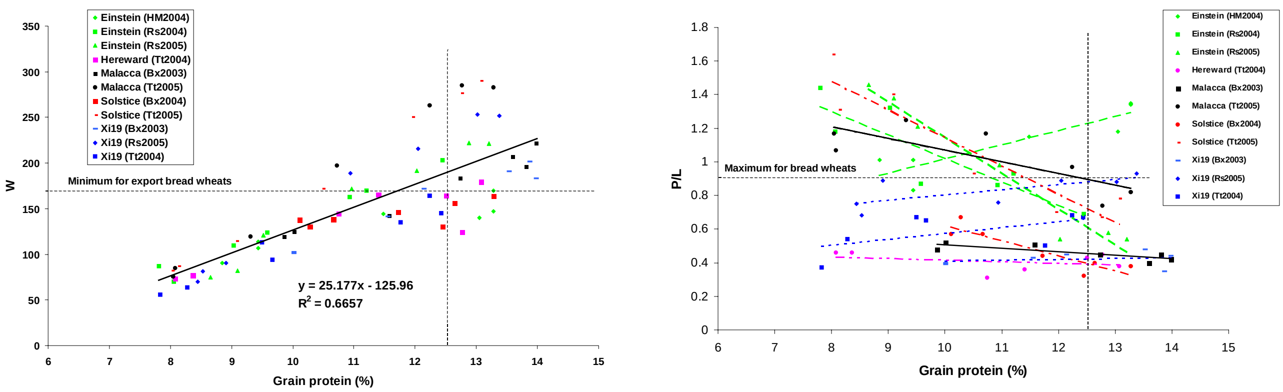


Figure 2.5 Relationship of grain protein with W and P/L values

Figure 2.5 shows that the W value increased linearly with protein content up to around 11.0% protein that was largely independent of site or variety (c.25 W per 1% protein). The relationship was more erratic above this protein content. At least 11.0-11.5% protein was needed to achieve the critical level of W>170. Above 11% protein, most samples exceeded a W of 170, but there were some that were over 12.5% protein (required for the export market) but below a W of 170. There were indications that Xi19 had a lower W value than some other varieties.

There was a general trend for both P and L to increase with both increasing N rate and protein content. The relationship with protein was stronger for L (dough extensibility) than for P (maximum pressure to burst dough bubble). The average rate of increase of L was approximately 13 L per 1% protein. At Terrington 2004, L was significantly higher ($p<0.05$) for Hereward than for Xi19. Significant differences ($p<0.05$) in P/L values between varieties were observed at 2 sites (Malacca>Xi19 at Boxworth 2003, Xi19>Hereward at Terrington 2004). However, Figure 2.5 shows that the relationship between grain protein content and P/L varies depending on variety and site factors. For several datasets, P/L appeared to decrease as protein increased. At low protein contents, P/L appeared to be higher in Einstein than Xi19. However, due to the slope of the response line, this difference was not apparent when grain protein exceeded 12.5%. Most grain samples that were above 12.5% protein were also below the critical P/L level of 0.9.

2.4.7 Strategies for applying late N

The Design 2 experiments tested the effects of different strategies for applying late N – see section 2.3 for more details. There were few significant effects on yield from application of late N. This would be expected since a standard base rate of N, intended to be close to the economic optimum (Nopt), was applied to all plots before the late N treatments were applied. Late N increased yield by up to 0.3t/ha at only 2 sites. At 3 of the 9 sites, late foliar urea gave a small yield reduction of up to 0.4t/ha compared to application of late solid AN, which was commonly associated with observed leaf scorch.

Application of late N had a large and consistent effect on grain protein content and there were differences in the effectiveness of the different application strategies (Figure 2.6). Use of AN prills at GS39 gave a significantly lower ($p<0.05$) protein than the other strategies at 7 of the 9 sites, and the AN+foliar urea strategy gave a significantly lower protein than foliar urea at 5 of the 9 sites. Over all N rates, application of solid AN prills at GS39-61(flag leaf emerged to flowering) was not as effective at raising the grain protein content as use of a foliar urea spray at GS 69-75 (watery to milky ripe). This was more noticeable at high N rates than at the typical farm practice rate of 40kg/ha N. The weaker effectiveness of solid AN may be due to delays in the movement of this N into the soil and then into the crop. Rainfall is needed for this process which can be unreliable.

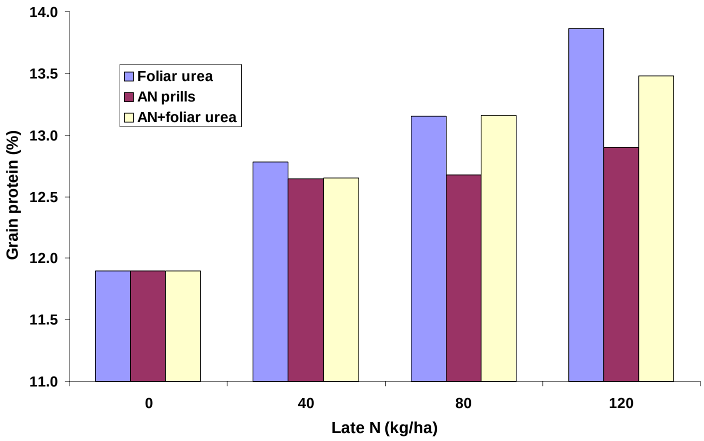


Figure 2.6 Overall effect of timing strategy and N rate on grain protein content

The average rate of protein response to 40kg/ha of late N was lower from use of AN prills (0.34%) than foliar urea (0.66%). However, the rate of response from use of foliar urea tended to be slightly lower as grain yield increased. This relationship might be expected due to a dilution effect, and may be a factor in explaining why the rate of response to 40kg/ha as foliar urea found here (0.66% protein response, 9.34t/ha mean yield), is lower than that found by Dampney *et al* (1995) in an earlier HGCA-funded research project (1.03% protein response, mean yield 7.15t/ha). There were no differences in grain protein at any site between use of foliar urea at full strength (20% N) compared to half strength (10% N).

The overall recovery of all late N treatments was lower than is typically found for the recovery of fertiliser N applied for yield during March to May - this is typically 60% recovery into grain and straw, or 45% into grain only. The average recovery of 40kg/ha of late N into grain was 33% for all late N strategies, and declined to around 20% as the rate of N application increased to over 80kg/ha. At Boxworth 2003 and Rosemaund 2003, late solid AN at GS39 was much less efficiently used than late N applied as foliar urea or as a split strategy.

In order to obtain a more precise measure of the fate of late applications of N, selected 2005 experiments from this project and HGCA project 3084 are being used to measure total crop N (grain and straw) and soil mineral N after harvest, and the uptake of residual N by a following wheat crop. This work is funded by Defra and will be reported elsewhere.

2.5 Key conclusions

- Using full nitrogen (N) response curves (7 N rates), the N requirements of selected modern high yielding Group 1 and 2 varieties (e.g. Einstein, Malacca, Xi19) was examined at 9 experimental sites (2002-2005), and compared to those of older and lower yielding varieties (e.g. Avalon and Mercia) that represent the dataset used to underpin the recommendations in Defras ‘Fertiliser Recommendations (RB209)’ publication (7^{th} edition, 2000). Chopin Alveograph analyses were done at selected sites. At a further 9 sites, alternative strategies for applying extra late N for protein was examined, including combinations of late solid and foliar urea spray applications. It is anticipated that these results will be considered in any future revision of RB209.

- As expected, the average yield of the modern varieties was about 1t/ha higher than the older varieties (9.09 compared to 8.09t/ha). Using a linear plus exponential curve fitting procedure, economic optimum N rates (Nopt) were derived for each variety tested, and at different economic breakeven ratios. Nopt values for yield (3:1 ratio) ranged from zero to over 340kg/ha N and there was a significant relationship ($p<0.05$) that showed that the higher yielding varieties had higher Nopt values by an average of 17.3kg N/t grain yield. At Nopt rates (3:1 ratio), the grain protein contents were mostly between 12.5-13.5% and averaged 12.76% - this is close to the current critical level for breadmaking wheat in RB209 (2.2% grain N or 12.5% protein). It was not possible to show any consistent differences in the N uptake efficiency of different varieties.
- Overall, the fitted Nopt values for yield (3:1 ratio) for the modern varieties were higher than the current RB209 recommendations. When each recommendation was adjusted for the grain N (protein) content of the experimental crop (as recommended in RB209), the Nopt was 29kg/ha higher on average than the recommended rate. The adjusted recommendations were usually higher than the unadjusted recommendations. The results indicate that the current RB209 recommendations were generally under-estimating the Nopt for modern varieties at these sites. If the Nopt values were based on a breakeven ratio of 6:1 (equivalent to ammonium nitrate at £145/t and grain at £70/t) rather than 3:1 (as in RB209), the average Nopt reduced by 29kg/ha N, yield at the Nopt (Yopt) reduced by 0.13t/ha and grain protein at the Nopt reduced by 0.32%.
- From the response curves for the modern varieties, 6 out of 16 (38%) needed more than 280kg/ha N to achieve 13% protein, and 4 out of 16 (25%) needed more than 300kg/ha N. The highest unadjusted recommendation for yield and protein in the current RB209 is 280kg/ha N. At N rates needed to achieve 13% protein, the extra margin over N cost (above that from achieving Yopt alone) was around £100/ha assuming a £13/t premium and a 100% success rate of crops that obtained the premium. At lower premiums and success rates (e.g. £5/t and 1 in 3 success rate), the extra margin did not generally justify growing milling compared to feed wheats.
- Late N applications increased protein contents but foliar urea was generally more effective than solid ammonium nitrate (0.66 and 0.34% protein from 40kg/ha late N respectively). Effects of late N on yield were uncommon and small, though small yield reductions were observed due to leaf scorch from late foliar urea application.

3. Project objectives and background

3.1 Project objectives

The overall aim of the project was ‘To develop optimum nitrogen fertiliser application practices for realising the high yield potential of modern Group 1 and 2 wheat varieties whilst also meeting the grain protein and Alveograph quality requirements set by both home and export market.’

Specific objectives were:

1. To test if modern high yielding varieties have different nitrogen requirements for achieving their yield potential, compared to older lower yielding varieties which form the scientific underpinning basis of current national standard fertiliser recommendations.
2. To identify optimal methods for applying extra N in addition to that required for yield in order to achieve large increases in grain protein content.
3. To investigate the effect of different nitrogen management approaches on grain Alveograph values**.** Grain quality as measured by the Chopin Alveograph is an important criterion for most export markets.

3.2 Background

Winter wheat is well known to be highly responsive to an adequate supply of nitrogen (N) in order to meet the N requirement of the crop. The use of N can typically double grain yields or more, and is commonly regarded as one of the most important inputs for profitable wheat production. Adequate use of N is also needed for producers of quality wheat where target grain protein contents are set by the market. These are typically 13% protein (on 100% DM) for the UK breadmaking market, or 12.5% for the export market. Meeting the full range of quality targets is necessary for grain to qualify for any financial premium. The other main quality parameters are specific weight, Hagberg Falling Number and Chopin Alveograph (export market only, see section 5.6.2).

There are several important issues and developments that provide the background to this project. These are summarised below, then described in more detail.

1. Over many years, new Group 1 and 2 varieties have been bred with a higher yield potential than older varieties, and with a yield potential that is only slightly lower than modern feed wheat varieties. Sowings of Group 1 and 2 varieties have thus increased as they combine good yield potential with the prospect of being marketed as quality wheat that might attract a significant financial premium. Meeting the target grain protein content is a critical quality requirement, and this requires an adequate supply of N.

2. The price of fertiliser N has increased substantially in recent years due to increasing energy prices. Future prices may increase further. This represents a significant pressure to optimise N use, but also alters the ‘breakeven ratio’ (kg grain to pay for a kg of N) that is used to define the economic optimum N rate.

3. Nitrate Vulnerable Zones (NVZ) have been designated across large parts of the UK arable area. For land inside an NVZ, farmers must comply with the NVZ Action Programme (NVZ-AP) rules (Defra 2002). Complying with the NVZ-AP rules is a cross compliance Statutory Management Requirement (SMR), and failure to comply can result in a reduction in the Single Farm Payment (SFP). The NVZ-AP rules are being revised, but the current rules require farmers to justify their fertiliser N use for each crop.

4. The recommendations contained in Defra’s ‘Fertiliser Recommendations (RB209)’ (Anon 2000) publication are the recognised industry standard, and are used by the Environment Agency (EA) as the preferred basis for judging compliance of field-level N use with the current NVZ-AP rules. It is important therefore, that these recommendations are maintained fully up to date and relevant to modern growing conditions. The current RB209 recommendations for N use on wheat are based on over 280 experiments, but are now being questioned since these experiments were mostly carried out between 1981 and 1994, and on varieties with a significantly lower yield potential than modern varieties.

3.2.1 Trends in wheat production and nitrogen use

National trends in wheat production and nitrogen fertiliser use show the following trends which are discussed in the following sections.

- Increased interest in growing quality wheat varieties for home and export markets
- Increased grain yields
- Increased requirement for total N in grain
- Static average fertiliser N application rates
- Falling grain protein contents

3.2.1.1 Wheat production and markets

Approximately 1.9m ha of wheat is drilled each year in the UK, producing around 15mt of grain. The UK market for Group 1 and 2 varieties (Table 3.1) is around 5.5mt of which around 80-85% is home produced. A further 2.5mt are exported (mainly Group 2 varieties). Marketing wheat to export markets has been increasingly important in recent years as financial support mechanisms have been dismantled.

Table 3.1 Winter wheat varieties in NABIM Groups 1 and 2 (from 2002)

Group 1	**Group 2**
Hereward *Malacca* *Xi19*	Charger Cordiale *Einstein* Mascot *Option* Soissons *Solstice*

(varieties in italics were used in the experiments in this project)

Data for the distribution of certified seed for each variety Group (Figure 3.1) indicates that around 30% of the wheat area is sown with Group 1 or 2 varieties which are intended for the home or export markets and where a financial premium for quality may be obtained. The highest premiums are obtained for all Group 1 varieties, and Solstice which has been accepted by some millers as having good breadmaking potential. Similarly, British Survey of Fertiliser Practice (BSFP) data from the last 5 years also shows that 30% of the wheat surveyed has been described as 'milling' (Figure 3.2). The typical quality requirements for the home and export markets are shown below though, depending on supply and demand, lower qualities may be accepted with financial 'dockage':-

- UK market 13.0% protein, 250 Hagberg Falling Number, 76kg/hl specific weight
- Export market 12.5% protein, 180 Hagberg Falling Number, 74kg/hl specific weight

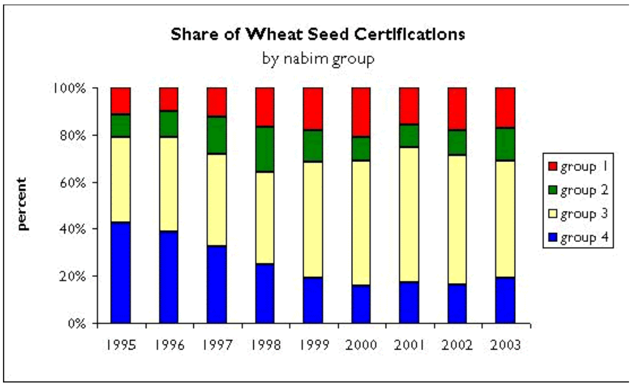


Figure 3.1 Proportion of **nabim** wheat variety groups (HGCA)

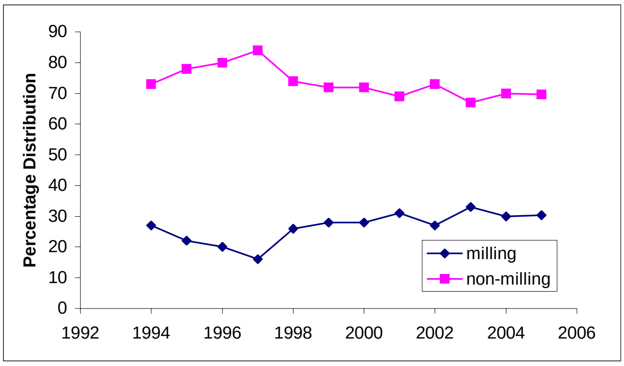


Figure 3.2 Proportion of 'milling' and 'non milling' varieties (BSFP)

The proportion of Group 1 and 2 grain that does actually achieve a financial premium for quality varies from year to year depending on the season (Table 3.2). Although the protein target is achieved in around 50–80% of samples, achievement of ***all*** quality targets (protein, specific weight and Hagberg Falling Number) is typically achieved in only around 50% or less of Group 1 varieties (mean of 34% for 2002-2005 harvest years), or 80% or less of Group 1 and 2 varieties (HGCA Cereal Quality Survey, based on 9,000-12,000 grain samples each year). This ‘success rate’ will take account of all management inputs, including the use of late N to increase grain protein, but is strongly influenced by seasonal weather. The success rate was noticeably low in 2004 due to the very wet harvest conditions.

Table 3.2 Success rate (%) of achieving quality targets (HGCA Cereal Quality Survey)

	Group 1		**Group 1 and 2**	
	Protein (13.0%)	**All targets**	**Protein (12.5%)**	**All targets**
2005	75	43	70	63
2004 (wet harvest)	72	23	74	41
2003	78	53	84	77
2002	51	16	65	44
Mean	**69**	**34**	**73**	**56**

- Group 1 varieties require 76kg/hl, 250 Hagberg Falling Number, 13% protein
- Group 1 & 2 varieties require 74kg/hl, 180 Hagberg Falling Number, 12.5% protein

The success rate in an individual season has an important influence on the level of financial premium paid, which fluctuates widely but has averaged £13.60/t over the last 6 years (Figure 3.3). This premium is additional to the typical feed wheat price of £65-75/t. It has been as high as £25/t in 2004 due to the difficult (wet) harvest conditions in this year that caused low Hagberg Falling Number values in many crops. Unless a quality premium is obtained, the lower yield potential of the Group 1 and 2 varieties will usually give a lower financial return compared to use of feed varieties. For an 8t/ha crop, a typical premium of £13.60 is equivalent to £108/ha. Since the only additional costs for growing these varieties is typically around £35/ha (an extra 40kg/ha late N for protein costing c. £23/ha including £5/ha application cost, plus c.0.15t/ha foregone yield worth £12/ha from not sowing a feed variety), it is not surprising that many farmers are sowing these varieties in the hope or expectation of achieving a significant extra return. However, although the extra return of £75/ha in this example appears attractive, this assumes a perfect success rate. If the farm success rate were only 1 in 3, the value of the premium for the successful crop (£108/ha) would be very similar to the extra cost of late N applied to all crops (3 x £35/ha = £105/ha). Where farms have a good success rate, once a Group 1 or 2 variety is sown the crop management practices will usually be designed to achieve the required quality targets. For Group 1 varieties, this will often include the use of higher rates of N than to feed wheats in order to achieve the protein target.

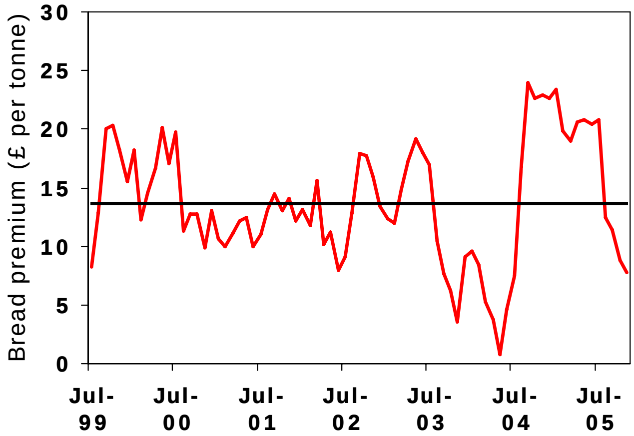


Figure 3.3 Changes in premium for **nabim** Group 1 varieties with 13% protein, 250 Hagberg Falling Number and 76kg/hl specific weight (HGCA)

3.2.1.2 Increasing grain yields

Due to varietal improvements and better general management, wheat grain yields have increased steadily over the last 20-30 years at approximately 2% per year. Modern Group 1 and 2 varieties have a significantly higher yield potential than older varieties as illustrated by changes in annual national wheat yields (Figure 3.4), and changes in the average yield of breadmaking varieties obtained from Recommended List (RL) experiments (Figure 3.5). During the 1980s, the average national wheat yield was around 6t/ha, but is now 8t/ha. Also, the average yield of breadmaking varieties from the RL experiments has increased from between 6.5-8.5t/ha in the 1980s, to over 10t/ha in the early 2000s (NB. experimental plot yields are always higher than commercial field yields).

The Cereal Production Survey (Defra 2005) indicates that the most common *farm average* wheat yield is between 8 and 9t/ha (Figure 3.6), but that nearly 5% of the wheat area has an average of over 10t/ha. A farm with an overall average yield of 10t/ha is bound to have fields yielding both lower and higher than the farm average value, indicating that individual field yields of 10t/ha and over must be regarded as quite common. All these data confirm that wheat yields have increased significantly in the last 20 years, and since the period (1981-1994) when the majority of experiments were carried out that underpin the current edition of RB209.

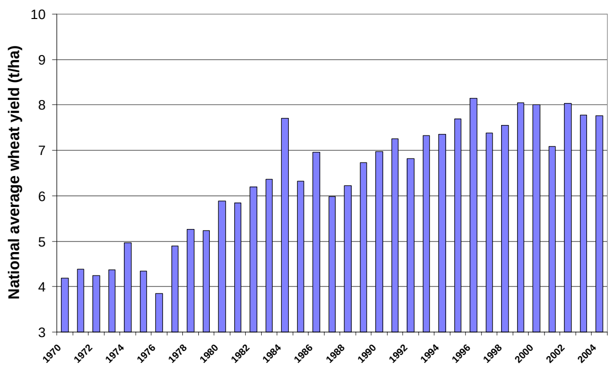


Figure 3.4 Trend in average annual wheat yields (all varieties)

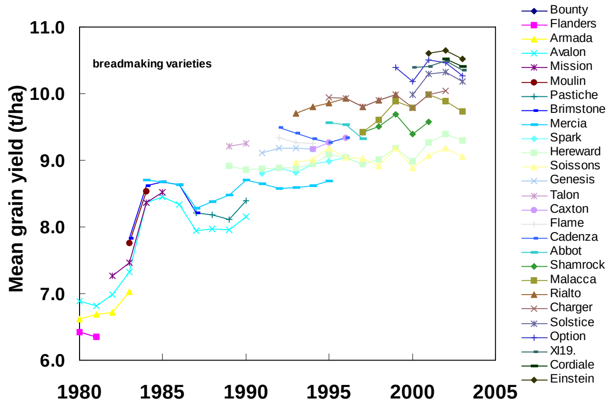


Figure 3.5 Trend in breadmaking wheat yields from Recommended List experiments

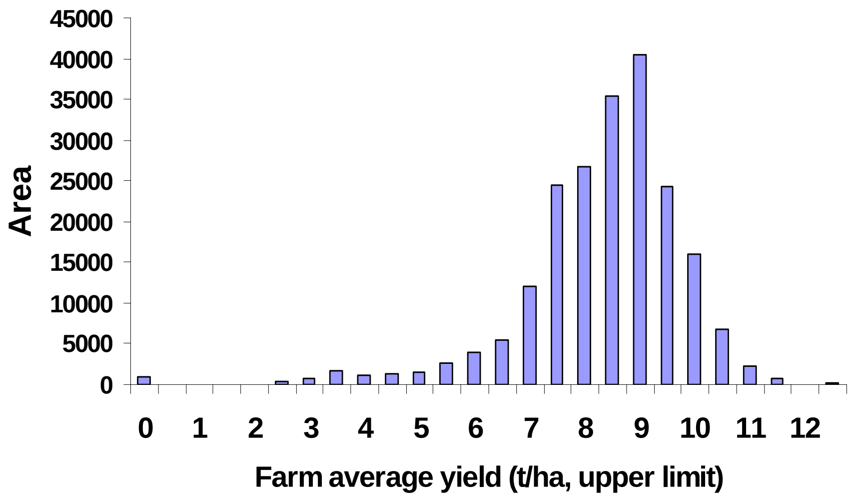


Figure 3.6 Distribution of *farm* average yields in 2005

3.2.1.3 Falling grain protein contents

The grain protein content is largely a reflection of the balance between the N supply (from the soil, organic manures and fertiliser) and grain yield. For a constant level of N supply, dilution will usually mean that the protein content will reduce as the grain yield increases. Data from the annual HGCA Cereal Quality Survey (Figure 3.7) shows significant year to year variation in protein levels, but there are indications of a trend towards lower protein contents in recent years. This would be expected as average yields have increased. This trend would also be supported by anecdotal comments from farmers that achieving a satisfactory protein content is becoming more difficult.

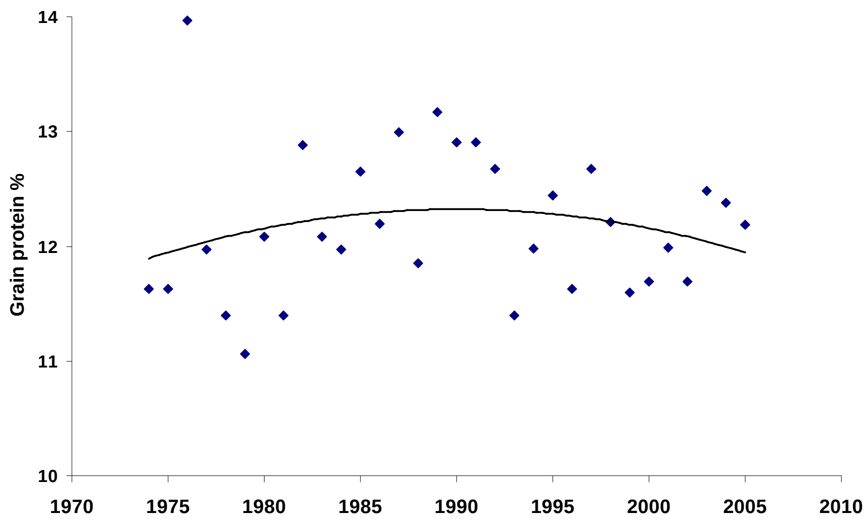


Figure 3.7 Trend in grain protein content (HGCA Cereal Quality Survey)

3.2.1.4 Increasing offtake of crop N

The national trend for the offtake of N in grain can be calculated from data for the annual average yield and grain protein content (Figure 3.8). This has increased from a mean of 118kg/ha (1980-1989) to 136kg/ha (1990-1999) and 140kg/ha (2000-2005). Assuming a constant value of 75% for the nitrogen harvest index (NHI, the proportion of total above-ground crop that is harvested), the equivalent figures for N in the total above ground crop (grain and straw) would be 157, 181 and 187kg/ha – an increase of 30kg/ha (19%) between the 1980s and early 2000s. In theory, based on a 60% recovery of fertiliser N, it would need an extra 50kg/ha of fertiliser N to meet this higher requirement for the total above ground crop N.

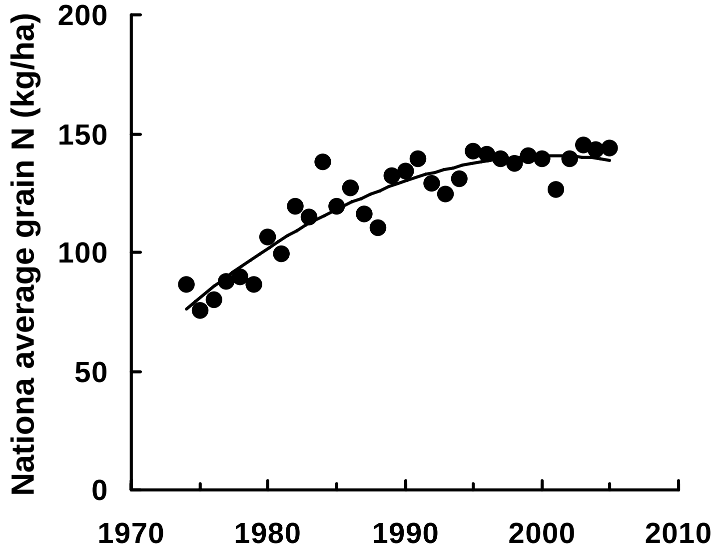


Figure 3.8 Trends in wheat grain N offtake (calculated from data used in Figures 3.4 and 3.7)

Changes in the theoretical total above ground crop N requirement of Group 1 and 2 wheat varieties (grain and straw) can also be calculated, assuming either a 13% (2.28% N) or 12.5% (2.19% N) grain protein target, an NHI of 75%, a typical soil N supply of 70kg/ha (SNS Index 1 with a 100% crop uptake efficiency), and a 60% crop uptake efficiency of applied fertiliser N by the whole above ground crop. These requirements are shown in Table 3.3 for different yield levels. For each 1t/ha of grain yield, the theoretical requirement for fertiliser N increases by 50kg/ha where the protein target is 13% or12.5%. Using these assumptions, the theoretical fertiliser N requirement for a 10t/ha crop and 13% protein would be 390kg/ha N. If the protein target was 12.5%, the theoretical requirement would reduce by 20kg/ha to 370kg/ha N.

Table 3.3 Theoretical above-ground crop N and fertiliser N requirements

	13% protein target		**12.5% protein target**	
Grain yield (t/ha)	**Crop N (kg/ha N)**	**Fertiliser N (kg/ha N)**	**Crop N (kg/ha N)**	**Fertiliser N (kg/ha N)**
7.0	213	238	204	223
8.0	243	288	234	273
9.0	274	340	263	322
10.0	304	390	292	370
11.0	334	440	321	418

<u>Example calculation (7t/ha grain yield, 12.5% protein target):</u>
Grain with 12.5% protein (2.19% grain N) contains 7 x 1000 x 0.0219 = 153kg/ha N
Total crop N (grain and straw) contains 153 / 0.75 = 204kg/ha N
Soil nitrogen supply = 70kg/ha
Fertiliser N needed = (204-70) / 0.6 = 223kg/ha

3.2.1.5 Static nitrogen fertiliser use

The average application rate of fertiliser N to winter wheat increased steadily during the 1970s and 1980s, but has stayed at around 190kg/ha since the late 1980s (Figure 3.9). Although correct use of N is very cost-effective, the recent large increases in the price of fertiliser N may result in an overall lowering of average N rates. If future N prices increase further, the downward pressure on N rates is likely to increase.

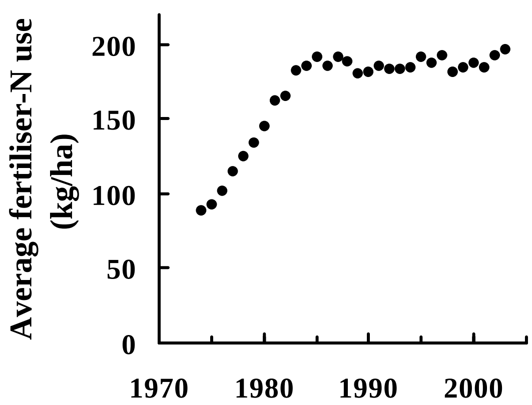


Figure 3.9 Long term trends in the average rate of fertiliser N use on wheat (BSFP)

The BSFP also shows that the average N rate for milling wheat is consistently higher than for feed wheat, and that the difference has increased over the last 3 years to 38 kg/ha N in 2005 (Figure 3.10). An analysis of BSFP 2003 data for England only (Goodlass, pers. comm.) suggests that about two thirds of the milling wheat crop receives 'extra N' specifically to increase protein content, and that 15% of this 'extra N' is applied as a late foliar spray of urea.

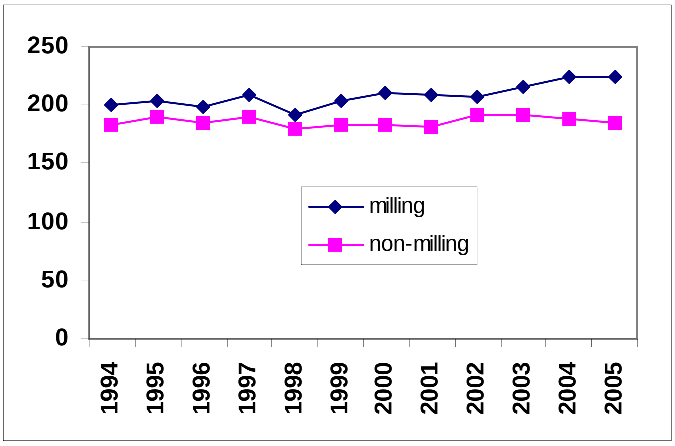


Figure 3.10 Recent trends in the average rate of fertiliser N use on milling and non-milling wheat (BSFP)

3.2.2 Nitrogen prices and economic optimum N rates

Current RB209 recommendations are for the economic optimum N rate. This is the application rate that is economically best for crop production and represents the point on the nitrogen response curve where the cost of using more N would not be covered by the value of the extra crop output produced. Current RB209 recommendations for wheat are based on a ratio of 3:1 (3kg grain is needed to pay for 1 kg of N) which has been appropriate up until the early 2000s (Figure 3.11). In recent years however, fertiliser N prices have increased so that the appropriate breakeven ratio for purposes of calculating the economic optimum is now well above 3:1. Table 3.4 shows the breakeven ratio for different prices of ammonium nitrate and grain (both as £/t). In 2006, applying N based on a ratio of 6:1 would have been appropriate for many practical situations. Use of higher ratios may be needed in future.

Table 3.4 Breakeven ratios for feed wheat

Cereal grain *(£/tonne)*	**Ammonium nitrate (34.5% N)** ***(£/tonne)***				
	90	**110**	**130**	**150**	**170**
	Breakeven ratio				
50	5.2	6.4	7.5	8.7	9.9
60	4.3	5.3	6.3	7.2	8.2
70	3.7	4.6	5.4	6.2	7.0
90	2.9	3.5	4.2	4.8	5.5
110	2.4	2.9	3.4	4.0	4.5
130	2.0	2.5	2.9	3.3	3.8
150	1.7	2.1	2.5	2.9	2.9

Example calculation:
Ammonium nitrate at £150/t costs (150 x 100) / (34.5 x 10) = 43.5 pence/kg N
Grain at £70/t costs (70 x 100) / 1000 = 7 pence/kg
Breakeven ratio = 43.5 / 7 = 6.2

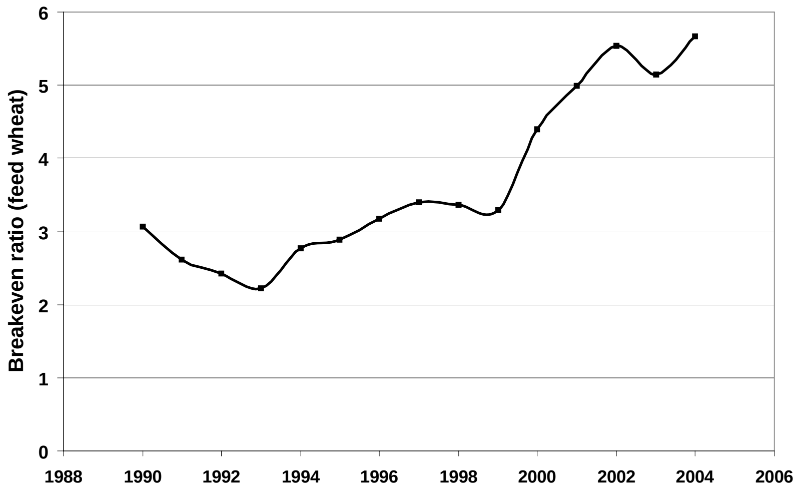


Figure 3.11 Trend in the breakeven ratio for wheat yield

3.2.3 Compliance with the Nitrate Vulnerable Zone (NVZ) Action Programme rules

In December 2002, approximately 55% of England, 3% of Wales, 13% of Scotland and parts of Northern Ireland were designated as NVZs. Land within an NVZ must be managed according to the specific NVZ-AP rules that have been set by each devolved Government. During 2006, all NVZ-AP rules throughout the UK are being revised. A key element of the current rules is that the use of fertiliser N should not exceed the crop requirement, taking account of crop uptake and the soil N supply from crop residues, soil organic matter and organic manures. Farmers need to be able to justify their N use decisions. For NVZs in England, Wales and Northern Ireland, the 7th edition of RB209 is cited as '…*one authoritative source but not the only information source that you can use* …' (Defra 2002). Nevertheless, the RB209 recommendations are commonly used by the compliance inspectors (the EA in England and Wales) as the initial reference point on which to judge compliance.

The current nitrogen recommendations in RB209 for winter wheat are based on over 280 nitrogen response experiments carried out over the last 30 years or more, mostly funded by Defra and HGCA (Dampney, 2000). However, most of these experiments were carried out between 1981 and 1994 using varieties with a significantly lower yield potential than modern varieties. This has raised doubts about the validity of the current RB209 recommendations. These recommendations are not directly adjusted for yield, although advice is given to adjust the recommended N rate *for grain yield* using past information for the grain N (protein) content. Use of grain N is a proxy for yield, as increasing yield will usually result in a lower content. Critical values are given that would be expected if economic optimum N rates have been applied for grain yield:- 2.0% N (11.4% protein) for feed wheat, and 2.2% N (12.5% protein) for breadmaking wheat. Higher N rates will be needed to achieve a grain protein content of 13% in breadmaking varieties.
Note:- If N recommendations reduce due to increases in the breakeven ratio, then these critical values may also reduce.

4. Experimental design, materials and methods

4.1 Experiment design

There were 2 distinct experimental designs within the project, each of which focused on a specific objective. One experiment of each design was commonly co-located at each site. The location and full details for each site are given in Appendix 1.

Design 1. Investigating the optimum N requirements of old and modern varieties for yield

Design 2. Investigating the optimum strategy for applying late N for protein

4.2 Design 1

4.2.1 Treatments and assessments

These experiments were designed to determine the economic optimum N rate for different varieties. There were 9 experimental sites between 2002 and 2005. At each experiment, there were 2 old varieties (reflecting varieties of relatively low yield potential, typical of those used in the experiments that underpin RB209, and 2 modern varieties with a high yield potential. The old varieties used were selected from Avalon, Mercia and Riband and varied from site to site (see Appendix 1 for details). Riband (a Group 3 variety) was included as it was well represented in the dataset of N response experiments that underpins RB209. The modern varieties were selected from Einstein, Hereward, Malacca, Option, Solstice and Xi19.

At each site, 7 N rates were tested for each variety ranging from zero to 300 or 340kg/ha N depending on the site, applied as 40kg/ha (late February/early March) and the balance split 50:50 at GS31 (1st node stage) and early May. The plots were organised in a randomised block design but with N rates as sub-blocks (except for Rosemaund where all plots were fully randomised). There were 3 replicates of each treatment. All plots were drilled using an Oyjord drill, fertiliser N was applied by hand as ammonium nitrate, and harvesting was with a small plot combine. All other crop management inputs were according to commercial farm practice to ensure that other nutrients were not limiting, and to control weed, pest, disease and lodging incidence. During the season the following assessments were carried out. Apart from Chopin Alveograph analyses (see footnote), all analytical determinations were carried out by Direct Laboratories:

- Description of soil type
- Soil analysis for soil mineral N (SMN), pH, P, K and Mg
- Lodging
- Grain yield, specific weight and grain N%
- Chopin Alveograph analysis (selected sites/varieties only)[1]

[1] Chopin Alveograph analyses were carried out by Andover Analytical laboratories

4.2.2 Statistical analysis

4.2.2.1 Analysis of variance

Each experiment was analysed as 3 blocks of a 7 by 4 factorial. The analyses tested for differences between varieties, N rate and the interaction between varieties and N rate - i.e. testing if the response to N over the range of N rates tested was the same for each variety. The apparent recovery of fertiliser N in grain was calculated as below, then statistically analysed omitting plots of the control treatment as these were always zero:-

$$\text{Apparent recovery (\%)} = \frac{\text{Grain N offtake (treatment)} - \text{Grain N offtake (control)}}{\text{Rate of fertiliser N applied}} \times 100$$

4.2.2.2 Grain yield response curves and deriving economic optimum (Nopt) rates

The method adopted to fit yield response curves and to derive Nopt rates was broadly the same as that used to underpin the current RB209 recommendations (Anon 2000). This assumed that yield increases due to fertiliser N, diminish successively as the N rate increases. There is a choice of mathematical functions that can describe such responses (e.g. quadratic, linear over quadratic, exponential, linear plus exponential). Most of these functions provide good descriptions of most experimental datasets, though for individual experiments one function may well be better than another. However, when analysing more than one experiment, it is desirable that one function is chosen, so that comparisons between experiments can be made on the same basis. Following a comparison of approaches by George (1984), the linear plus exponential (LEXP) function has been used as the standard method, and is the basis for determining recommended N rates in RB209. The LEXP function shown below has been used for fitting data from the experiments reported here.

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

where y is yield in t/ha, N is 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 features of the responses with which each parameter tends to be associated. These are as follows:

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

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

c: the slope of the response well beyond the region of maximum curvature. Where large N rates cause 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).

The fitting process does not use common values of parameters between sites or seasons, thus it is assumed that responses were unique to a site. In order to determine Nopt for each variety at each site, the LEXP function was fitted in 2 different ways.

1. Using an 'Individual curve' approach. Response curves were fitted independently to the data for each variety using the LEXP function with floating r. For those sites where the value of r was outside the range 0.8299-0.9999, the curve was refitted with r fixed at 0.99.
2. Using a 'Parallel curve' approach. The LEXP function was fitted to the measured yields of all varieties in a four-stage procedure.
   i) Fit a common curve to all varieties (i.e. keeping *a, b, c* and *r* constant for all varieties at a site).
   ii) Fit separate curves for each variety, with a common response but different intercepts (i.e. varying *a* but keeping *b, c* and *r* constant).
   iii) Fit separate curves for each variety allowing *a*, *b* and *c* all to vary (i.e. just keeping *r* constant).
   iv) Fit separate curves for each variety, allowing all parameters to vary.

In a few instances where the fitted value of *r* was outside the range 0.8299-0.9999, the curves were refitted with *r* fixed at 0.990. The sums of squares explained at each stage was calculated, and a test was made of the improvement in fit over the previous model. If there was no significant improvement between two stages, then the previous model was taken as the best description of the data. In general, fitting at stage 3 was most satisfactory.

Estimates of Nopt values were derived from the fitted parameters as follows:

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

where *k* is the breakeven ratio of N (p/kg) to grain (p/kg). The breakeven ratios studied ranged from 3 to 10. Standard errors (se) of each Nopt value were determined for each method of fitting the data (individual and parallel curve approaches). The yield at each Nopt rate (Yopt) was calculated from the fitted parameters.

4.2.2.3 Grain N/protein response curves

A response curve was fitted independently to each set of grain N data for each variety. Either a Normal Type curve with Depletion (NTD) or a Straight Line (SL) function was used, depending on which fitted the data better. This was decided by comparing the Residual Mean Squares (RMS) for the two fits. The one with the smaller RMS was selected. The function for the NTD curve is:-

$$y = d + c.\exp(-\exp(-a.(\text{N} - b)))$$

where *y* is grain N (%), *a*, *b*, *c* and *d* are fitted parameters determined by fitting, and N is applied N (kg/ha).

The function for the SL function is:-

$$N\% = a + b.N$$

Grain N% values were derived for selected Nopt values, and the associated grain protein content calculated using the formula:-

$$\text{Grain protein (\% at 100\% DM)} = \text{Grain N (\%)} \times 5.7$$

4.3 Design 2

4.3.1 Treatments and assessments

These experiments were designed to determine the optimum strategy for applying extra late N in order to increase grain protein content. There were 9 experimental sites between 2002 and 2005. At each experiment, there was a range of N treatments applied to a single modern variety, as drilled by the farmer. A standard 'base' application of N as ammonium nitrate (AN) prills was applied for yield – the N rate varied depending on the characteristics of each site. The following treatments were then superimposed on top of this base application of N.

- Control (no extra N)
- 40, 80, 120kg/ha total N as 'extra' to the base dressing, applied
    - all as AN prills at GS39-61 (flag leaf emerged to flowering)
    - all as foliar applied urea spray (10% N) at GS69-75 (watery to milky ripe)
    - all as foliar applied urea spray (20% N) at GS69-75 (watery to milky ripe)
    - half as AN prills at GS39-61, half as foliar urea (10% N)
    - half as AN prills at GS39-61, half as foliar urea (20% N)

The plots were organised in a randomised block design with 3 replicates of each treatment. Foliar urea (commercial product) was applied by hand spray equipment in equal 2-way (40 and 80kg/ha N rates) or 3-way (120kg/ha N rate) split applications. All AN treatments were applied by hand. All other crop management inputs were according to commercial farm practice to ensure that other nutrients were not limiting, and to control weed, pest, disease and lodging incidence. During the season the following assessments were carried out. All analytical determinations were carried out by Direct Laboratories.

- Description of soil type
- Soil analysis for soil mineral N (SMN), pH, P, K and Mg
- Lodging and leaf scorch
- Grain yield, specific weight and grain N%

4.3.2 Statistical analysis

4.3.2.1 Analysis of variance (ANOVA)

Each experiment was analysed as 3 blocks of a 3 by 5 factorial. The analyses compared the control with the mean of all the factorial treatments, and then analysed the factorial part of the trial testing for differences between N strategies, N rate and the interaction between N strategies and N rate - i.e. testing if the response to N over the range of N rates tested was the same for each strategy. The apparent recovery of applied fertiliser N in grain was calculated as:-

$$\text{Apparent recovery (\%)} = \frac{\text{Grain N offtake (treatment)} - \text{Grain N offtake (control)}}{\text{Rate of fertiliser N applied}} \times 100$$

5. Results and Discussion (Design 1)

Key results from the experiments are described and discussed in the following sections. Full data with statistics is given in Appendices 2-7. All protein data are given as % on a 100% dry matter basis.

5.1 Comparison of curve fitting approaches

Two curve fitting approaches (see 4.2.2.2) were compared to assess the sensitivity of the derived economic optimum rate for yield (Nopt) to the curve fitting process. There was close and consistent agreement between the Nopt for each variety derived from the parallel curve and individual curve fitting approaches with the overall mean value slightly lower from parallel curve fitting (201 compared to 204kg/ha). However, the Nopt standard error (se) was generally lower from parallel curve fitting (Figure 5.1), reflecting that this approach is less sensitive to outlier values. Standard errors were mostly below 25 but up to 340. The standard error is the statistical precision of the Nopt; where the standard error is high, the confidence in the Nopt rate will be low and caution is needed in its use and interpretation. For example, an Nopt of 200kg/ha with a standard error of 15 means that there is 95% confidence that the optimum lies between +/- 2 se's, i.e. between 170 to 230kg/ha N. All further results presented and discussed in this report use Nopt values taken from the parallel curve fitting approach.

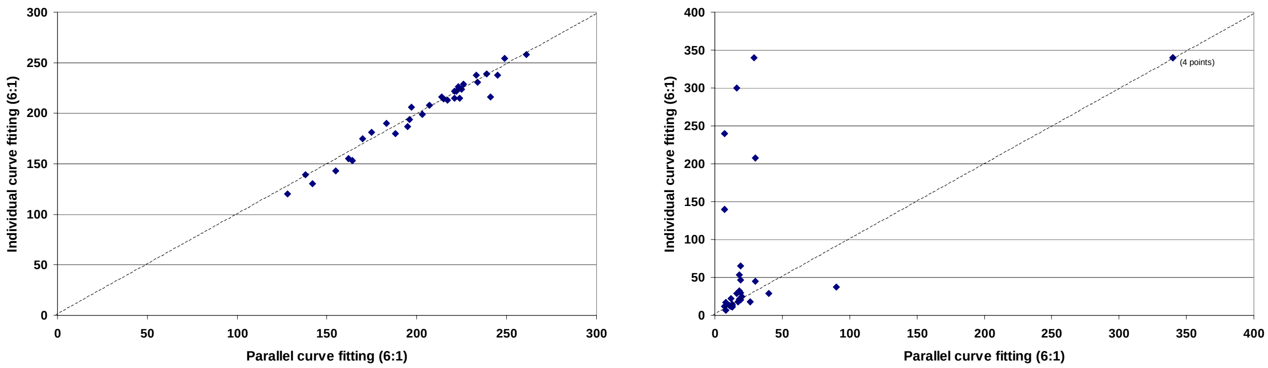


Figure 5.1 Relationship between i) Nopt and ii) se from parallel curve and individual curve fitting

5.2 Nopt for yield

Good yield responses to applied N were obtained at all sites except for Essex 2005 where the fitted Nopt was zero due to a high level of SMN at this site (185kg/ha, SNS Index 5). Values for the grain yield at the Nopt rate (Yopt) were derived for each variety at each experimental site. In a few instances, the Nopt was above the highest N rate tested. In these cases, for purposes of looking at some relationships and means, it was assumed that the Nopt was the same as the highest N rate tested, and that the Yopt was the maximum yield obtained. Grain yields at the Nopt were high at most sites (up to 11.5t/ha), though were low (down to 5.3t/ha) at High Mowthorpe 2004 due to take-all. At all sites, the modern varieties out-yielded the old varieties reflecting their anticipated higher yield potential. Overall (excluding Essex 2005), the mean Yopt for the modern varieties was 9.09t/ha, and 8.09t/ha for the old varieties, a difference of 1.0t/ha. However, differences in the Yopt between individual modern and old varieties ranged up to nearly 3t/ha (e.g. Boxworth 2004).

Responses of grain yield to increasing N rates at each site are shown in Figure 5.2. The charts also show the fitted Nopt for each variety based on the parallel curve fitting approach and a 3:1 breakeven ratio (i.e. comparable to the current RB209 recommendations). At most sites, the higher yielding varieties had a higher Nopt. Figure 5.3 shows this relationship across all sites by plotting the differences in Nopt and Yopt (both at 3:1 ratio) for each variety compared to the lowest yielding variety at each site. Data for Boxworth 2004 (fitted Nopt values were above the maximum N rate tested), High Mowthorpe 2004 (low yields due to take-all) and Essex 2005 (no response to N) were excluded from this relationship. The fitted line (R^2=0.24, $p<0.05$) shows that the Nopt increased by an average of 17.3kg/ha N per tonne of higher yield.

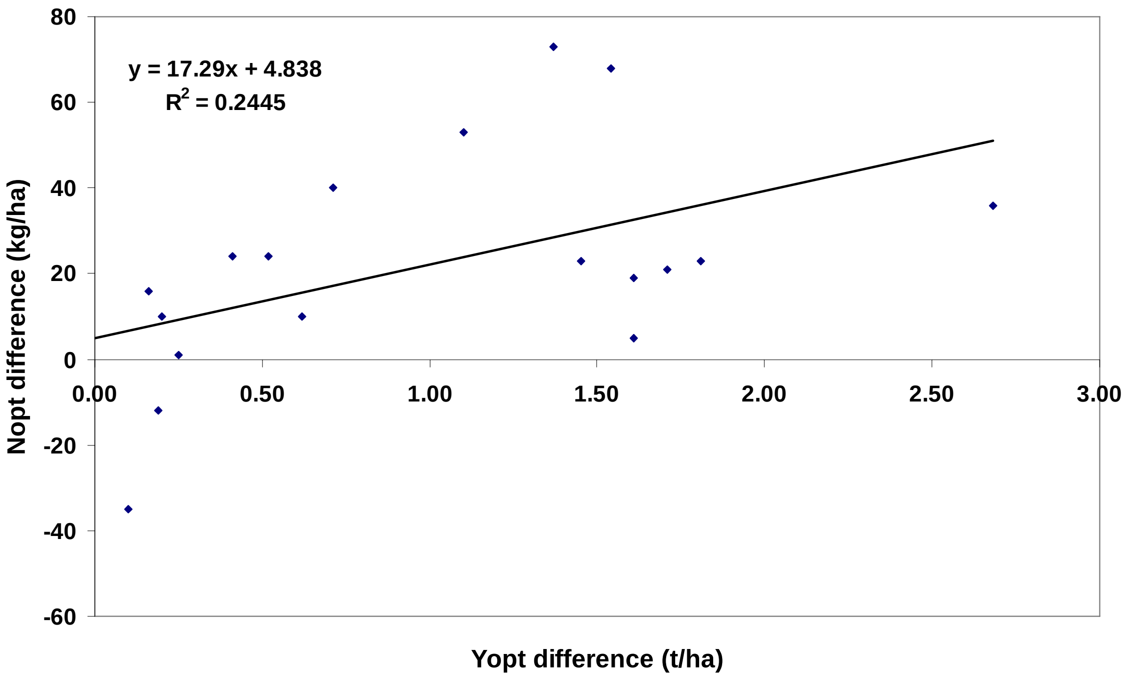
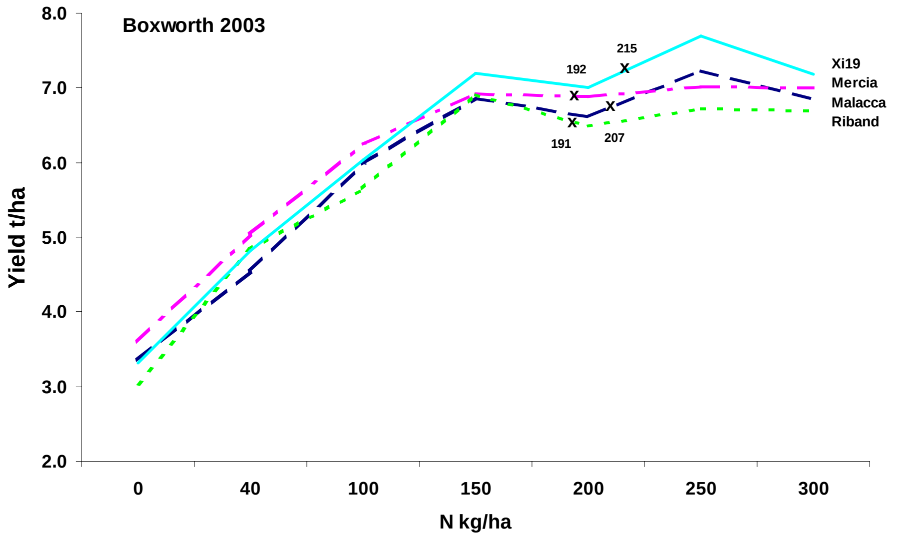
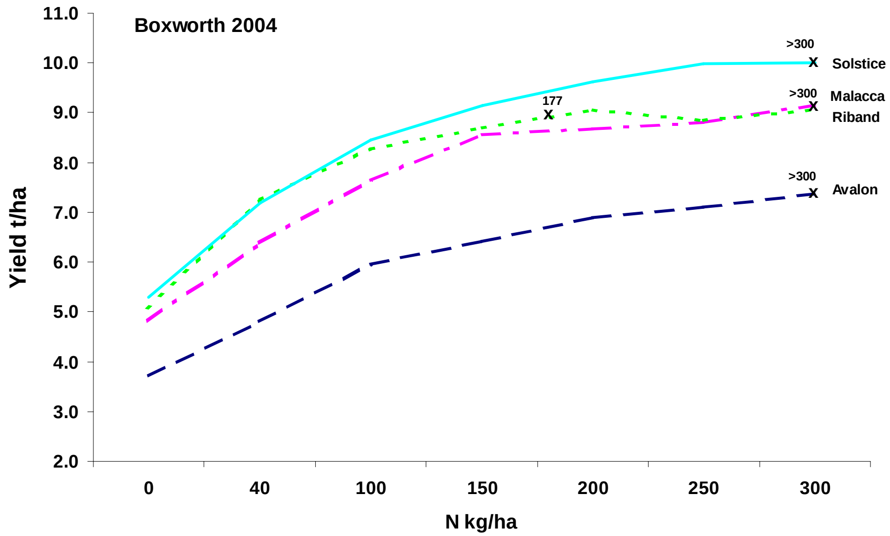
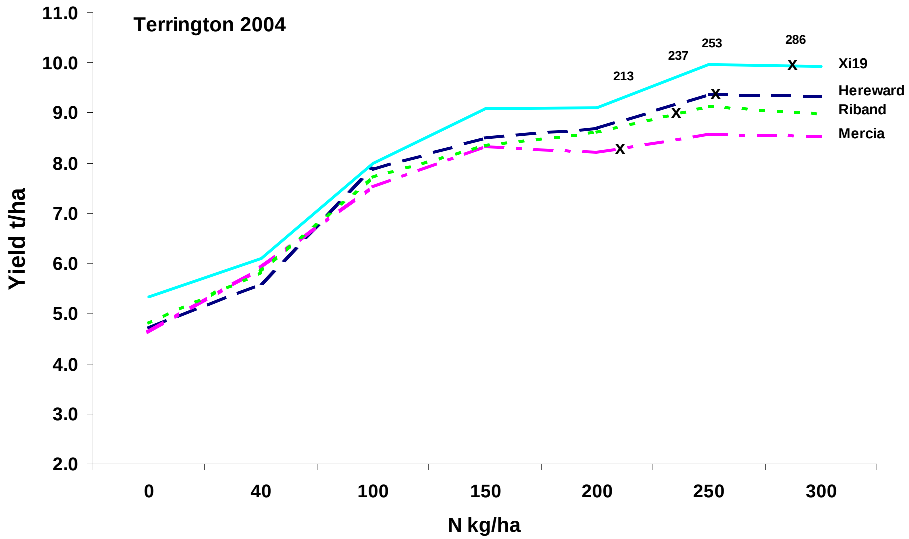
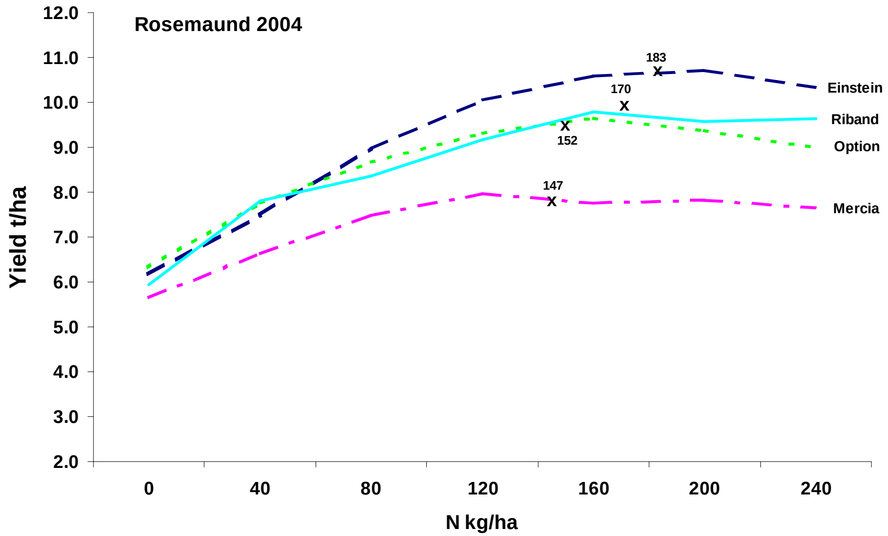


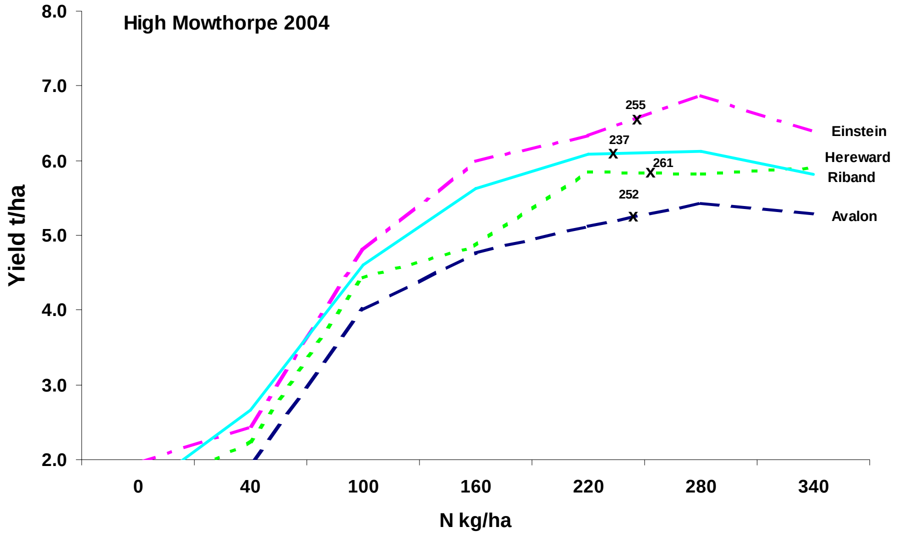
Figure 5.3 Relationship between differences in Nopt and Yopt (both at 3:1 ratio) between individual varieties and the lowest yielding variety at each site

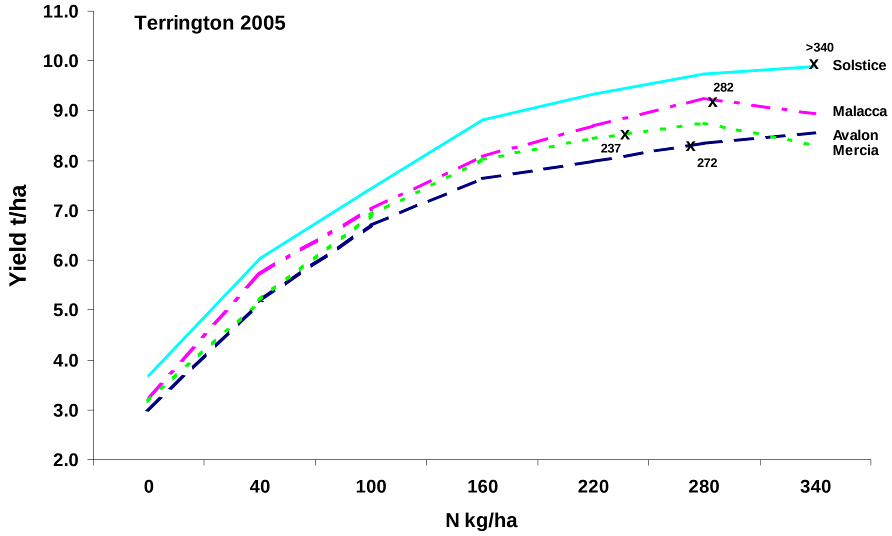

Boxworth 2003
Yield t/ha
N kg/ha
Xi19
Mercia
Malacca
Riband
192
215
191
207
8.0
7.0
6.0
5.0
4.0
3.0
2.0
0
40
100
150
200
250
300

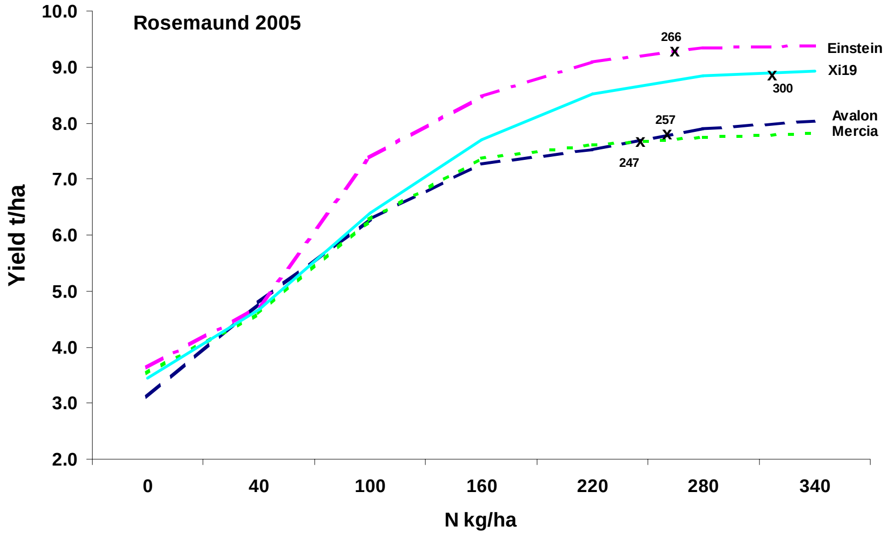

Boxworth 2004
Yield t/ha
N kg/ha
>300
Solstice
>300
Malacca
Riband
177
>300
Avalon
11.0
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
0
40
100
150
200
250
300

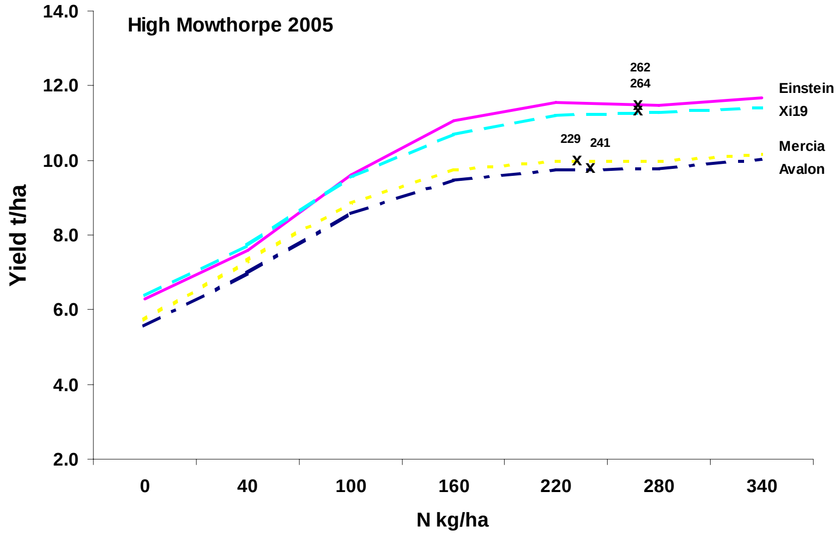

Terrington 2004
Yield t/ha
N kg/ha
213
237
253
286
Xi19
Hereward
Riband
Mercia
11.0
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
0
40
100
150
200
250
300


Rosemaund 2004
Yield t/ha
N kg/ha
183
170
152
147
Einstein
Riband
Option
Mercia
12.0
11.0
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
0
40
80
120
160
200
240


High Mowthorpe 2004
Yield t/ha
N kg/ha
Einstein
Hereward
Riband
Avalon
255
237
261
252
8.0
7.0
6.0
5.0
4.0
3.0
2.0
0
40
100
160
220
280
340


Terrington 2005
Yield t/ha
N kg/ha
Solstice
Malacca
Avalon
Mercia
>340
282
237
272
11.0
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
0
40
100
160
220
280
340


Rosemaund 2005
Yield t/ha
N kg/ha
Einstein
Xi19
Avalon
Mercia
266
300
257
247
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
0
40
100
160
220
280
340


High Mowthorpe 2005
Yield t/ha
N kg/ha
Einstein
Xi19
Mercia
Avalon
262
264
229
241
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0
40
100
160
220
280
340

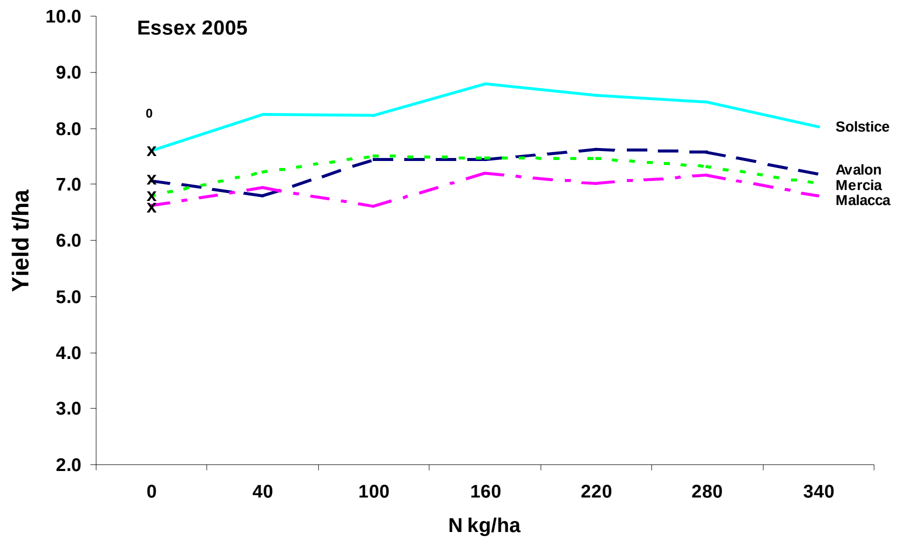


Figure 5.2 Grain yield response curves to rate of applied fertiliser-N at 9 experimental sites. Fitted Nopt values (3:1 ratio) are shown for each variety.

Table 5.1 shows the grain protein content at the Nopt rate for yield (3:1 ratio) for each variety at each site, and Figure 5.4 shows the distribution of these protein contents. RB209 recommends that past grain N (protein) content information can be used to adjust N rates - the critical level for breadmaking wheat is 2.2% N (12.5% protein) or 2.0% (11.4% protein) for feed wheat.

Table 5.1 Grain protein contents at Nopt from parallel curve fitting (3:1 ratio)

Site	**Avalon**	**Mercia**	**Riband**	**Einstein**	**Hereward**	**Malacca**	**Option**	**Solstice**	**Xi19**
Boxworth 2003		13.36	13.17			13.62			13.53
Boxworth 2004	>14.10		11.07			>13.21		>13.01	
Terrington 2004		12.59	11.98		12.85				12.48
Rosemaund 2004		11.37	10.48	11.21			10.27		
H Mowthorpe 2004	14.23		12.11	13.19	13.26				
Terrington 2005	12.77	12.31				12.91		>12.90	
Rosemaund 2005	13.54	13.13		12.76					13.17
H Mowthorpe 2005	12.71	11.98		11.61					11.99
Essex 2005	13.09	13.05				12.94		12.43	
Mean	**13.41**	**12.54**	**11.76**	**12.19**	**13.06**	**13.17**	**10.27**	**12.81**	**12.79**
Overall mean	**12.94 (ex Riband)**			**12.38**					

Note: the overall mean excludes Riband as it is not a breadmaking wheat variety

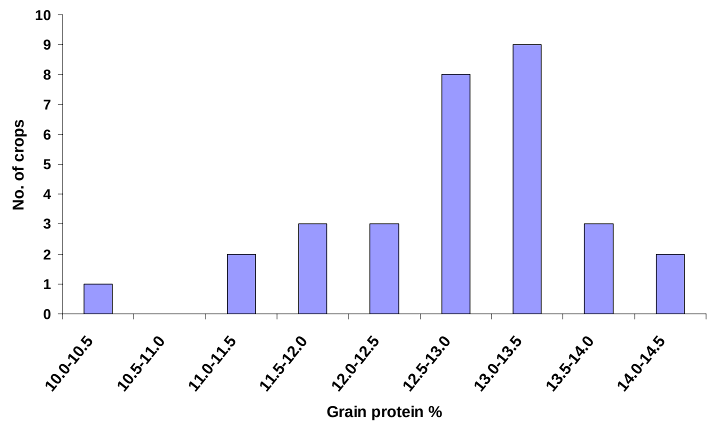


Figure 5.4 Distribution of grain protein content at Nopt (excluding Riband)

Key points are:

- The grain protein content at the Nopt rate for yield (3:1 ratio) ranged from 10.27 to 14.23%, but averaged 12.76% (2.24% N), excluding Riband. This is similar though slightly higher than the current critical level in RB209 for breadmaking wheat (2.2% N or 12.5% protein). For 50% of the crop responses, the protein at Nopt was between 12.5 and 13.5% (2.20-2.37% N). For 42% of crop responses, application of the fitted Nopt rate (3:1 ratio) resulted in a grain protein content of over 13.0%, and for 64% it gave over 12.5%.

- These data indicate that use of the Nopt rate (3:1 ratio) will usually achieve either close to, or above, 13% grain protein content, even for high yielding Group 1 and 2 varieties. However, lower protein contents will result if future economic optimum N rates need to be reduced due to increasing fertiliser N prices. Section 5.5 shows that fertilising according to a ratio of 6:1 rather than 3:1 will reduce grain protein by about 0.3%.

5.2.1 Comparison with current RB209 recommendations (modern varieties only)

For the modern varieties only, Table 5.2 shows the RB209 recommended N rate for yield (Nrec) at each site, using both the Field Assessment Method (FAM) and the Soil Mineral Nitrogen (SMN) method (Anon 2000), with the mean fitted Nopt for yield (3:1 ratio) and the associated Yopt. The FAM approach uses information on soil type, previous cropping and rainfall, whereas the SMN method uses SMN analysis information (0-90cm). The RB209 recommendations are given with and without an adjustment for the grain N (protein) content - the adjusted recommendations were calculated using the mean fitted grain N value at the unadjusted RB209 recommended N rate, then using an adjustment factor of 30kg/ha N per 0.1% grain N difference to the critical value of 2.2% grain N for breadmaking wheats.

Table 5.2 RB209 recommended N rates, fitted Nopt for yield and Yopt (3:1 ratio) for each site (mean of modern varieties only)

Site	**RB209 Nrec (unadjusted)**		**RB209 Nrec (adjusted)**		**Nopt (kg/ha N)**	**Yopt (t/ha)**
	FAM	**SMN**	**FAM**	**SMN**		
Boxworth 2003	180	100	146	160	211	7.12
Boxworth 2004	180	180	203	203	>300[a]	9.59
Terrington 2004	150	180	231	231	270	9.61
Rosemaund 2004	220	100	263	273	168	10.10
High Mowthorpe 2004	240	200	215	206	258	6.24
Terrington 2005	150	150	261	261	311	9.43
Rosemaund 2005	220	220	240	240	283	9.14
High Mowthorpe 2005	200	110	269	254	263	11.48
Essex 2005	100	40-80[b]	100	40-80[b]	0	7.60
Mean	**193**	**155**	**229**	**229**	**258**	**9.09**

a Taken as 300kg/ha for calculating the mean
b Essex 2005 excluded from all mean values

For both the FAM and SMN methods, the relationship between the mean Yopt and the difference between the fitted Nopt (3:1) is shown in Figure 5.5 (unadjusted) and Figure 5.6 (adjusted RB209 recommendations).

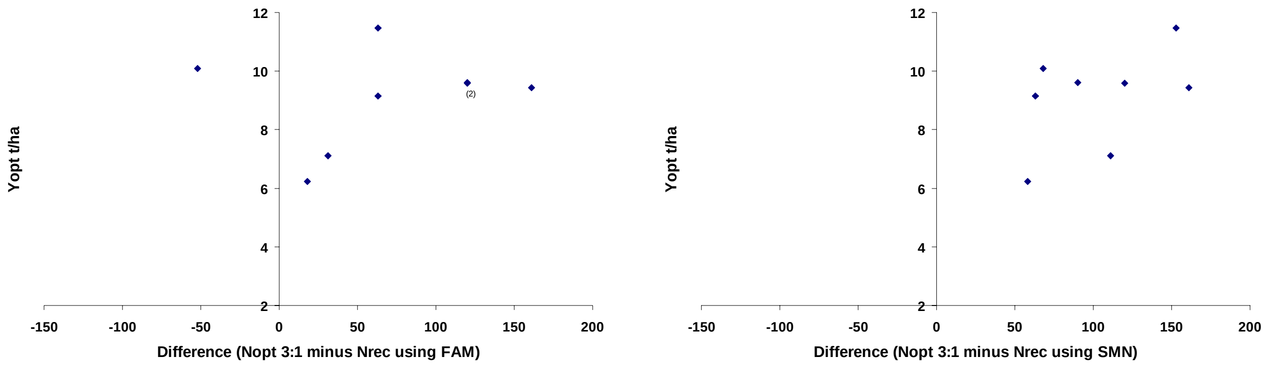


Figure 5.5 Relationship of Yopt to the difference between the fitted Nopt (3:1) and the <u>unadjusted</u> RB209 recommendation using i) the FAM and ii) the SMN method (excluding Essex 2005)

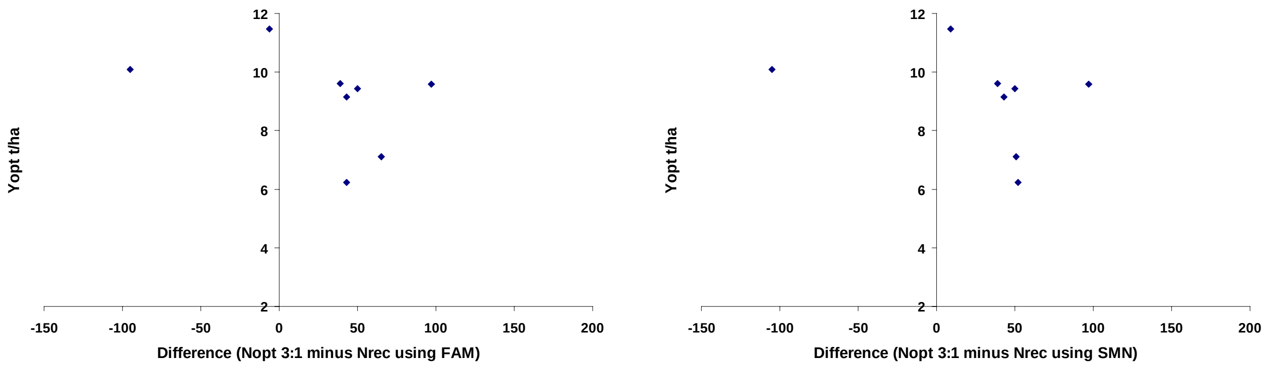


Figure 5.6 Relationship of Yopt to the difference between the fitted Nopt (3:1) and the <u>adjusted</u> RB209 recommendation using i) the FAM and ii) the SMN method (excluding Essex 2005)

Key points are:

- At all sites apart from Essex 2005 and Rosemaund 2004, the fitted Nopt for yield of the modern varieties was larger than the <u>unadjusted</u> RB209 Nrec using either the FAM or SMN methods. The mean fitted Nopt for all sites (excluding Essex 2005) was 258kg/ha N – this was 65kg/ha N higher than the mean RB209 Nrec using the FAM (193kg/ha N), and 103kg/ha higher using the SMN method (144kg/ha N). At 6 of the 9 sites, the fitted Nopt was above 240kg/ha N, the highest unadjusted RB209 recommended N rate.

- If the RB209 Nrec was adjusted for the grain N (protein) content achieved at harvest, most recommendations were increased. The average adjusted RB209 Nrec was 229kg/ha N, which was higher than the unadjusted Nrec using either the FAM or SMN methods. However, at 6 of the 9 sites, the adjusted RB209 Nrec was still less than the fitted Nopt for yield. The mean fitted Nopt across all sites was 29kg/ha N higher than the adjusted RB209 Nrec using either the FAM or SMN method, but up to nearly 100kg/ha N higher (Boxworth 2004).

- There were some indications that differences between the fitted Nopt and the unadjusted RB209 Nrec were larger where the Yopt was high, but this was not consistent (Figure 5.5). As would be expected, differences between the Nopt and the adjusted Nrec were not related to the Yopt (Figure 5.6), as the adjustment process should take account of differences in Yopt. The impact of previous cropping on these differences could not be assessed as this was very similar for all sites (mostly following cereals in a combinable crop rotation).
- There was reasonable agreement between the RB209 Nrec using the FAM compared to the SMN method, except at Boxworth 2003, Rosemaund 2003 and High Mowthorpe 2005. At these sites, use of the FAM gave a higher recommended N rate than from the SMN method.

5.3 N rate for yield and high grain protein content

At all sites, grain protein increased significantly with increasing N rate. Commonly, varieties that gave a high Yopt, also gave a low protein content. A typical example is shown in Figure 5.7 (High Mowthorpe 2005), where Einstein yielded well but gave a low protein content, and vice versa for Avalon. This relationship, due to dilution of protein by the higher yielding crop, is well known.

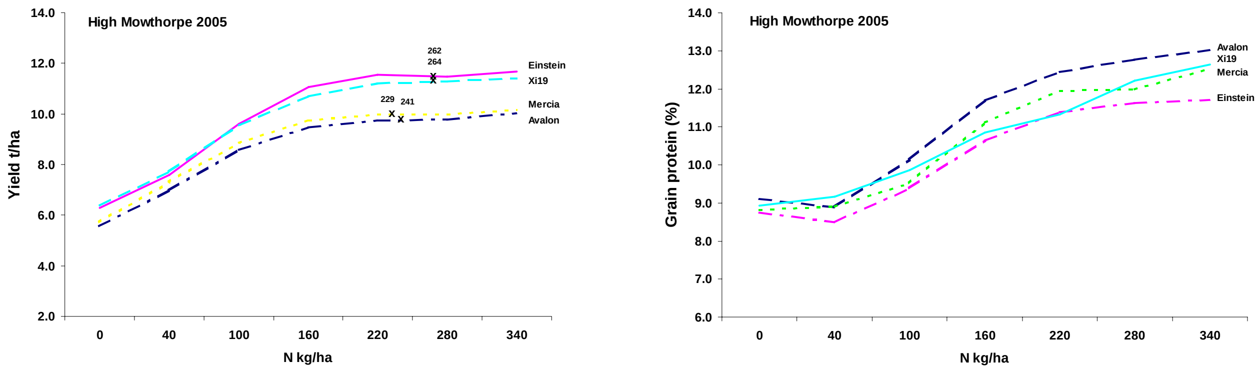


Figure 5.7 Response of grain yield and protein to increasing N rates (High Mowthorpe 2004)

Where Group 1 and 2 varieties are grown, farmers will normally manage these crops with the intention of obtaining a financial premium for quality. This effectively means that the use of fertiliser N needs to be judged in order to achieve the protein target required by the market-place (13% for the home market, 12.5% for export markets) rather than the economic optimum for yield. Tables 5.3 and 5.4 show the N rate needed to achieve 13% and 12.5% protein for each variety at each site, compared to the unadjusted RB209 Nrec for yield.

Table 5.3 N rate needed to achieve 13% grain protein (values from the fitted response curves)

Site	**RB209 Nrec (FAM)**	**RB209 Nrec (SMN)**	**Avalon**	**Mercia**	**Riband**	**Einstein**	**Hereward**	**Malacca**	**Option**	**Solstice**	**Xi19**
Boxworth 2003	180	100		166	175			161			177
Boxworth 2004	180	180	126		>300			264		268	
Terrington 2004	150	180		>300	>300		>300				>300
Rosemaund 2004	220	100		226	>240	>240			>240		
H Mowthorpe 2004	240	200	183		285	231	242				
Terrington 2005	150	150	316	301				294		317	
Rosemaund 2005	220	220	216	238		298					278
H Mowthorpe 2005	200	110	>340	>340		>340					>340
Essex 2005	100	40-80	0	61				57		43	

Table 5.4 N rate needed to achieve 12.5% grain protein (values from the fitted response curves)

Site	**RB209 Nrec (FAM)**	**RB209 Nrec (SMN)**	**Avalon**	**Mercia**	**Riband**	**Einstein**	**Hereward**	**Malacca**	**Option**	**Solstice**	**Xi19**
Boxworth 2003	180	100		139	143			137			152
Boxworth 2004	180	180	73		298			214		208	
Terrington 2004	150	180		197	>300		202				288
Rosemaund 2004	220	100		202	>240	>240			>240		
H Mowthorpe 2004	240	200	164		256	197	211				
Terrington 2005	150	150	243	250				244		260	
Rosemaund 2005	220	220	192	208		243					238
H Mowthorpe 2005	200	110	214	>340		>340					321
Essex 2005	100	40-80	0	0				0		0	

Key points are:

- Excluding Essex 2005, which was unresponsive to N and had a high grain protein content with no N applied, 38% of modern variety crops (6 out of 16) would have needed more than 280kg/ha N in order to achieve the 13% protein target, and 25% (4 out of 16) would have needed more than 300kg/ha N. 50% of the modern variety crops (8 out of 16) would have needed more than 240kg/ha N to achieve a 12.5% protein target. The highest unadjusted recommendation in the current RB209 is 280kg/ha N.

  Note: It must be recognised though that the above comments are based on all of the N being applied by early May. Application of part of the total N rate as late N would probably achieve the same yield and a 13% protein content but with a slightly lower total N rate.

- High Mowthorpe 2005 (shallow soil over chalk) had the highest N rate needed to achieve 13% protein (over 340kg/ha N). Even at 340kg/ha N, the grain protein contents ranged from as low as 11.7% for

Einstein yielding 11.6t/ha, 12.6% for Xi19 yielding 11.4t/ha, to 13.0% for Avalon yielding 10.1t/ha – see Figure 5.7.

- Excluding those sites where 13% protein was not achieved at the highest N rate tested, an average of 41kg/ha less N was needed to achieve a grain protein content of 12.5% than was needed to achieve 13.0%.

Including both old and modern varieties, Figure 5.8 compares the difference between the measured N rate needed to achieve 13% protein (from table 5.3) and the unadjusted RB209 Nrec rate by ii) the FAM and ii) the SMN method, with the Yopt.

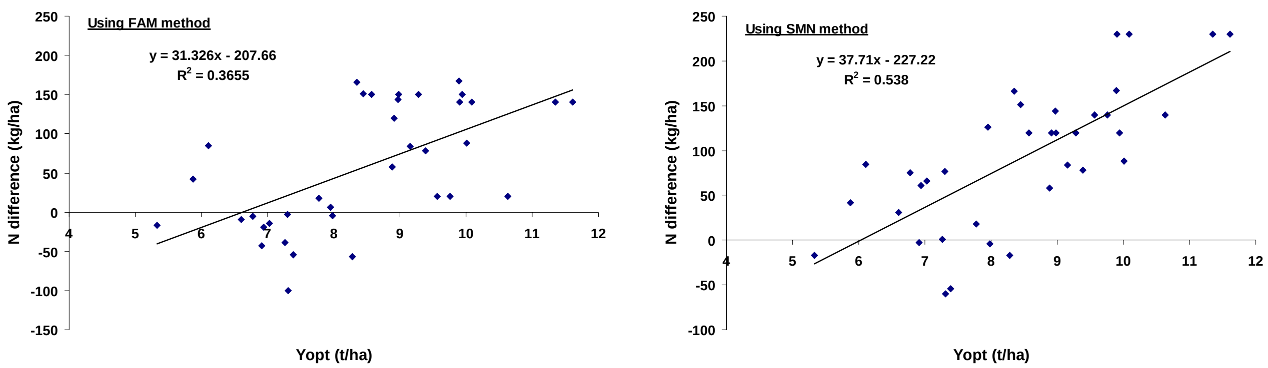


Figure 5.8 Relationship between Yopt and the difference between the N rate needed to achieve 13% grain protein and the unadjusted RB209 recommended N rate by i) the FAM and ii) the SMN method

Key points are:

- As crop yields increase, the difference between the N rate needed to achieve 13% protein and that currently recommended by RB209 increases, irrespective of whether the RB209 recommendation is assessed using the FAM or SMN methods. To meet the 13% protein target, the regression lines indicate that N rates needed to increase by around 35kg N/t of yield increase (e.g. 35kgha more N needed for a 9t/ha crop compared to an 8t/ha crop in order to achieve 13% protein).

The financial margin over the cost of fertiliser N for different N rates was calculated from each dataset for all Group 1 varieties and Solstice (i.e. those varieties that command the highest premiums). The cost of fertiliser-N was assumed to be 43 pence/kg (equivalent to £148 per tonne of ammonium nitrate) and feed wheat at £70/t, a scenario where economic optimum N rates would be based on a breakeven ratio of 6:1. Figure 5.9 plots the margins against N rate assuming a 1 in 1 success rate[2] and a £13/t premium over the feed wheat price for grain with 13.0% protein. Figure 5.10 shows the margins assuming a £5/t premium and a 1 in 3 success rate. The average premium between 1999 and 2005 has been £13.60/t and the average success rate between 2002 and 2005 has been 1 in 3 (see 3.2.1.1). Dockage of the premium was assumed to take place between 12.5 and 13.0% at the rate of £1/t for each 0.1% protein below 13.0%, with no premium payable below 12.5% protein.

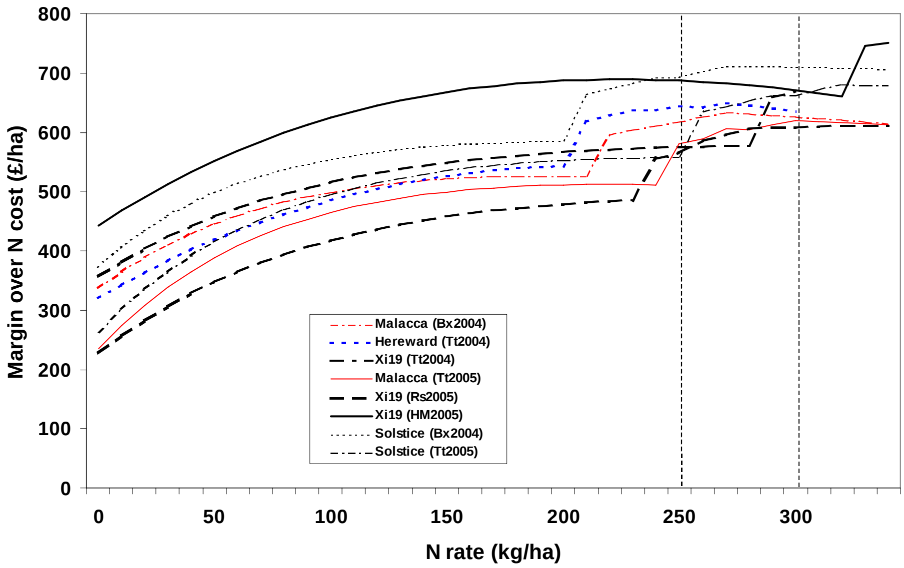


Figure 5.9 Margin over fertiliser-N cost for Group 1 varieties and Solstice (1 in 1 success rate and £13/t premium)

[2] The success rate is the proportion of the milling wheat area on a farm that actually obtains a financial premium for quality.

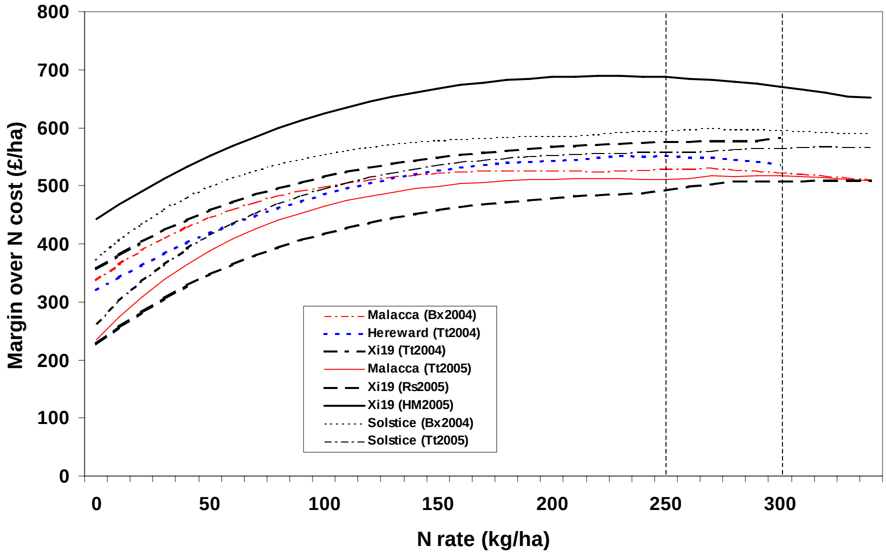


Figure 5.10. Margin over fertiliser-N cost for Group 1 varieties and Solstice (1 in 3 success rate and £5/t premium)

Table 5.5 shows the maximum extra margin (compared to no premium, i.e. feed wheat price) that would be obtained for different premium/success rate scenarios (premiums of £13/t or £5/t, each with success rates of 1 in 1, 1in 3 and 1 in 5 crops). Figure 5.11 illustrates how the margin changes with N rate for each scenario for Solstice at Boxworth 2004 and Xi19 at High Mowthorpe 2005. The calculated margins do not take account of the yield difference between growing a Group 1 or 2 variety compared to a higher yielding feed variety. This is assumed to be around 0.15t/ha, worth about £12/ha. Thus, any extra margin due to quality premiums needs to exceed £12/ha to make growing milling varieties more profitable than feed varieties.

Table 5.5 Maximum margin (£/ha) over fertiliser-N cost for different premium and success rate scenarios at each site (N priced at 43pence/kg and feed grain at £70/t)

	Premium and success rate						
	No premium	**£13/t**	**£13/t**	**£13/t**	**£5/t**	**£5/t**	**£5/t**
	n/a	**1 in 1**	**1 in 3**	**1 in 5**	**1 in 1**	**1 in 3**	**1 in 5**
Hereward (HM2004)	305	+75	+24	+14	+28	+8	+4
Hereward (Tt2004)	545	+103	+31	+18	+29	+6	+3
Malacca (Bx2004)	526	+107	+29	+13	+35	+4	0
Malacca (Tt2004)	512	+108	+30	+16	+36	+6	+1
Solstice (Bx2004)	586	+126	+40	+22	+46	+13	+7
Solstice (Tt2004)	558	+123	+37	+20	+44	+11	+4
Xi19 (HM2005)	689	+61	0	0	0	0	0
Xi19 (Rs2005)	493	+118	+39	+24	+45	+15	+9
Xi19 (Tt2004)	>578	+91	+30	+18	+10	+3	+2
Mean	**533**	**+101**	**+29**	**+16**	**+30**	**+7**	**+3**

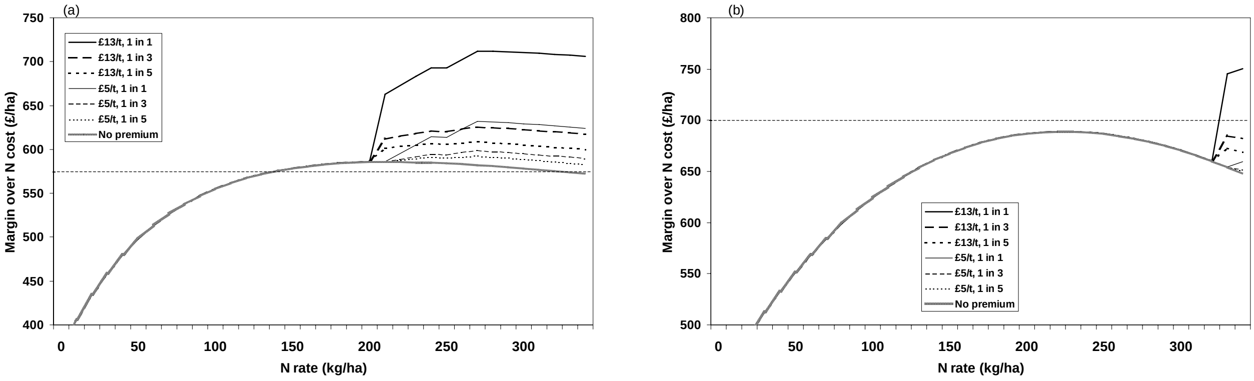


Figure 5.11 Margin over fertiliser-N cost for different premium and success rate scenarios for (a) Solstice at Boxworth 2004 and (b) Xi19 at High Mowthorpe 2005

Key points are:

- In the scenarios examined here, a premium of £13/t with a perfect 1 in 1 success rate increased the margin over the cost of fertiliser N by £101/ha on average (above that from achieving Yopt alone), and up to £126/ha (Table 5.5). In recent years, premiums have been well over £20/t which would nearly double this extra margin.

  Note:- These data are all based on N applied up to GS32 (2^{nd} node stage). The target protein contents and maximum margins would probably be achieved at slightly lower total N rates if than earlier part of application was applied as late foliar urea which usually gives a larger increase in protein applied N.

- If the premium value or success rate dropped, the extra margin quickly reduced. For a £13/t premium, the average extra margin reduced from £101/ha for 1 in 1 success rate, to £29/ha for a 1 in 3 success rate and only £16/ha for a 1 in 5 success rate. If the premium value was only £5/t, the respective extra margins were £30/ha, £7/ha and £3/ha. If the difference in yield potential between Group 1 and feed varieties is considered to be worth around £12/ha, then growing milling rather than feed varieties would on average have been worthwhile where the success rate was 1 in 1 even where the premium was only £5/t, or if the premium was £13/t even if the success rate was only 1 in 5. In most cases, it would not have been worthwhile where the premium was £5/t and the success rate was 1 in 3 or worse.

- The response of Xi19 at High Mowthorpe 2005 is noteworthy (Figure 5.11b). Although 12.6% protein and 11.4t/ha yield was obtained from use of very high rates of N (340kg/ha), this was only profitable under a scenario of £13/t premium and a perfect 1 in 1 success rate. This was because the Nopt for yield (6:1 ratio) was only 223kg/ha, so a large amount of additional N above this was needed (c.120kg/ha costing over £50/ha) before the premium could be obtained.

- The majority of the extra margin due to payment of a £13/t premium (the main step in each response line in Figure 5.9) comes from achievement of 12.5% protein. The extra N needed to increase the protein content from 12.5 to 13.0% was justifiable though less profitable at most sites under the assumed premium payment and dockage structure.

5.4 Varietal differences

One of the objectives of the project was to investigate if there were any inherent differences between varieties in their ability to recover soil or fertiliser N. Improving the ability of a crop to recover both soil and applied fertiliser N more efficiently is important for both economic and environmental reasons.

5.4.1 Crop uptake of soil N

The relative ability of crops to scavenge for soil N can be examined using crop N uptake data where no N has been applied (i.e. the control nil N treatment). Table 5.6 shows grain N uptake for each variety at each site, relative to the variety with the lowest grain N uptake at that site.

Table 5.6 Relative grain N offtake with no applied N (100 = variety with lowest offtake at each site)

Site	**Avalon**	**Mercia**	**Riband**	**Einstein**	**Hereward**	**Malacca**	**Option**	**Solstice**	**Xi19**
Boxworth 2003		119	***100***			110			111
Boxworth 2004	***100***		122			117		125	
Terrington 2004		***100***	102		102				112
Rosemaund 2004		***100***	118	140			133		
H Mowthorpe 2004	107		***100***	127	102				
Terrington 2005	***100***	104				106		119	
Rosemaund 2005	104	112		112					***100***
H Mowthorpe 2005	***100***	***100***		109					112
Essex 2005	108	103				***100***		110	
Mean	**103**	**105**	**108**	**122**	**102**	**108**	**133**	**118**	**109**
Overall mean		**106**				**115**			

Key points are:

- The overall average relative uptake was 106 for the old varieties and 115 for the modern varieties and, at 7 of the 9 sites, the variety with the lowest grain N uptake was an old variety (Avalon, Mercia or Riband). This indicates a tendency that modern varieties may have an inherent better ability than old varieties to scavenge for soil N or partition N to the grain rather than straw, in the absence of applied fertiliser N. However, there was no clear evidence of any consistent differences between the variety groups, or individual varieties, that could be relied on. Although there were differences between modern varieties at individual sites, these were not consistent. For instance, Einstein had a much higher uptake than Mercia at Rosemaund 2004, but there was no difference between these varieties at Rosemaund 2005.

5.4.2 Apparent recovery of fertiliser N

Data for the percentage recovery of applied N into grain (mean of all N rates, calculated as described in 4.2.2.1) showed that there were significant differences ($p<0.05$) between varieties at 4 of the 9 sites as follows:

- Mercia higher than Riband or Xi19 (Terrington 2004)
- Solstice higher than Mercia (Terrington 2005)
- Avalon and Einstein higher than Mercia (Rosemaund 2005)
- Solstice higher than Avalon, Mercia or Malacca (Essex 2005, but this site was unresponsive to N)

Since the recovery of fertiliser N can be influenced by the rate of applied N, relative differences between varieties at each site are summarised in Table 5.7 as the mean recovery of applied N into grain for the N4, N5 and N6 rates which will reflect the range of typical practical application rates (N1=nil N, N7=highest N rate).

Table 5.7 Relative recovery (%) of applied fertiliser N (mean of N4, N5 and N6 rates) (100 = variety with lowest recovery at each site)

Site	**Avalon**	**Mercia**	**Riband**	**Einstein**	**Hereward**	**Malacca**	**Option**	**Solstice**	**Xi19**
Boxworth 2003		*100*	101			102			104
Boxworth 2004	101		*100*			107		111	
Terrington 2004		104	101		106				*100*
Rosemaund 2004			103	109			*100*		
H Mowthorpe 2004	*100*		101	106	101				
Terrington 2005	*100*	102				104		105	
Rosemaund 2005	103	*100*		109					106
H Mowthorpe 2005	102	*100*		105					103
Essex 2005	*100*	101				102		109	
Mean	**101**	**101**	**101**	**107**	**104**	**104**	**100**	**108**	**103**
Overall mean	**101**			**104**					

Key points are:

- The overall average relative recovery was 101 for the old varieties and 104 for the modern varieties. At 7 of the 9 sites, the variety with the lowest grain N uptake was an old variety (Avalon, Mercia or Riband). However, as with data for crop uptake of soil N, there was no clear evidence of any consistent differences between the variety groups, or individual varieties.

5.5 Effect of breakeven ratio on Nopt

The fitted response curves for grain yield and protein content can be examined to identify the effects of changes to the economic breakeven ratio. Although, current RB209 recommendations are based on a ratio of 3:1, a breakeven ratio of 6:1 would be more appropriate where feed grain is valued at £70/t and ammonium nitrate costs £145/t (42pence/kg N). Table 5.8 shows the impact of changing the breakeven ratio from 3:1 to 6:1 on Nopt for yield, Yopt and grain protein content – the table excludes those sites where Nopt (3:1) was higher than the maximum N rate tested (Boxworth 2004 and Terrington 2005), and Essex 2005 where there was no response to N.

Table 5.8 Nopt, Yopt and grain protein content at breakeven ratios of 3:1 and 6:1 (mean of modern varieties based on parallel curve fitting)

	Nopt (kg/ha)		**Yopt (t/ha)**		**Grain protein (%)**	
	3:1	**6:1**	**3:1**	**6:1**	**3:1**	**6:1**
Boxworth 2003	211	179	7.12	6.98	13.58	13.17
Terrington 2004	270	234	9.61	9.45	12.67	12.35
Rosemaund 2004	168	154	10.10	10.04	10.74	10.47
H Mowthorpe 2004	258	234	6.24	6.14	13.23	12.95
Rosemaund 2005	283	250	9.14	8.99	12.97	12.63
H Mowthorpe 2005	263	225	11.48	11.31	11.80	11.49
Mean	**242**	**213**	**8.95**	**8.82**	**12.50**	**12.18**
Overall change	**-29**		**-0.13**		**-0.32**	

Key points are:

- Changing the breakeven ratio from 3:1 to 6:1 for these crops would reduce Nopt by 29kg/ha N, reduce Yopt by 0.13t/ha, and reduce grain protein by 0.32%.

5.6 Other quality parameters

5.6.1 Specific weight

At all sites where there was a yield response to N, there was also a small positive response of specific weight. However, the majority of the response was at N rates that were well below the Nopt rate for yield. Although there were significant ($p<0.05$) differences between some varieties at most sites, there were no consistent relative differences between individual varieties (Table 5.9).

Table 5.9 Relative specific weight (mean of all N rates) (100 = variety with lowest specific weight at each site)

Site	**Avalon**	**Mercia**	**Riband**	**Einstein**	**Hereward**	**Malacca**	**Option**	**Solstice**	**Xi19**
Boxworth 2003		104	101			***100***			101
Boxworth 2004	101		***100***			100		102	
Terrington 2004		103	101		106				***100***
Rosemaund 2004		104	***100***	103			101		
H Mowthorpe 2004	***100***		***100***	102	103				
Terrington 2005	100	104				***100***		104	
Rosemaund 2005	100	102		100					***100***
H Mowthorpe 2005	***100***	104		102					100
Essex 2005	101	104				***100***		104	
Mean	**100**	**104**	**100**	**102**	**105**	**100**	**101**	**103**	**100**
Overall mean	**101**			**102**					

5.6.2 Chopin Alveograph

Chopin Alveograph information is required to meet the quality requirements of export markets, but not for the UK market. In essence, the Chopin Alveograph measures the quality of the wheat gluten that holds the loaf together. The key requirements for the ukp bread wheat standard (appropriate for Group 1 and 2 varieties) is for W>170, P/L<0.9 and protein 11-13%; for the uks soft wheat brand, the requirements are for W<120, P/L<0.55 and protein 10.5-11.5%. W is a measure of the baking strength of the dough, P the maximum pressure required to burst the dough bubble, L the extensibility of the dough and P/L the dough strength and extensibility (HGCA Chopin Alveograph Guide).

Chopin Alveograph analyses were carried out on samples from all replicates of all N rates of the following 11 modern variety datasets: - Boxworth 2003 (Malacca and Xi19), Boxworth 2004 (Solstice), High Mowthorpe 2004 (Einstein), Rosemaund 2004 (Einstein), Terrington 2004 (Hereward and Xi19), Rosemaund 2005 (Einstein and Xi19), Terrington 2005 (Malacca and Solstice). Some significant differences were observed at 4 sites where direct comparisons were possible between 2 varieties (Table 5.10).

Table 5.10 Differences in Chopin alveograph parameters between varieties at individual sites ($p<0.05$)

Site	Varieties compared	W	P/L	P	L
Boxworth 2003	Malacca Xi19	Malacca>Xi19	Malacca>Xi19	No difference	No difference
Terrington 2004	Hereward Xi19	Hereward>Xi19	Xi19>Hereward	No difference	Hereward>Xi19
Rosemaund 2005	Einstein Xi19	No difference	No difference	No difference	No difference
Terrington 2005	Malacca Solstice	No difference	No difference	No difference	No difference

5.6.2.1 *Effect on W*

In addition to the information in Table 5.10, Figure 5.12 shows the relationship between N rate and W value, and Figure 5.13 between grain protein and W value.

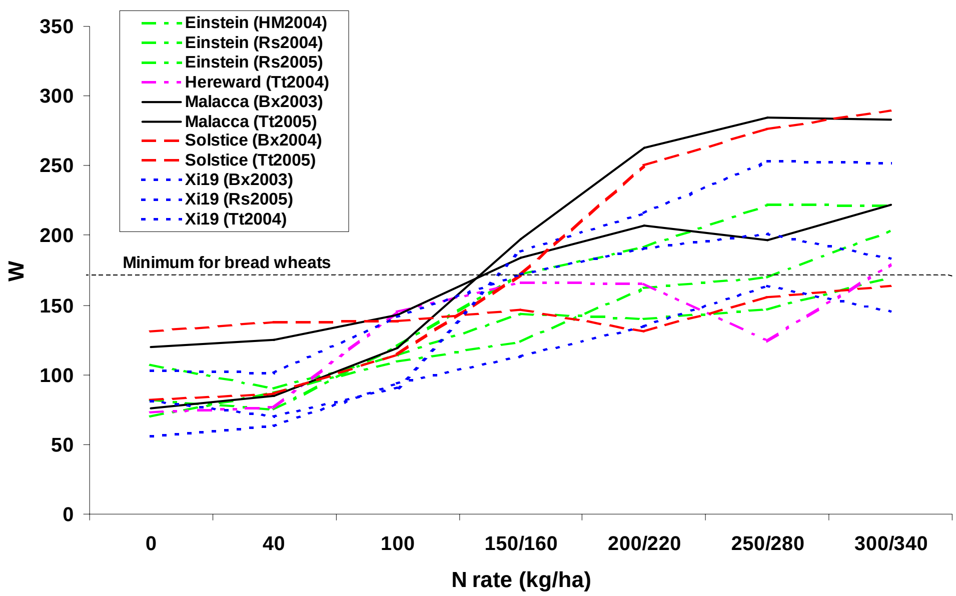


Figure 5.12 Response of W value to rate of applied N

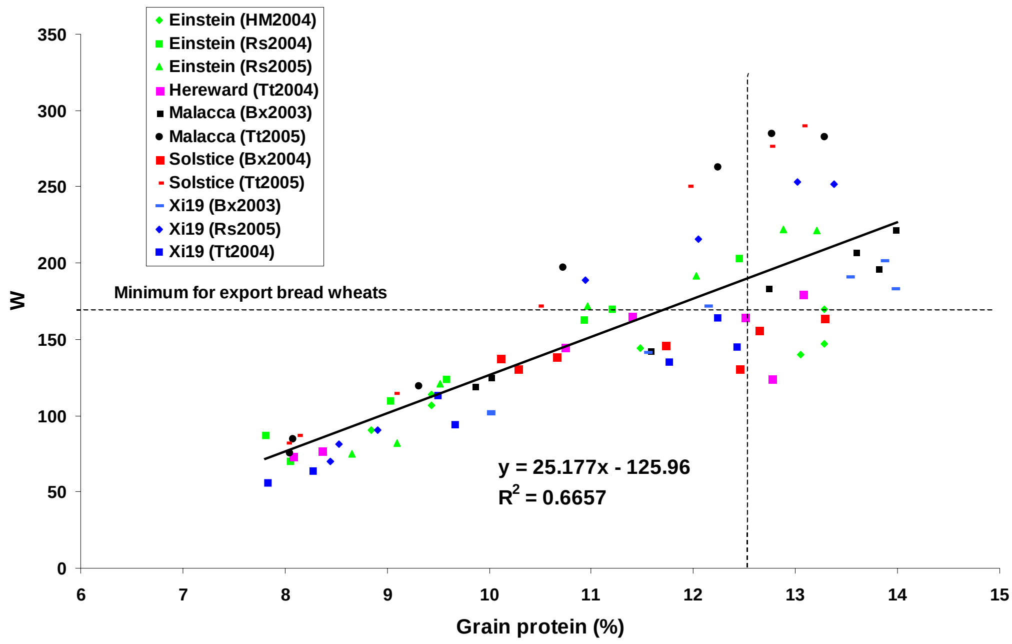


Figure 5.13 Relationship of grain protein with W value

Key points are:

- The W value generally increased with N rate, and there was also a clear relationship that W increased linearly with protein content up to around 11.0% protein that was largely independent of site or variety (c.25 W per 1% protein). The relationship was more erratic above this protein content. At least 11.0-11.5% protein was needed to achieve the critical level of W>170.
- The critical W value of 170 was usually achieved when the grain protein content reached 11.0-11.5%, but in a few cases was not achieved at 12.5% protein (required for export).
- There were indications (Table 5.10) that Xi19 had a lower W value than some other varieties (e.g. than Malacca at Boxworth 2003; than Hereward at Terrington 2004). However, the dataset is too limited to identify if these might be consistent differences between these varieties.

5.6.2.2 Effect on P, L and P/L

Figure 5.14 shows the effect of N rate on P, L and P/L. Figure 5.15 shows the relationships with grain protein content.

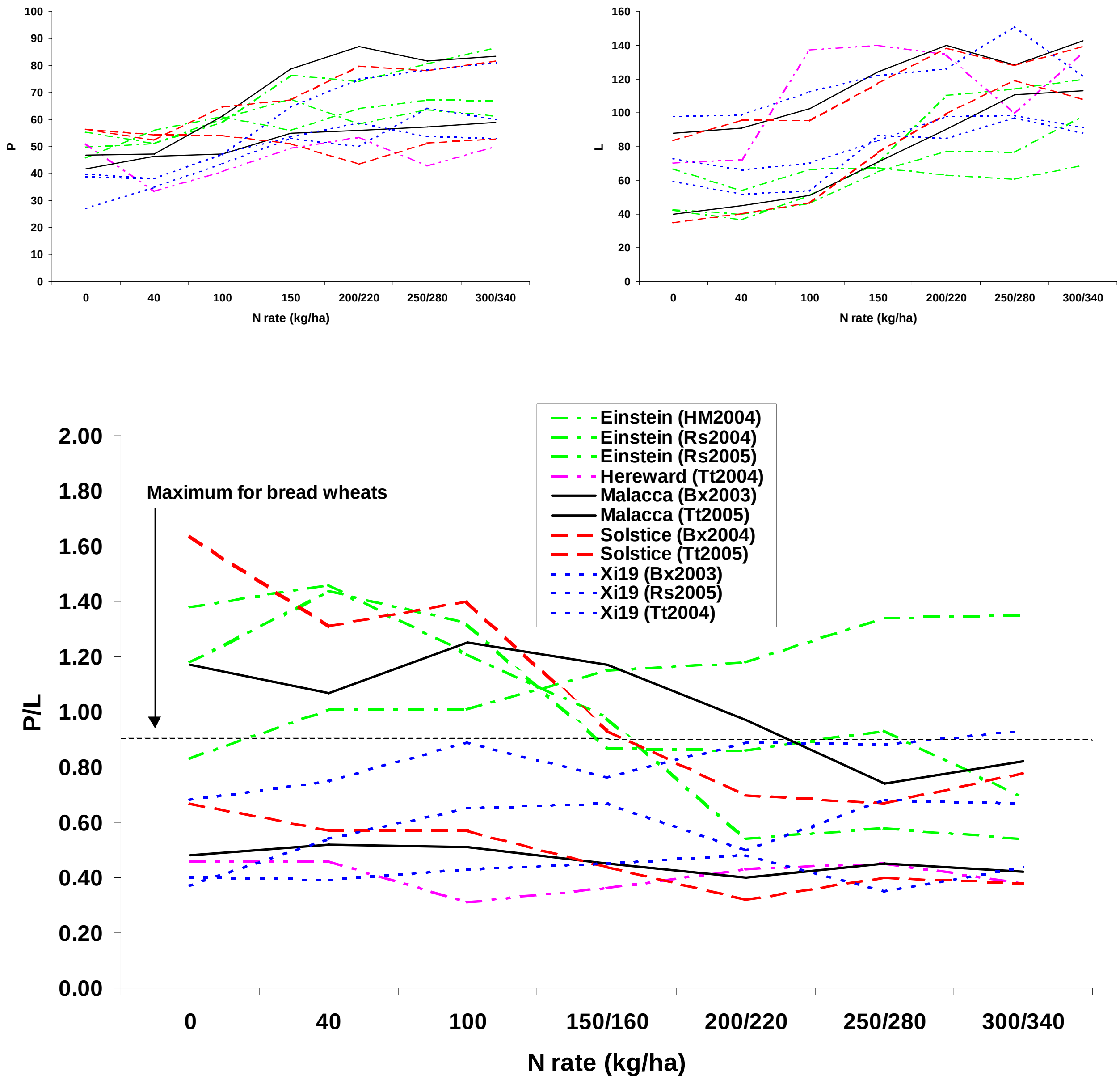


Figure 5.14 Effect of N rate on P, L and P/L

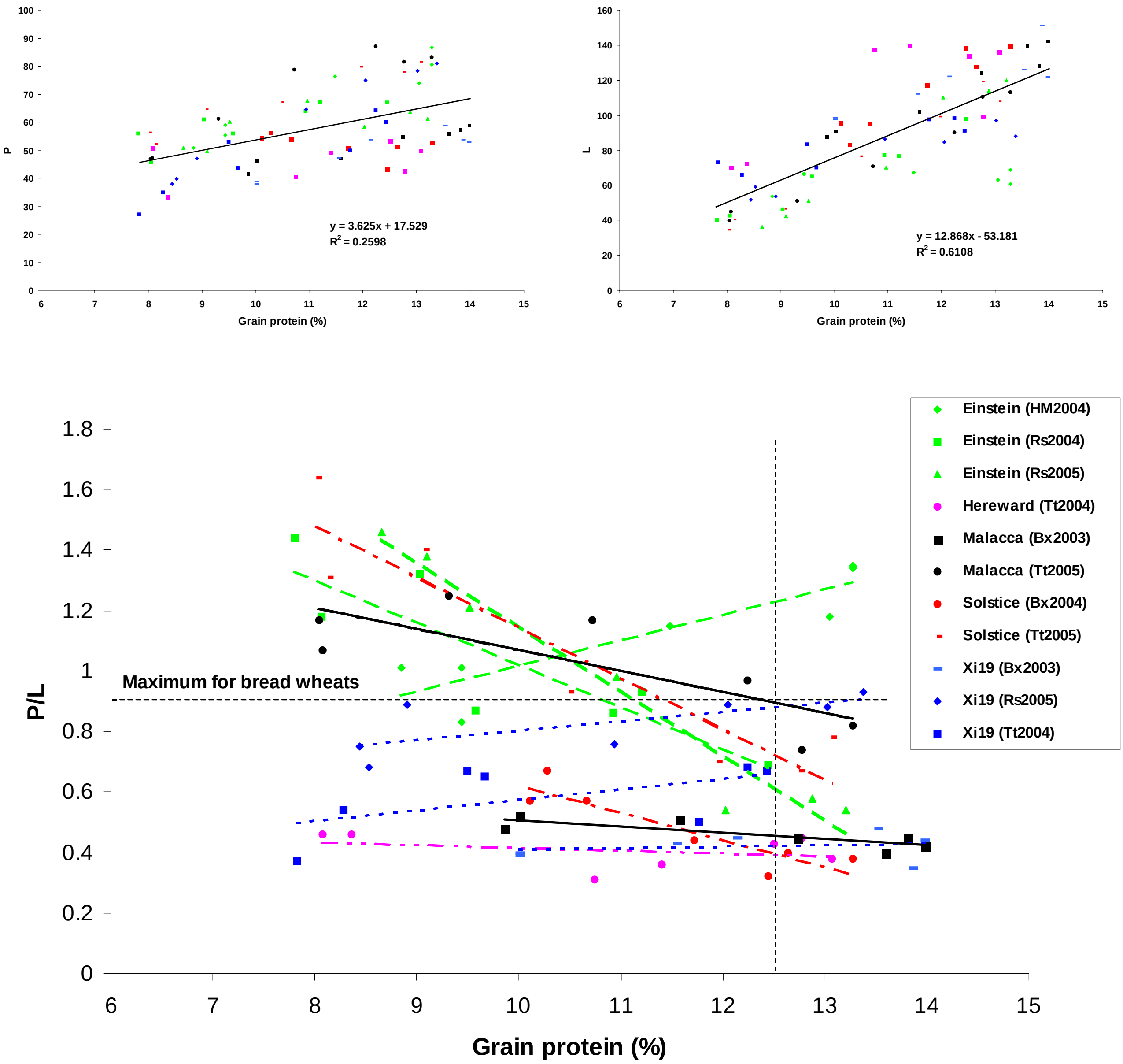


Figure 5.15 Relationship of grain protein content with P, L and P/L

Key points are:

- There was a general trend for both P and L to increase with both increasing N rate and protein content. The relationship with protein was stronger for L (dough extensibility) than for P (maximum pressure to burst dough bubble). The average rate of increase of L was approximately 13 L per 1% protein. At Terrington 2004, L was significantly higher ($p<0.05$) for Hereward than for Xi19 (Table 5.10).
- Most grain samples that were above 12.5% protein were also below the critical P/L level of 0.9.

- Significant differences in P/L values between varieties were observed at 2 sites (Malacca>Xi19 at Boxworth 2003, and Xi19>Hereward at Terrington 2004 – see Table 5.10). However, Figure 5.15 shows that the relationship between grain protein content and P/L varied depending on variety and site factors. For several datasets (Einstein except HM2004, Solstice and Malacca), P/L appeared to decrease as protein increased – the unusual relationship at HM2004 may be influenced by the low yield at this site due to take-all. For Xi19 and Hereward, there was either no effect, or suggestions of a small increase in P/L as grain protein increased. At low protein contents, P/L appeared to be higher in Einstein than Xi19. However, due to the slope of the response line, this difference was not apparent when grain protein exceeded 12.5%.
- From this limited dataset, it is not possible to identify the nature of any site factors influencing P/L, or if any of the observed differences between varieties might be consistent across sites and seasons.

6. Results and Discussion (Design 2)

The Design 2 experiments tested the following alternative strategies for applying late extra N. Three N rates (40, 80, 120kg/ha N) were tested for each application strategy.

- all as ammonium nitrate (AN) prills at GS39-61 (flag leaf emerged to flowering)
- all as foliar applied urea spray (10% N) at GS69-75 (watery to milky ripe)
- all as foliar applied urea spray (20% N) at GS69-75 (watery to milky ripe)
- half as AN prills at GS39-61, half as foliar urea (10% N)
- half as AN prills at GS39-61, half as foliar urea (20% N)

Full treatment details are given in 4.3. Key results are described and discussed in the following sections. Full data with statistics is given in the tables in Appendix 8. All protein data are given as % on a 100% dry matter basis.

6.1 Effects on crop growth and grain yield

6.1.1 Leaf scorch

There were few noticeable treatment effects on crop growth or appearance. Although use of foliar urea can cause leaf scorch, every effort was made to minimise this by applying treatments on dull days and in the evening. A long cool period following application allows assimilation of the nitrogen under low transpiration conditions. Scorch of leaf tips is thought to be caused by accumulation of unassimilated ammonium-N in the leaf tips due to the transpiration stream. Some leaf scorch following foliar urea application was observed but at only 3 of the 9 sites as follows:

- Rosemaund 2003 – all late N treatments.
- Terrington 2003 – 40kg/ha N as foliar urea caused up to 5% scorch (up to 10% when meaned over all N rates). Full strength urea (20% N) caused significantly *less* scorch ($p<0.05$) than half strength urea (10% N) – see Figure 6.1.
- High Mowthorpe 2005 – there was no scorch from 40kg/ha N as foliar urea, but up to 10% from higher N rates.

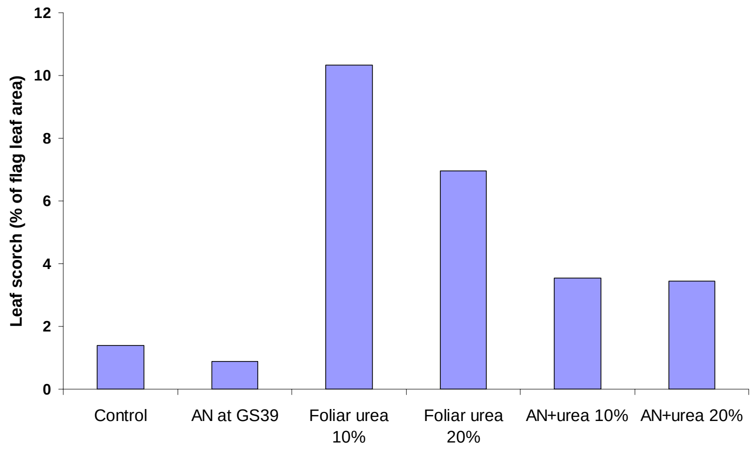


Figure 6.1 Flag leaf scorch at Terrington 2003 (mean of all N rates)

6.1.2 Grain yield

There were few significant effects on yield from application of late N. This would be expected since a standard base rate of N, intended to be close to the economic optimum (Nopt), was applied to all plots before the late N treatments were applied. Late N increased yield at only 2 sites ($p<0.05$) – at Boxworth 2004, there was a mean increase of 0.26t/ha from late N but no difference between the application strategies; at High Mowthorpe 2005, AN applied at GS39 increased yield by 0.27t/ha (Figure 6.2). Take-all reduced yield at High Mowthorpe 2003 which is likely to have reduced any potential response to late N.

At 3 sites (Terrington 2003, Rosemaund 2004, High Mowthorpe 2005), late foliar urea gave a small yield reduction ($p<0.05$). At Terrington 2003 (Figure 6.2), the 0.3t/ha yield reduction appeared to be due to foliar urea causing an actual yield reduction compared to the control, possibly due to the leaf scorch that was observed following use of foliar urea. Although no leaf scorch was observed at Rosemaund 2004, there was a 0.2t/ha lower yield from use of foliar urea compared to solid AN. At High Mowthorpe 2005 (Figure 6.2), some leaf scorch was observed from high rates of foliar urea-N, and appeared to be associated with around 0.4t/ha lower yields than was achieved from use of solid AN.

At the 3 above sites where leaf scorch was observed, the 20% urea-N solution (full strength) gave a higher yield ($p<0.05$) than the 10% (half strength) solution at High Mowthorpe 2004, but there was no difference at Terrington 2003 and Rosemaund 2004. At Essex 2005, the 10% solution gave a higher yield but there was no leaf scorch observed at this site.

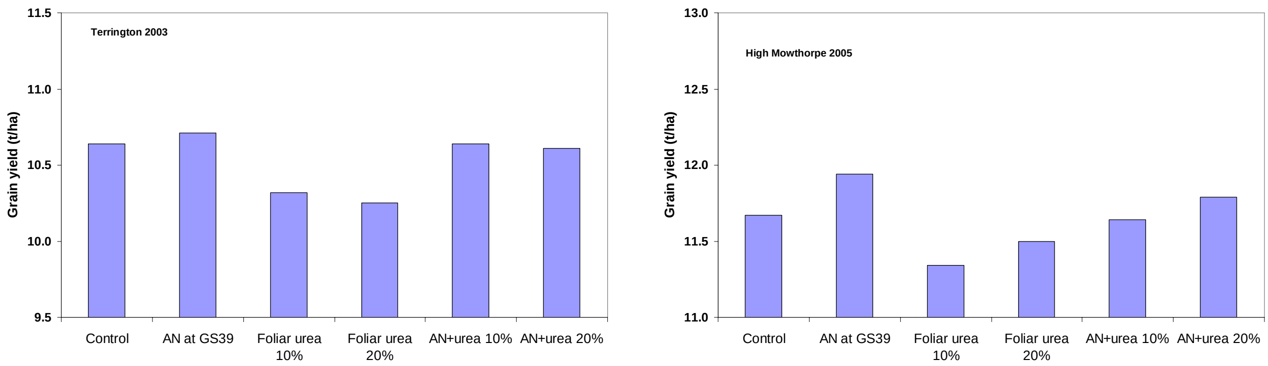


Figure 6.2 Effect of late N strategy on grain yield (Terrington 2003 and High Mowthorpe 2005)

6.2 *Effects on grain protein*

Application of late N had a large and consistent effect on grain protein content and there were significant differences in the effectiveness of the different application strategies (Figure 6.3). Use of AN prills at GS39 gave a significantly lower protein ($p<0.05$) than the mean of the other strategies at 7 of the 9 sites. The AN+foliar urea strategy gave a significantly lower protein than the foliar urea strategy at 5 of the 9 sites.

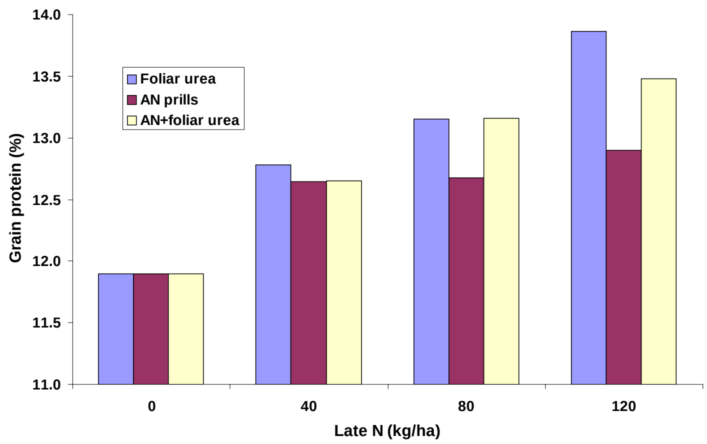


Figure 6.3 Overall effect of timing strategy and N rate on grain protein content

The average response rate of grain protein to 40kg/ha late N for the different strategies is shown below, assuming a linear relationship with N rate. Figure 6.4 shows the relationship between the increase in grain protein from 40kg/ha late N and grain yield.

	Protein increase per 40kg/ha late N
Applied all as AN prills at GS39	0.34%
Applied all as foliar urea at GS70-75	0.66%
Applied as a split application	0.53%

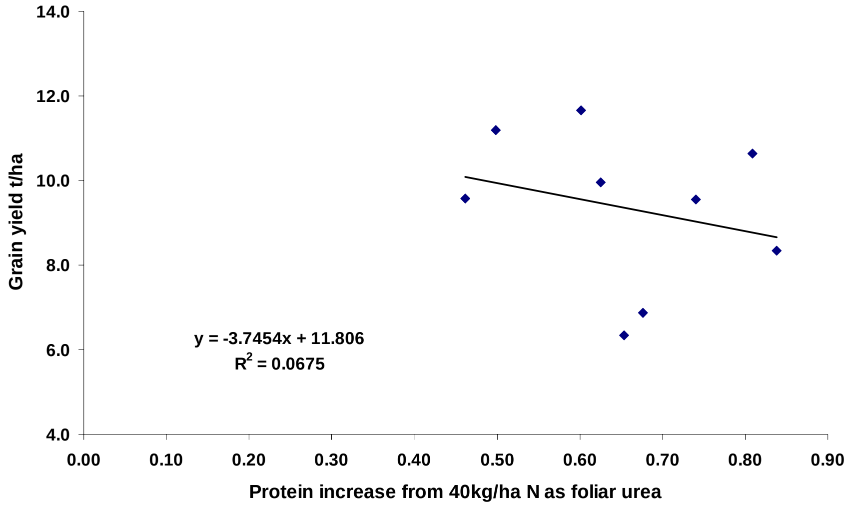


Figure 6.4 Relationship between grain yield and the rate of increase of grain protein to late N application as foliar urea

Key points are:

- Over all N rates, application of solid AN prills at GS39-61 was not as effective at raising the grain protein content as use of foliar urea at GS 69-75 (Figure 6.3). This was more noticeable at high N rates than at the typical farm practice rate of 40kg/ha N. The weaker effectiveness of solid AN may be due to delays in the movement of this N into the soil and then into the crop. Rainfall is needed for this process which can be unreliable.

- The average rate of protein response to 40kg/ha of late N was lower from use of AN prills (0.34%) than foliar urea (0.66%). However, Figure 6.4 shows that the rate of response from use of foliar urea tended to be slightly lower as grain yield increased. Although the R^2 of this relationship was very low, this relationship might be expected due to a dilution effect. It may also be a factor to explain why the rate of response to 40kg/ha as foliar urea found in these experiments (0.66% protein response, mean yield = 9.34t/ha) is lower than that found by Dampney *et al* (1995) in an earlier HGCA research project (1.03% protein response, mean yield 7.15t/ha).

- There were no differences in grain protein at any site between use of foliar urea at full strength (20% N) compared to half strength (10% N).

- If the effects of late N strategy on yield and protein are considered together, although use of solid AN may increase yield by up to 0.2-0.3t/ha, this approach may result in a 0.3% lower grain protein. If late N was applied using the solid AN prills strategy, the value of 0.25t/ha yield would be worth c.£23 (milling wheat at £90/t). However, the strategy could also result in failure to meet the protein target and thus the milling premium. Then, the financial penalty could be over £115/ha (e.g. £13/t on a 9t/ha crop) but depending on the premium value on offer.

6.3 Recovery of late applied N

The overall recovery of all late N treatments was lower than is typically found for the recovery of fertiliser N applied for yield in the March to May period. This is typically 60% into grain and straw, or 45% into grain only. Figure 6.5 shows that the average recovery of 40kg/ha of late N into grain was 33% for all late N strategies, and declined to around 20% as the rate of N application increased to over 80kg/ha. At most sites, there was no difference in N recovery between any of the application strategies. However at Boxworth 2003 and Rosemaund 2003, late solid AN at GS39 was much less efficiently used than late N applied as either the foliar urea or the AN+foliar urea strategies.

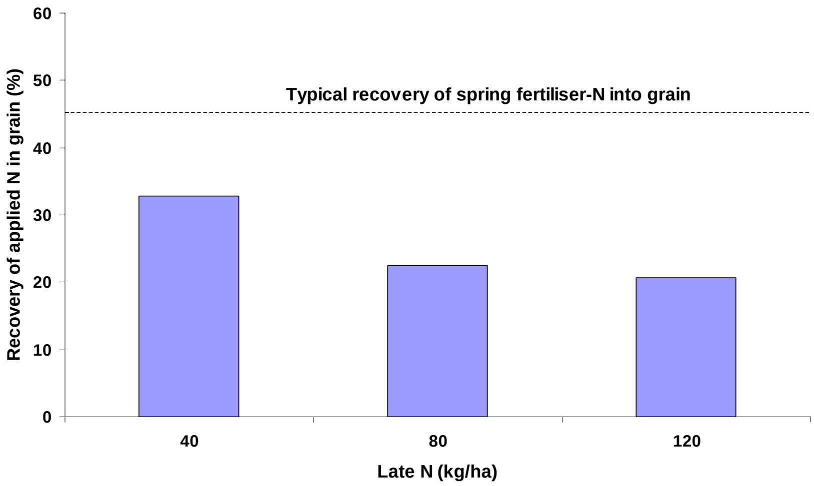


Figure 6.5 Overall effect of late N on the recovery of applied N in grain

In order to obtain a more precise measure of the fate of late applications of N, selected 2005 experiments from this project and HGCA project 3084 are being used to measure total crop N (including straw N) and soil mineral N after harvest, and the uptake of residual N by a following wheat crop. This work is funded by Defra and will be reported elsewhere.

7. Key conclusions

7.1 Nitrogen requirements of modern versus old varieties

- Direct comparison of modern recommended Group 1 and 2 wheat varieties with 'older', outclassed varieties at 9 experimental sites (fully replicated small plot experiments) showed that the modern varieties out-yielded the old varieties by an average of about 1t/ha. This would be expected and reflects the increase in national average wheat yields in the last 10-20 years. The average yield of the modern varieties in these experiments was 9.09t/ha (Einstein, Hereward, Malacca, Option, Solstice, Xi19), and 8.09t/ha from the old varieties (Avalon, Mercia, Riband). The difference in the actual yield of the best modern variety with the worst old variety at a site ranged up to 2.7t/ha (Rosemaund 2004). At each of the 9 sites, the highest yielding variety was one of the modern varieties. At 8 of the 9 sites, the lowest yielding variety was one of the old varieties.

- Following a review by George (1984), the linear plus exponential (LEXP) curve fitting function has been considered most appropriate for fitting cereal yield response curves to nitrogen cereal yield data. The output from this function has been used as the basis for the recommendations in the current 7th edition of RB209, and has been used to evaluate the data from the experiments in this project. It is recognised that further consideration of alternative response functions may be appropriate as part of any revision of RB209, but any such study will need to be carried out on a larger dataset than is available from this project. This project has however compared two alternative LEXP curve fitting procedures – i) individual curve fitting and ii) parallel curve fitting (see 4.2.2.2). The parallel curve fitting procedure proved most robust and was selected as the basis for evaluating the data.

- Using the LEXP parallel curve fitting procedure, economic optimum N rates for yield (Nopt) were determined for each variety at each experimental site, using a 3:1 breakeven ratio (3kg grain needed to pay for 1 kg of fertiliser N). There was a significant relationship (R^2=0.24, $p<0.05$) that showed that the higher yielding varieties at each site had higher Nopt values. The average increase in Nopt (3:1 ratio) was 17.3kg of fertiliser N/t grain yield. This is slightly lower than the recommendation in the previous 6th edition of RB209 (Anon 1994) which stated that '*the recommendation should be adjusted by plus or minus 20kg/ha N per t/ha yield variation'*. It is similar to the nitrogen application limits within NVZs in some other EU Member States which refer to yield-corrected N rates for wheat, using factors of between 15 and 20kg N/t yield above a standard yield level. Examples are Denmark (pers. comm.) and Southern Ireland (Anon 2006).

- For the modern varieties, the fitted Nopt values for yield varied from 0 to over 340kg/ha N depending on site characteristics. At 7 of the 9 sites, the fitted Nopt rate was higher than the RB209 N recommendation even when this was adjusted for the grain N% (protein) achieved at the site (adjusted by 30kg/ha per 0.1% variation from 2.2% grain N or 12.5% grain protein, as recommended in RB209). The overall mean fitted Nopt was 258kg/ha N, 29kg/ha more than the overall mean adjusted RB209 recommendation of 229kg/ha N. The highest Nopt for yield was over 300kg/ha N, found at 2 sites (Boxworth 2004 and Terrington 2005). The RB209 recommendations adjusted for grain N% were usually higher than the equivalent recommendations that were not adjusted. This indicates that both the current unadjusted and adjusted RB209 recommendations were generally under-estimating Nopt at these sites. It also emphasises the potential benefit from considering past grain N (protein) information to adjust the RB209 table recommendations when making N decisions (as recommended in RB209).

- When Nopt rates were applied, the grain protein contents achieved ranged from 10.27 to 14.23%, but averaged 12.76%. This is close to the current critical level for breadmaking wheats given in RB209 (i.e. 2.2% grain N or 12.5% protein). For 64% of the modern variety crops, use of the Nopt rate for yield resulted in a grain protein of over 12.5%; for 42%, the grain protein was over 13.0%. This shows that use of the correct Nopt rate for yield will commonly produce grain that is at, or close to, the market requirement for 12.5 or 13% protein, even for high yielding crops.
- High rates of nitrogen were needed at many sites in order to achieve a 13% grain protein content. For the modern variety crops, 38% (6 out of 16) needed more than 280kg/ha N, and 25% (4 out of 16) needed more than 300kg/ha N. It must be recognised though that these conclusions are based on all of the N being applied by early May, and that application of part of the total N rate as late N would probably achieve the same yield and a 13% protein content but with a slightly lower total N rate. However, these results are significant in the context that the highest unadjusted recommended N rate in RB209 is 280kg/ha N for breadmaking wheat on a shallow soil (includes 40kg/ha extra N for protein).
- There were possible indications that modern varieties may be slightly more efficient at recovering or partitioning both soil N and fertiliser N than the old varieties, though any differences were small and inconsistent. However, it was not possible to clearly show the existence of any inherent, consistent, genetic differences in N uptake efficiency between the varieties. It is possible that consideration of these data with other similar datasets may provide further clarification of this question.
- Although current RB209 recommendations are based on a breakeven ratio of 3:1, the recent increase in N prices means that future N recommendations will probably need to be based on higher ratios, maybe 6:1 (equivalent to ammonium nitrate at £145/t and grain at £70/t). Evaluation of the experimental data showed the following implications from use of N recommendations based on a 6:1 ratio compared to a 3:1 ratio:-
    - Nopt reduced by 29kg/ha N
    - Yield (Yopt) reduced by 0.13t/ha
    - Grain protein reduced by 0.32%

7.1.1 Effect of N rate on Chopin Alveograph

- Chopin Alveograph measurements showed a clear positive relationship between the W and L value and grain protein, with W increasing by about 25 W, and L increasing by about 13 L per 1% protein. Both responses seemed to be largely independent of site or variety, though there were indications that Xi19 had a lower W value than some other varieties. The critical level of W=170 was usually achieved when the grain protein was 11.0-11.5%, though there were a few cases where this W level was not reached at 12.5% protein (required for export). P/L values generally decreased with grain protein but the relationship was weak. There were only a few samples that had a protein of 12.5% or over, but a P/L above the critical value of 0.9. These results broadly agree with those reported by South *et al.* (1998) who also showed that N rate increased W and L values, but decreased P/L values.

7.2 Growing milling or feed wheat varieties?

- Analysis of the experimental data confirms that the extra financial return from growing varieties that achieve a quality premium can be high but will crucially depend on the level of premium in £/t, and the success rate of growing crops that obtain the premium (i.e. the proportion of crops grown on a farm that are managed in anticipation of obtaining a premium, and that actually do obtain a premium). Current premiums will be greatest for the Group 1 varieties (Hereward, Malacca and Xi19) and the Group 2 variety Solstice. For a typical premium of £13/t, there would have been an extra average financial margin of c.£100/ha for crops grown where there was a 100% success rate, provided sufficient N was used to achieve the 13% protein target. Under these circumstances, growing these varieties would clearly be well worthwhile even though there may be a small yield penalty (estimated to be 0.15t/ha on average, worth c.£12/ha) compared to growing feed varieties. The extra margin would reduce to c.£30/ha if the premium was £5/t but a success rate of 100%, or if the premium was £13/t but a success rate of only 1 in 3 (the national average for 2002-2005) – but this extra margin would still make growing milling varieties more profitable than feed varieties. At lower success rates or premium levels (e.g. £13/t with a 1 in 5 success rate, or £5/t with a 1 in 3 success rate), the small extra margin from growing and managing milling varieties in the hope of obtaining a premium, may mean it is more profitable to grow feed rather than milling varieties.

- These results confirm that farmers need to examine carefully how successful they are at achieving a quality premium, not just in respect of achieving the protein target but also all other quality targets that must be met (e.g. Hagberg Falling Number, specific weight, moisture). Ways to improve the success rate should be considered (e.g. increase N use if protein content is the limitation) but a realistic assessment should also be made of the potential of the land and its location, the relative yields of milling and feed varieties, and the farm management system (e.g. ability to segregate varieties after harvest). For farms with a high success rate, growing milling varieties would appear to be significantly more profitable than feed varieties even at low premium levels. Where the success rate is less than 1 in 5, a premium of over

£10-13/t is likely to be needed to justify growing milling varieties. The level of premium is, of course, difficult to predict when establishing crops.

7.3 Strategies for applying late 'extra' N

- If N fertilisation for yield is not expected to achieve the required grain protein content needed by the market, extra N specifically to increase the protein content is often needed. Many previous studies have shown that applications during late stages of crop growth are most effective in achieving this objective and that the extra protein generated does have positive benefits by improving the breadmaking quality of the wheat flour (Dampney, *et al.,* 1995; Turley *et al.*, 2001; Gooding, 2005).
- In these experiments, there were few significant effects of late N on grain yield, though where effects were observed, use of solid ammonium nitrate (AN) prills at GS39-61 (flag leaf emerged to flowering) gave slightly higher yields (up to 0.3t/ha) than use of a foliar urea applied at GS69-75 (watery to milky ripe). Where a yield effect was seen, it was considered to have been due to either compensation for the use of below optimum rates of basal N, or yield loss resulting from leaf scorch following use of foliar urea. Under-estimating basal N rates is always possible but significant under-estimation should be rare following careful and thorough approaches to N rate decision making. Leaf scorch from foliar urea application was seen at only 3 of the 9 sites as applications were made during and before dull, cool conditions when the transpiration stream is slow (e.g. evenings). Where scorch was seen it was generally less than 5-10% of the leaf area. Impacts of different late N strategies on grain yield are therefore likely to be small.
- All late N strategies consistently increased the grain protein content and by large amounts where large quantities of extra N were applied. This confirms previous research (e.g. Turley *et al.*, 2001, Gooding, 2005). The average rates of response were much higher from the use of 40kg/ha late N as foliar urea applied at watery to milky ripe stage (0.66% protein) than when applied as AN prills at flag leaf emerged to flowering stage (0.34% protein). The protein increases were lower than found by Dampney *et al.* (1995) in a previous HGCA-funded project (40kg/ha late N gave 1.04% protein when applied as foliar urea, and 0.71% when applied as AN prills). This may be due to the higher grain yields obtained in this research (mean 9.34t/ha) than in the earlier HGCA-funded project (mean 7.15t/ha); higher yields would be expected to give a lower protein increase due to the dilution effect.
- The optimum strategy for the management of Group 1 and 2 wheat varieties needs to consider the likely effect of different forms and timings of N applications on grain yield and quality, and the likely value of the crop grown, including the level of premium that may be available. The costs of the different strategies will be very similar at around £3/t for an 8t/ha crop (c. £20-25/ha for 40kg/ha late N and application). For Group 1 varieties or Solstice where premiums are likely to be high (e.g. £10 or over for 13% protein), the difference in the extra return between obtaining the premium or not, may be over

£100/ha and substantially higher in 'high premium years'. In such circumstances, crops need to be fertilised and managed to maximise the yield potential of the crop, but any additional late N should focus on ensuring that the protein target is met. This research and previous studies have shown that application of late foliar urea at watery to milky ripe stage is the most reliable method to increase the grain protein content. Although this approach will generally not increase grain yield and may occasionally give a small yield reduction if excessive leaf scorch is caused, any effects will usually be small with an impact of less than £20/ha. This potential negative effect from using foliar urea has to be balanced against the increased probability and return from obtaining a premium. In most cases therefore, strategies for the use of late N should be selected for maximum effect on grain protein, i.e. using foliar urea at the watery to milky ripe stage.

- Decisions on whether any extra late N is needed should be based on farm experience of the management and performance of the same or comparable varieties, likely premiums or contract requirements and crop growth. Currently, there is no test that can be used to estimate the need for late N, though this was investigated in the Defra LINK project 'MAnaging Late N Applications to meet wheat protein market requirements using pre-harvest near infrared (NIR) sensing (MALNA)', which was supported by HGCA (Bhandari *et al*., 2006). If the protein target is only 12.5% (e.g. for export), application of the economic optimum N rate for yield (Nopt) will often produce this protein content without the use of any extra late N. However, if revised RB209 recommended N rates are based on a breakeven ratio that is higher than the current 3:1, then the protein content of crops fertilised with these N rates will reduce.

7.4 Overall comments

- Considered in isolation from other datasets, these results indicate that the current (7th edition) RB209 recommendations need to be reviewed to take account of the higher crop nitrogen requirements of higher yielding crops that have resulted from the introduction of new varieties due to improved crop breeding. Using the current economic basis of RB209 (i.e. 3:1 breakeven ratio), these data indicate that increasing crop yields does justify an *increase* in current RB209 recommendations both in terms of the economic optimum N rates for yield, and the N rates needed to achieve a 13% grain protein target.

  However, any revision of the current edition of RB209 will need to consider and be based on the full range of available datasets and scientific understanding, including relevant research that has been conducted outside of this project, and which is made available to the revision process. No other relevant recent UK-based research information has been published. A revision will also need to take account of current and projected crop and fertiliser N prices; these factors are likely to mean a *reduction* in recommended N rates as the typical breakeven ratio increases above 3:1.

- The implications of using higher N rates on the quantity of residual N left in the soil/crop debris after harvest has not been directly studied in this project, but is being studied at some of these experimental sites in related work funded by Defra. However, use of any fertiliser N is inherently inefficient, and it must be expected that the use of increasingly high N rates will result in more residual N that may leach and add to the diffuse nitrate pollution of surface or ground waters. The balance between allowing the use of economic optimum N rates for crop production and ensuring the control of nitrate pollution of waters, is a current key policy issue for Defra.

- Farmers need to consider carefully whether growing Group 1 or Group 2 wheat is appropriate and economically worthwhile on their farm. Even if the potential financial premium is significant, this will not be obtained unless all of the necessary quality requirements are met. Any additional costs in growing the crop (e.g. lost yield, cost of extra N for protein) will then become a financial loss. Individual farms need to carefully consider the success rate of achieving the quality targets and thus the available financial premium. If the past success rate on a farm is low, then attempting to grow these varieties may not be worthwhile (the national average for Group 1 varieties in 2002-2005 was 34%).
- Continuation of the current UK market requirement for wheat grain with 13% protein is an important question that needs to be considered. Although there is good evidence that adequate protein is needed for breadmaking (e.g. Dampney *et al.*, 1995), it has been suggested that modern breadmaking processes do not need as high a protein content as older processes. The export market only needs grain with 12.5% protein. Farmers seeking to meet a 13% protein requirement will usually apply extra N solely for this purpose (commonly 40kg/ha N), which is likely to significantly increase the potential amount of residual nitrate that might cause pollution of waters. Since farmers cannot afford to miss the financial premium that is obtained for a quality sample, and because there is no current method to predict what the protein content will be at harvest, there may often be a tendency for farmers to apply more N than absolutely necessary. Increasing prices for fertiliser N will reduce economic optimum N rates and therefore also reduce the grain protein contents that will be achieved from use of these N rates. The 'protein gap' (gap between 13% protein and protein achieved from use of economic N rates for yield) will therefore get larger, which will aggravate the economic and environmental problems for farmers who seek to apply sufficient N to bridge the gap.

There is an urgent need to review if the 13% grain protein target is realistic and necessary for downstream uses of wheat grain in the UK (e.g. breadmaking).

8. Knowledge transfer

Since start of the project, selected field experimental sites have been demonstrated at annual ADAS Open Days at Boxworth, Rosemaund and High Mowthorpe. Additionally, the nature and interim conclusions of the work was demonstrated at the Cereals 2004 and 2005 events. More recently, provisional conclusions have been discussed at a range of farmer/adviser meetings including several HGCA breakfast meetings in 2006.

The most important future element of knowledge transfer from this project will be the potential inclusion of the results in the revision process of RB209. However, at the time of writing (May 2006), Defra have not yet decided if or how RB209 is to be revised. The data will represent an important new source of information that will need to be considered when setting new recommendations for winter wheat. Consideration should also be given by HGCA to production of a Wheat Nitrogen Management Guide for use by farmers.

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Appendix 1. Site locations and details (Design 1)

Site	Soil type (series)	RB209 soil type	Previous cropping	Spring SMN (kg/ha N)	RB209 Nrec (kg/ha) [a]	Test varieties	Drilling date	Dates of N applied	Harvested
Boxworth 2003 (Cambs)	Calcareous clay loam over chalky boulder clay (Hanslope)	Deep clay	2002 – W Wheat 2001 –WOSR 2000 – W Wheat	116	100 (SMN) 180 (FAM)	Malacca Mercia Riband Xi 19	19.10.2002	04.03.03 15.04.03 14.05.03	07/08.08. 2003
Boxworth 2004 (Cambs)	Calcareous clay loam over chalky boulder clay (Hanslope)	Deep clay	2003 – WWheat 2002 – WOSR 2001 – W Wheat	76	180 (SMN) 180 (FAM)	Avalon Malacca Riband Solstice	03.10.2003	02.03.04 13.04.04 07.05.04	02.09.2004
Terrington 2004 (Norfolk)	Silty clay loam (Agney)	Deep fertile silty soil	2003 – W Wheat 2002 – WOSR 2001 – W Wheat	56	180 (SMN) 150 (FAM)	Hereward Mercia Riband Xi19	03.10.2003	18.02.04 30.04.04 13.05.04	07.08.2004
Rosemaund 2004 (Hereford)[c]	Silty Clay Loam (Bromyard)	Deep clay	2003 – W Oats 2002 – W Wheat 2001 – F Maize	146	100 (SMN) 220 (FAM)	Einstein Option Riband Mercia	09.10.2003	09.03.04 14.04.04 06.05.04	28.08.2004
High Mowthorpe 2004 (North Yorkshire) [d]	Silty clay loam over chalk (Panholes – deeper, calcareous)	Shallow soil	2003 – W Wheat 2002 – WOSR 2001 – W Barley	88	200 (SMN) 240 (FAM)	Avalon Einstein Hereward Riband	07.10.2003	10.03.04 28.04.04 11.05.04	17.08.2004
Terrington 2005 (Norfolk)	Silty clay loam (Agney series)	Deep fertile silty soil	2004 – W Wheat 2003 – S Beet 2002 – W Wheat	80	150 (SMN) 150 (FAM)	Avalon Malacca Mercia Solstice	11.10.2004	16.03.05 12.04.05 06.05.05	09.08.2005
Rosemaund 2005 (Hereford)[c]	Silty Clay Loam (Bromyard)	Deep clay	2004 – W Oats 2003 – W Wheat 2002 – WOSR	65	220 (SMN) 220 (FAM)	Avalon Einstein Mercia Xi19	06.10.2004	11.03.05 14.04.05 14.05.05	12.08.2005

High Mowthorpe 2005 (North Yorkshire)	Deeper silty clay loam, non-calcareous, overlying chalk (Wold series)	Shallow soil	2004 – WOSR 2003 – W Barley 2002 – WWheat	124	110 (SMN) 200 (FAM)	Avalon Einstein Mercia Xi19	11.10.2004	21.03.05 06.05.05 23.05.05	08.09.2005

Essex 2005 (Essex) [e]	Tertiary Clay (Windsor series)	Deep clay	2004 – WOSR 2003 – W Wheat 2002 – WOSR	185	40-80 (SMN) 100 (FAM)	Avalon Malacca Mercia Solstice	27.09.2004	16.03.05 20.04.05 06.05.05	12.08.2005

a RB209 recommendations given based on SMN method (SMN) and Field Assessment Method (FAM) method but with no adjustment for grain N/protein information

b Only 2 reps (Nil plots on 1 rep only) Poor establishment in soil which was waterlogged for long periods.

c Set up trial without blocks of N rate.

d 'Take all' reported

e High SMN due to sewage sludge application in Aug 2003

Site locations and details (Design 2)

Site	Soil type (series)	RB209 soil type	Previous cropping	Spring SMN (kg/ha N)	Test variety	Base N (kg/ha)	Drilling date	Dates of N applied (first four dates solid N last three foliar urea)	Harvested
Boxworth 2003 (Cambs)	Calcareous clay loam over chalky boulder clay (Hanslope)	Deep clay	2002 –W Wheat 2001 – WOSR 2000 – W Wheat	116	Xi19	200	19.10.2002	04.03.03 15.04.03 14.05.03 03.06.03 25.06.03 27.06.03 04.07.03	07.08.2003
Terrington 2003 (Norfolk)	Silt Loam (Romney)	Deep fertile silty soil	2002 – S Beet 2001 – W Wheat 2000 - Potatoes	110	Xi19	200	08.11.2002	18.02.03 29.04.03 15.05.03 09.06.03 27.06.03 04.07.03 09.07.03	08.08.2003
Rosemaund 2003 (Hereford)	Silty clay loam (Bromyard)	Deep clay	2002 – W Oats 2001 – W Wheat 2000 – F Maize	82	Xi19	200	24.10.2002	31.03.03 29.04.03 09.05.03 06.06.03 20.06.03 24.06.03 28.06.03	14.08.2003
Boxworth 2004 (Cambs)	Calcareous clay loam over chalky boulder clay (Hanslope)	Deep clay	2003 – W Wheat 2002 – WOSR 2001 – W Wheat	76	Solstice	200	03.10.2003	02.03.04 13.04.04 07.05.04 09.06.04 01.07.04 06.07.04 08.07.04	02.09.2004

Terrington 2004 (Norfolk)	Silty clay loam (Agney)	Deep fertile silty soil	2003 – W Wheat 2002 – WOSR 2001 – WWheat	56	Xi19	200	03.10.2003	18.02.04 30.04.04 13.05.04 08.06.04 25.06.04 29.06.04 06.07.04	07.08.2004
Rosemaund 2004 (Hereford)	Silty clay loam (Bromyard)	Deep clay	2003 – W Oats 2002 – WWheat 2001 – F Maize	146	Option	160	09.10.2003	10.03.04 15.04.04 06.05.04 13.06.04 29.06.04 05.07.04 13.07.04	26.08.2004
High Mowthorpe 2004 (North Yorkshire)[a]	Silty clay loam over chalk (Panholes – deeper, calcareous)	Shallow soil	2003 – W Wheat 2002 – WOSR 2001 – W Barley	88	Einstein	200	07.10.2003	10.03.04 20.04.04 10.05.04 16.06.04 25.06.04 02.07.04 09.07.04	17.08.2004
Essex 2005 (Essex)	Tertiary Clay (Windsor series)	Deep clay	2004 – WOSR 2003 – W Wheat 2002 – WOSR	172 (sewage sludge applied in Aug 2003)	Einstein	100	27.09.2004	21.03.05 20.04.05 - 24.05.05 28.06.05 01.07.05 04.07.05	12.08.2005
High Mowthorpe 2005 (North Yorkshire)	Deeper silty clay loam, non-calcareous, overlying chalk (Wold series)	Shallow soil	2004 – WOSR 2003 – W Barley 2002 – WWheat	124	Einstein	200	01.10.2004	29.03.05 21.04.05 05.05.05 05.07.05 08.07.05 12.07.05	07.09.2005

a ‘Take all’ reported

Appendix 2. Raw data and ANOVA (Design 1)

Grain yield (t/ha @ 85% DM)

Site	Variety	Fertiliser N applied (kg/ha N)							Mean	cv%
		0	**40**	**100**	**150**	**200**	**250**	**300**		
Boxworth 2003	Malacca	3.35	4.54	5.98	6.86	6.62	7.24	6.85	5.92	
	Mercia	3.60	5.04	6.25	6.93	6.89	7.02	7.00	6.11	
	Riband	3.04	4.84	5.65	6.92	6.49	6.72	6.70	5.77	3.9
	Xi19	3.32	4.82	6.04	7.19	7.00	7.69	7.18	6.18	
	Mean	3.33	4.81	5.98	6.97	6.75	7.17	6.93		
	sed		0.477 (N rate)	0.505 (interactions)		0.192 (varieties at same N rate)			0.073	
		0	**40**	**100**	**150**	**200**	**250**	**300**	**Mean**	**cv%**
Boxworth 2004	Avalon	3.72	4.82	5.96	6.42	6.91	7.11	7.39	**6.05**	
	Malacca	4.82	6.39	7.65	8.56	8.69	8.82	9.16	**7.73**	
	Riband	5.05	7.26	8.28	8.71	9.07	8.86	9.07	**8.04**	
	Solstice	5.30	7.18	8.46	9.14	9.62	9.99	10.01	**8.53**	3.5
	Mean	**4.72**	**6.41**	**7.59**	**8.21**	**8.57**	**8.69**	**8.91**		
	sed		0.121 (N rate)	0.223 (interactions)		0.216 (varieties at same N rate)			0.082	
		0	**40**	**100**	**150**	**200**	**250**	**300**	**Mean**	**cv%**
Terrington 2004	Hereward	4.71	5.60	7.87	8.51	8.71	9.38	9.33	**7.73**	
	Mercia	4.63	5.91	7.54	8.34	8.23	8.59	8.55	**7.40**	
	Riband	4.82	5.83	7.73	8.36	8.63	9.15	8.98	**7.64**	
	Xi19	5.34	6.10	8.00	9.09	9.10	9.97	9.93	**8.22**	4.1
	Mean	**4.88**	**5.86**	**7.78**	**8.58**	**8.67**	**9.27**	**9.19**		
	sed		0.210 (N rate)	0.307 (interactions)		0.259 (varieties at same N rate)			0.098	
		0	**40**	**80**	**120**	**160**	**200**	**240**	**Mean**	**cv%**

Rosemaund 2004	Einstein	6.16	7.48	8.98	10.06	10.59	10.73	10.33	**9.19**	3.1
	Mercia	5.65	6.63	7.49	7.98	7.76	7.84	7.66	**7.28**	
	Option	6.31	7.76	8.69	9.31	9.65	9.39	8.99	**8.58**	
	Riband	5.94	7.81	8.37	9.16	9.78	9.57	9.63	**8.60**	
	Mean	**6.01**	**7.42**	**8.46**	**9.13**	**9.44**	**9.38**	**9.15**		
	sed	0.105 (N rate) 0.211 (interactions) N/A (varieties at same N rate) *(Experiment design with varieties and N rates fully randomised, without sub plots for N rates)*							0.080	
		0	**40**	**100**	**160**	**220**	**280**	**340**	**Mean**	**cv%**
High Mowthorpe 2004	Avalon	1.46	1.93	4.01	4.77	5.13	5.43	5.30	**4.00**	7.8
	Einstein	1.96	2.45	4.79	5.99	6.34	6.88	6.39	**4.97**	
	Hereward	1.51	2.24	4.44	4.86	5.86	5.83	5.91	**4.38**	
	Riband	1.55	2.66	4.60	5.62	6.09	6.12	5.82	**4.64**	
	Mean	**1.62**	**2.32**	**4.46**	**5.31**	**5.86**	**6.06**	**5.85**		
	sed	0.345 (N rate) 0.425 (interactions) 0.286 (varieties at same N rate) *(Low yields due to 'Take all')*							0.108	
		0	**40**	**100**	**160**	**220**	**280**	**340**	**Mean**	**cv%**
Terrington 2005	Avalon	2.95	5.17	6.72	7.64	8.00	8.35	8.56	6.77	3.9
	Malacca	3.27	5.71	7.04	8.08	8.70	9.25	8.95	7.29	
	Mercia	3.17	5.19	6.90	8.03	8.45	8.76	8.32	6.98	
	Solstice	3.69	6.04	7.43	8.81	9.33	9.73	9.89	7.85	
	Mean	3.27	5.53	7.03	8.14	8.62	9.02	8.93		
	sed	0.280 (N rate) 0.342 (interactions) 0.227 (varieties at same N rate)							0.086	
		0	**40**	**100**	**160**	**220**	**280**	**340**	**Mean**	**cv%**
Rosemaund 2005	Avalon	3.11	4.80	6.29	7.27	7.54	7.91	8.05	6.42	5.0
	Einstein	3.64	4.72	7.38	8.49	9.09	9.36	9.39	7.44	
	Mercia	3.54	4.60	6.27	7.38	7.62	7.75	7.82	6.42	
	Xi19	3.44	4.67	6.39	7.71	8.52	8.84	8.92	6.93	
	Mean	3.43	4.69	6.58	7.71	8.19	8.47	8.55		
	sed	0.138 (N rate) 0.277 (interactions) N/A (varieties at same N rate) *(Experiment design with varieties and N rates fully randomised, without sub plots for N rates)*								

		0	40	100	160	220	280	340	Mean	cv%
High Mowthorpe 2005	Avalon	5.58	6.97	8.58	9.49	9.76	9.79	10.03	8.60	
	Einstein	6.28	7.59	9.62	11.07	11.56	11.47	11.67	9.89	
	Mercia	5.74	7.32	8.86	9.77	9.99	9.98	10.17	8.83	2.2
	Xi19	6.39	7.72	9.57	10.71	11.21	11.30	11.43	9.76	
	Mean	6.00	7.40	9.16	10.26	10.63	10.64	10.82		
	sed	0.265 (N rate)		0.303 (interactions)		0.168 (varieties at same N rate)			0.064	
		0	**40**	**100**	**160**	**220**	**280**	**340**	**Mean**	**cv%**
Essex 2005	Avalon	7.07	6.80	7.45	7.44	7.63	7.58	7.20	7.31	
	Malacca	6.63	6.95	6.61	7.21	7.02	7.18	6.80	6.91	
	Mercia	6.80	7.23	7.52	7.48	7.46	7.32	7.02	7.26	
	Solstice	7.60	8.25	8.23	8.79	8.58	8.46	8.02	8.28	5.9
	Mean	7.03	7.31	7.45	7.73	7.67	7.64	7.26		
	sed	0.439 (N rate)		0.536 (interactions)		0.356 (varieties at same N rate)			0.135	

Grain N (%)

Site	Variety	Fertiliser N applied (kg/ha N)							Mean	cv%
		0	40	100	150	200	250	300		
Boxworth 2003	Malacca	1.73	1.76	2.03	2.23	2.38	2.42	2.45	2.14	1.9
	Mercia	1.74	1.79	2.05	2.23	2.36	2.39	2.47	2.15	
	Riband	1.73	1.77	2.01	2.21	2.35	2.30	2.39	2.11	
	Xi19	1.76	1.76	2.03	2.13	2.37	2.43	2.45	2.13	
	Mean	1.74	1.77	2.03	2.20	2.37	2.39	2.44		
	sed	0.035 (N rate)		0.045 (interactions)		0.032 (varieties at same N rate)			0.012	
Boxworth 2004		0	40	100	150	200	250	300	Mean	cv%
	Avalon	2.05	2.14	2.25	2.33	2.41	2.49	2.56	2.32	4.3
	Malacca	1.85	1.89	1.89	2.08	2.18	2.23	2.34	2.06	
	Riband	1.84	1.82	1.85	1.92	1.94	2.12	2.19	1.95	
	Solstice	1.80	1.77	1.87	2.06	2.18	2.22	2.33	2.03	
	Mean	1.89	1.91	1.96	2.10	2.18	2.26	2.35		
	sed	0.036 (N rate)		0.073 (interactions)		0.074 (varieties at same N rate)			0.028	
		0	40	100	150	200	250	300	Mean	cv%
Terrington 2004	Hereward	1.42	1.47	1.88	2.00	2.19	2.24	2.29	1.93	5.0
	Mercia	1.41	1.63	1.93	2.12	2.21	2.19	2.26	1.96	
	Riband	1.38	1.38	1.77	1.89	2.04	2.17	2.10	1.82	
	Xi19	1.37	1.45	1.70	1.67	2.06	2.15	2.18	1.80	
	Mean	1.40	1.48	1.82	1.92	2.13	2.19	2.21		
	sed	0.066 (N rate)		0.094 (interactions)		0.077 (varieties at same N rate)			0.029	
		0	40	80	120	160	200	240	Mean	cv%
Rosemaund 2004	Einstein	1.41	1.37	1.58	1.68	1.92	1.97	2.18	1.73	3.9
	Mercia	(1.55)	(1.61)	1.72	(1.91)	2.12	2.17	2.30	1.91	
	Option	1.31	1.45	1.59	1.72	1.78	1.99	2.07	1.70	
	Riband	1.24	1.33	1.37	1.64	1.76	1.99	2.02	1.63	
	Mean	1.38	1.44	1.57	1.74	1.89	2.03	2.15		
	sed	0.028 (N rate)		0.056 (interactions)		N/A (varieties at same N rate) *(Values in brackets are estimates)*			0.021	

		0	40	100	160	220	280	340	Mean	cv%
High Mowthorpe 2004	Avalon	1.86	1.74	1.87	2.21	2.38	2.50	2.61	2.17	
	Einstein	1.66	1.55	1.66	2.01	2.29	2.33	2.33	1.98	
	Hereward	1.72	1.87	1.76	2.05	2.21	2.41	2.43	2.06	5.7
	Riband	1.62	1.43	1.65	1.85	1.98	2.30	2.39	1.89	
	Mean	1.71	1.65	1.73	2.03	2.22	2.39	2.44		
	sed	0.048 (N rate)		0.095 (interactions)		0.094 (varieties at same N rate)			0.036	
		0	**40**	**100**	**160**	**220**	**280**	**340**	**Mean**	**cv%**
Terrington 2005	Avalon	1.48	1.47	1.67	1.96	2.11	2.23	2.31	1.89	
	Malacca	1.41	1.42	1.63	1.88	2.15	2.24	2.33	1.87	
	Mercia	1.44	1.39	1.71	1.89	2.08	2.28	2.31	1.87	
	Solstice	1.41	1.43	1.59	1.84	2.10	2.24	2.29	1.84	2.5
	Mean	1.43	1.43	1.65	1.89	2.11	2.25	2.31		
	sed	0.025 (N rate)		0.041 (interactions)		0.038 (varieties at same N rate)			0.014	

		0	40	100	160	220	280	340	Mean	cv%
Rosemaund 2005	Avalon	1.73	1.62	1.74	2.05	2.30	2.37	2.46	2.04	
	Einstein	1.60	1.52	1.67	1.92	2.11	2.26	2.32	1.91	
	Mercia	1.63	1.57	1.77	1.99	2.23	2.37	2.43	2.00	3.1
	Xi19	1.50	1.48	1.56	1.92	2.11	2.28	2.35	1.89	
	Mean	1.61	1.55	1.69	1.97	2.19	2.32	2.39		
	sed	0.024 (N rate)		0.049 (interactions)		N/A (varieties at same N rate)			0.018	
		0	**40**	**100**	**160**	**220**	**280**	**340**	**Mean**	**cv%**
High Mowthorpe 2005	Avalon	1.60	1.56	1.78	2.05	2.18	2.24	2.29	1.96	
	Einstein	1.54	1.49	1.65	1.87	2.00	2.04	2.06	1.81	
	Mercia	1.55	1.56	1.67	1.95	2.10	2.10	2.20	1.88	2.7
	Xi19	1.57	1.61	1.73	1.90	1.99	2.14	2.22	1.88	
	Mean	1.56	1.56	1.71	1.94	2.07	2.13	2.19		
	sed	0.028 (N rate)		0.046 (interactions)		0.042 (varieties at same N rate)			0.016	
		0	**40**	**100**	**160**	**220**	**280**	**340**	**Mean**	**cv%**

Essex 2005	Avalon	2.30	2.32	2.36	2.44	2.41	2.40	2.47	2.38	
	Malacca	2.27	2.26	2.36	2.44	2.50	2.43	2.47	2.39	
	Mercia	2.29	2.21	2.39	2.40	2.41	2.35	2.39	2.35	
	Solstice	2.18	2.28	2.36	2.40	2.41	2.40	2.41	2.35	2.4
	Mean	2.26	2.27	2.37	2.42	2.43	2.40	2.44		
	sed	0.027 (N rate) 0.048 (interactions) 0.046 (varieties at same N rate)							0.018	

Grain Protein (at 100% DM)

Site	Variety	Fertiliser N applied (kg/ha N)							Mean	cv%
		0	40	100	150	200	250	300		
Boxworth 2003	Malacca	9.86	10.01	11.57	12.73	13.59	13.81	13.98	12.22	
	Mercia	9.90	10.20	11.69	12.71	13.45	13.64	14.08	12.24	
	Riband	9.88	10.11	11.44	12.62	13.41	13.11	13.64	12.03	
	Xi19	10.01	10.01	11.55	12.14	13.53	13.87	13.98	12.16	1.9
	Mean	9.91	10.08	11.56	12.55	13.49	13.61	13.92		
	sed	0.130 (N rate) 0.255 (interactions) 0.185 (varieties at same N rate)							0.070	
Boxworth 2004		0	40	100	150	200	250	300	Mean	cv%
	Avalon	11.69	12.22	12.83	13.28	13.76	14.17	14.59	13.22	
	Malacca	10.56	10.77	10.75	11.84	12.41	12.69	13.32	11.76	
	Riband	10.47	10.39	10.53	10.96	11.06	12.07	12.48	11.14	4.3
	Solstice	10.28	10.11	10.66	11.72	12.45	12.64	13.28	11.59	
	Mean	10.75	10.87	11.19	11.95	12.42	12.89	13.42		
	sed	0.205 (N rate) 0.417 (interactions) 0.419 (varieties at same N rate)							0.158	
		0	40	100	150	200	250	300	Mean	cv%
Terrington 2004	Hereward	8.08	8.36	10.74	11.40	12.50	12.77	13.07	10.99	
	Mercia	8.06	9.29	10.98	12.08	12.58	12.50	12.90	11.20	
	Riband	7.87	7.85	10.07	10.79	11.63	12.35	11.95	10.36	5.0
	Xi19	7.83	8.28	9.67	9.50	11.76	12.24	12.43	10.24	
	Mean	7.96	8.45	10.36	10.94	12.12	12.46	12.59		
	sed	0.376 (N rate) 0.5336 (interactions) 0.437 (varieties at same N rate)							0.165	
		0	40	80	120	160	200	240	Mean	cv%
Rosemaund 2004	Einstein	8.06	7.81	9.03	9.58	10.93	11.21	12.45	9.86	
	Mercia	(8.81)	(9.17)	9.78	(10.87)	12.07	12.39	13.13	10.89	
	Option	7.45	8.25	9.08	9.82	10.13	11.34	11.80	9.70	
	Riband	7.05	7.58	7.81	9.35	10.05	11.34	11.53	9.25	3.9
	Mean	7.84	8.20	8.93	9.91	10.79	11.57	12.23		
	sed	0.160 (N rate) 0.318 (interactions) N/A (varieties at same N rate) *(Values in brackets are estimates)*							0.120	

		0	40	100	160	220	280	340	Mean	cv%
High Mowthorpe 2004	Avalon	10.60	9.92	10.64	12.62	13.59	14.27	14.90	12.36	
	Einstein	9.44	8.85	9.44	11.48	13.05	13.28	13.28	11.26	
	Hereward	9.79	10.66	10.05	11.69	12.58	13.74	13.85	11.76	5.7
	Riband	9.25	8.17	9.39	10.56	11.31	13.11	13.64	10.78	
	Mean	9.77	9.40	9.88	11.59	12.63	13.60	13.92		
	sed	0.273 (N rate)		0.540 (interactions)		0.538 (varieties at same N rate)			0.203	
		0	**40**	**100**	**160**	**220**	**280**	**340**	**Mean**	**cv%**
Terrington 2005	Avalon	8.46	8.38	9.52	11.17	12.05	12.73	13.19	10.78	
	Malacca	8.04	8.08	9.31	10.72	12.24	12.77	13.28	10.63	
	Mercia	8.19	7.94	9.77	10.77	11.84	13.00	13.19	10.67	2.5
	Solstice	8.02	8.13	9.08	10.49	11.95	12.75	13.07	10.50	
	Mean	8.17	8.13	9.42	10.79	12.02	12.81	13.18		
	sed	0.142 (N rate)		0.234 (interactions)		0.215 (varieties at same N rate)			0.081	
		0	**40**	**100**	**160**	**220**	**280**	**340**	**Mean**	**cv%**
Rosemaund 2005	Avalon	9.84	9.23	9.92	11.67	13.09	13.53	14.02	11.61	
	Einstein	9.10	8.66	9.52	10.96	12.03	12.88	13.21	10.91	
	Mercia	9.31	8.97	10.11	11.32	12.69	13.53	13.83	11.39	3.1
	Xi19	8.53	8.44	8.91	10.94	12.05	13.02	13.38	10.75	
	Mean	9.20	8.83	9.61	11.22	12.46	13.24	13.61		
	sed	0.140 (N rate)		0.2787 (interactions)		N/A (varieties at same N rate)			0.105	
		0	**40**	**100**	**160**	**220**	**280**	**340**	**Mean**	**cv%**
High Mowthorpe 2005	Avalon	9.12	8.89	10.13	11.70	12.45	12.77	13.03	11.16	
	Einstein	8.76	8.51	9.39	10.64	11.40	11.63	11.72	10.29	
	Mercia	8.82	8.91	9.52	11.12	11.95	11.99	12.54	10.69	2.7
	Xi19	8.93	9.16	9.86	10.85	11.32	12.22	12.64	10.71	
	Mean	8.91	8.87	9.72	11.08	11.78	12.15	12.48		
	sed	0.160 (N rate)		0.262 (interactions)		0.239 (varieties at same N rate)			0.090	

		0	**40**	**100**	**160**	**220**	**280**	**340**	**Mean**	**cv%**
Essex 2005	Avalon	13.09	13.21	13.43	13.91	13.74	13.66	14.10	13.59	2.4
	Malacca	12.94	12.88	13.47	13.89	14.23	13.87	14.10	13.63	
	Mercia	13.05	12.58	13.64	13.66	13.74	13.41	13.64	13.39	
	Solstice	12.43	12.98	13.45	13.68	13.76	13.68	13.76	13.39	
	Mean	12.88	12.91	13.50	13.78	13.87	13.66	13.90		
	sed	0.151(N rate) 0.274 (interactions) 0.264 (varieties at same N rate)							0.100	

Grain N Offtake (kg/ha N)

Site	Variety	Fertiliser N applied (kg/ha N)							Mean	cv%
		0	**40**	**100**	**150**	**200**	**250**	**300**		
Boxworth 2003	Malacca	49.05	67.66	103.07	130.18	134.25	149.00	142.82	110.86	4.1
	Mercia	52.97	76.69	108.95	131.45	138.16	142.81	146.89	113.99	
	Riband	44.60	72.75	96.26	130.25	130.00	131.46	136.16	105.92	
	Xi19	49.58	71.77	103.58	130.11	141.15	158.92	149.49	114.94	
	Mean	49.05	72.22	102.97	130.50	135.89	145.55	143.84		
	sed	7.493 (N rate) 8.156 (interactions) 3.719 (varieties at same N rate)							1.406	
		0	**40**	**100**	**150**	**200**	**250**	**300**	**Mean**	**cv%**
Boxworth 2004	Avalon	64.94	87.75	114.12	127.11	141.63	150.19	160.70	120.92	5.4
	Malacca	75.86	102.69	122.66	151.16	160.74	(165.15)	181.93	137.17	
	Riband	78.96	112.83	129.63	142.65	149.36	159.29	168.75	134.49	
	Solstice	81.30	108.38	134.41	159.76	178.50	188.28	198.33	149.85	
	Mean	75.26	102.91	125.20	145.17	157.56	165.73	177.43		
	sed	2.791 (N rate) 5.908 (interactions) 6.013 (varieties at same N rate) *(Values in brackets are estimates)*							2.273	
		0	**40**	**100**	**150**	**200**	**250**	**300**	**Mean**	**cv%**
Terrington 2004	Hereward	56.68	69.79	126.44	144.69	162.37	178.68	181.74	131.48	6.3
	Mercia	55.71	82.05	123.57	149.84	154.47	160.18	164.40	127.17	
	Riband	56.68	68.33	116.60	133.76	149.55	168.39	159.73	121.86	
	Xi19	62.26	75.43	115.37	128.96	159.83	181.62	183.95	129.63	
	Mean	57.83	73.90	120.50	139.31	156.55	172.22	172.46		
	sed	5.276 (N rate) 7.735 (interactions) 6.531 (varieties at same N rate)							2.468	

		0	**40**	**80**	**120**	**160**	**200**	**240**	**Mean**	**cv%**
Rosemaund 2004	Einstein	73.96	87.18	120.86	143.61	172.49	179.34	191.63	138.44	5.1
	Mercia	(52.98)	(74.31)	108.54	(119.94)	139.61	144.74	149.73	112.84	
	Option	70.32	95.39	117.62	136.36	145.84	158.93	158.18	126.09	
	Riband	62.55	88.25	101.61	127.75	146.62	161.55	165.51	121.98	
	Mean	64.95	86.28	112.16	131.91	151.14	161.14	166.26		
	sed	2.603 (N rate) 5.207 (interactions) N/A (varieties at same N rate) *(Values in brackets are estimates)*							1.968	

		0	**40**	**100**	**160**	**220**	**280**	**340**	**Mean**	**cv%**
High Mowthorpe 2004	Avalon	23.00	28.43	62.91	89.63	103.97	115.06	117.69	77.24	
	Einstein	27.45	32.02	66.77	102.35	123.46	136.37	126.54	87.85	
	Hereward	21.97	35.85	65.54	84.28	109.92	119.06	121.94	79.79	9.4
	Riband	21.55	32.28	64.80	88.44	102.01	119.60	118.46	78.16	
	Mean	23.49	32.15	65.01	91.17	109.84	122.52	121.16		
	sed		5.597 (N rate)	7.742 (interactions)		6.176 (varieties at same N rate)			2.334	

		0	**40**	**100**	**160**	**220**	**280**	**340**	**Mean**	**cv%**
Terrington 2005	Avalon	37.14	64.62	95.49	127.39	143.86	158.57	168.41	113.64	
	Malacca	39.17	68.59	98.12	129.18	158.84	176.02	177.44	121.05	
	Mercia	38.70	61.50	100.68	128.96	149.22	169.81	163.63	116.07	5.1
	Solstice	44.04	73.25	100.72	137.79	166.12	184.88	192.74	128.51	
	Mean	39.76	66.99	98.75	130.83	154.51	172.32	175.56		
	sed		4.897 (N rate)	6.508 (interactions)		4.950 (varieties at same N rate)			1.871	

		0	**40**	**100**	**160**	**220**	**280**	**340**	**Mean**	**cv%**
Rosemaund 2005	Avalon	45.35	66.01	93.07	126.37	146.98	159.41	168.39	115.08	
	Einstein	49.10	60.84	105.00	138.95	163.20	180.11	185.01	126.03	
	Mercia	48.96	61.47	94.57	124.49	144.07	156.26	161.39	113.03	5.7
	Xi19	43.73	58.62	85.07	125.96	152.97	171.66	177.92	116.56	
	Mean	46.78	61.74	94.43	128.94	151.81	166.86	173.18		
	sed		2.731 (N rate)	5.462 (interactions)		N/A (varieties at same N rate)			2.064	

		0	**40**	**100**	**160**	**220**	**280**	**340**	**Mean**	**cv%**
High Mowthorpe 2005	Avalon	75.90	92.44	129.73	165.65	181.13	186.44	194.97	146.61	
	Einstein	82.11	96.34	134.63	175.62	196.56	198.94	203.89	155.44	
	Mercia	75.66	97.28	125.84	161.86	178.09	178.46	190.05	143.89	3.5
	Xi19	85.06	105.32	140.88	173.29	189.29	205.85	215.38	159.30	
	Mean	79.68	97.85	132.77	169.11	186.27	192.42	201.07		
	sed		4.975 (N rate)	6.244 (interactions)		4.356 (varieties at same N rate)			1.647	

		0	40	100	160	220	280	340	Mean	cv%
Essex 2005	Avalon	138.06	134.21	149.32	154.22	156.34	154.53	151.31	148.29	6.4
	Malacca	127.48	133.39	132.69	149.36	149.05	148.53	142.96	140.49	
	Mercia	131.59	135.61	152.85	150.32	152.79	146.36	142.93	144.93	
	Solstice	140.25	159.68	165.28	179.28	175.94	172.78	164.54	165.39	
	Mean	134.34	140.72	150.04	158.81	158.53	155.55	150.43		
	sed	8.35 (N rate) 10.76 (interactions) 7.84 (varieties at same N rate)							2.96	

Recovery of applied N in grain (% of N applied)

Site	Variety	Fertiliser N applied (kg/ha N)						Mean	cv%
		40	100	150	200	250	300		
Boxworth 2003	Malacca	46.5	54.0	54.1	42.6	40.0	31.3	44.7	
	Mercia	59.3	56.0	52.3	42.6	35.9	31.3	46.2	
	Riband	70.4	51.7	57.1	42.7	34.7	30.5	47.9	
	Xi19	55.5	54.0	53.7	45.8	43.7	33.3	47.7	15.3
	Mean	57.9	53.9	54.3	43.4	38.6	31.6		
	sed	13.43 (N rate) 14.35 (interactions) 5.83 (varieties at same N rate)						2.38	
Boxworth 2004		**40**	**100**	**150**	**200**	**250**	**300**	**Mean**	**cv%**
	Avalon	57.0	49.2	41.4	38.3	34.1	31.9	42.0	
	Malacca	67.1	46.8	50.2	42.4	(36.8)	35.4	46.5	
	Riband	84.7	50.7	42.5	35.2	32.1	29.9	45.8	
	Solstice	67.7	53.1	52.3	48.6	42.8	39.0	50.6	35.4
	Mean	69.1	49.9	46.6	41.1	36.5	34.1		
	sed	5.39 (N rate) 12.75 (interactions) 13.35 (varieties at same N rate) *(Values in brackets are estimates)*						5.45	
		40	**100**	**150**	**200**	**250**	**300**	**Mean**	**cv%**
Terrington 2004	Hereward	32.8	69.8	58.7	52.8	48.8	41.7	50.8	
	Mercia	65.9	67.9	62.8	49.4	41.8	36.2	54.0	
	Riband	29.1	59.9	51.4	46.4	44.7	34.3	44.3	24.0
	Xi19	32.9	53.1	44.5	48.8	47.7	40.6	44.6	
	Mean	40.2	62.7	54.3	49.4	45.8	38.2		
	sed	4.30 (N rate) 9.28 (interactions) 9.49 (varieties at same N rate)						3.87	
		40	**80**	**120**	**160**	**200**	**240**	**Mean**	**cv%**
Rosemaund 2004	Einstein	33.0	58.6	58.0	61.6	52.7	49.0	52.2	
	Mercia	*	*	*	*	*	*	*	
	Option	62.7	59.1	55.0	47.2	44.3	36.6	50.8	
	Riband	64.2	48.8	54.3	52.5	49.5	42.9	52.1	22.6
	Mean	53.3	55.5	55.8	53.8	48.8	42.8		
	sed	5.50 (N rate) 9.52 (interactions) N/A (varieties at same N rate)						3.89	

		40	100	160	220	280	340	Mean	cv%
High Mowthorpe 2004	Avalon	13.6	39.9	41.6	36.8	32.9	27.8	32.1	
	Einstein	11.4	39.3	46.8	43.6	38.9	29.1	34.9	
	Hereward	34.7	43.6	38.9	40.0	34.7	29.4	36.9	25.7
	Riband	26.8	43.2	41.8	36.6	35.0	28.5	35.3	
	Mean	21.6	41.5	42.3	39.2	35.4	28.7		
	sed	2.50 (N rate)		6.79 (interactions)	7.29 (varieties at same N rate)			2.98	
		40	**100**	**160**	**220**	**280**	**340**	**Mean**	**cv%**
Terrington 2005	Avalon	68.7	58.3	56.4	48.5	43.4	38.6	52.3	
	Malacca	73.6	59.0	56.3	54.4	48.9	40.7	55.5	
	Mercia	57.0	62.0	56.4	50.2	46.8	36.7	51.5	12.0
	Solstice	73.0	56.7	58.6	55.5	50.3	43.7	56.3	
	Mean	68.1	59.0	56.9	52.2	47.3	39.9		
	sed	5.21 (N rate)		6.93 (interactions)	5.29 (varieties at same N rate)			2.16	
		40	**100**	**160**	**220**	**280**	**340**	**Mean**	**cv%**
Rosemaund 2005	Avalon	51.6	47.7	50.6	46.2	40.7	36.2	45.5	
	Einstein	29.4	55.9	56.2	51.9	46.8	40.0	46.7	
	Mercia	31.3	45.6	47.2	43.2	38.3	33.1	39.8	16.3
	Xi19	37.2	41.3	51.4	49.7	45.7	39.5	44.1	
	Mean	37.4	47.6	51.3	47.7	42.9	37.2		
	sed	2.93 (N rate)		5.85 (interactions)	N/A (varieties at same N rate)			2.39	
		40	**100**	**160**	**220**	**280**	**340**	**Mean**	**cv%**
High Mowthorpe 2005	Avalon	41.4	53.8	56.1	47.8	39.5	35.0	45.6	
	Einstein	35.6	52.5	58.4	52.0	41.7	35.8	46.0	
	Mercia	54.1	50.2	53.9	46.6	36.7	33.6	45.8	15.6
	Xi19	50.7	55.8	55.1	47.4	43.1	38.3	48.4	
	Mean	45.4	53.1	55.9	48.4	40.3	35.7		
	sed	7.87 (N rate)		9.39 (interactions)	5.92 (varieties at same N rate)			2.42	

		40	100	160	220	280	340	Mean	cv%
Essex 2005	Avalon	-9.6	11.3	10.1	8.3	5.9	3.9	5.0	
	Malacca	14.8	5.2	13.7	9.8	7.5	4.6	9.3	
	Mercia	10.0	21.3	13.0	9.6	5.3	3.3	10.4	
	Solstice	48.6	25.0	24.4	16.2	11.6	7.1	22.2	111.9
	Mean	15.9	15.7	15.3	11.0	7.6	4.7		
	sed	12.66 (N rate) 15.69 (interactions) 10.69 (varieties at same N rate)						4.36	

Specific weight (kg/hl)

Site	Variety	Fertiliser N applied (kg/ha N)							Mean	cv%
		0	40	100	150	200	250	300		
Boxworth 2003	Malacca	72.9	75.3	75.8	75.7	76.0	74.1	72.9	74.7	1.1
	Mercia	73.6	78.2	78.3	79.0	79.1	77.2	76.3	77.4	
	Riband	72.1	76.0	76.3	77.0	77.0	74.7	73.0	75.2	
	Xi19	73.0	76.9	76.6	76.3	77.3	75.5	74.5	75.7	
	Mean	72.9	76.6	76.8	77.0	77.3	75.4	74.2		
	sed	0.428 (N rate) 0.717 (interactions) 0.664 (varieties at same N rate)							0.251	
Boxworth 2004		**0**	**40**	**100**	**150**	**200**	**250**	**300**	**Mean**	**cv%**
	Avalon	73.6	74.0	74.4	74.4	75.4	74.9	75.1	74.6	0.6
	Malacca	73.3	74.0	74.2	74.5	74.4	74.6	75.2	74.3	
	Riband	73.2	73.9	73.9	74.3	74.1	74.3	74.6	74.0	
	Solstice	73.9	74.5	75.1	75.8	75.8	75.9	76.1	75.3	
	Mean	73.5	74.1	74.4	74.8	74.9	74.9	75.3		
	sed	0.193 (N rate) 0.363 (interactions) 0.355 (varieties at same N rate)							0.134	
		0	**40**	**100**	**150**	**200**	**250**	**300**	**Mean**	**cv%**
Terrington 2004	Hereward	63.7	63.8	64.5	73.7	71.6	71.3	73.4	68.8	7.8
	Mercia	67.2	64.1	69.3	64.2	70.4	65.7	69.5	67.2	
	Riband	62.0	64.9	64.5	68.9	66.8	67.6	67.2	66.0	
	Xi19	62.9	64.1	63.4	62.3	67.0	68.2	68.9	65.2	
	Mean	64.0	64.2	65.4	67.3	68.9	68.2	69.8		
	sed	1.335 (N rate) 3.905 (interactions) 4.237 (varieties at same N rate)							1.601	
		0	**40**	**80**	**120**	**160**	**200**	**240**	**Mean**	**cv%**
Rosemaund 2004	Einstein	72.5	72.7	73.4	73.8	74.3	74.0	73.6	73.5	1.3
	Mercia	73.8	74.1	75.1	75.1	74.5	74.3	74.0	74.4	
	Option	71.7	72.6	73.4	71.5	73.5	73.0	72.0	72.5	
	Riband	70.6	71.6	71.6	72.2	71.7	72.4	72.1	71.7	
	Mean	72.1	72.7	73.4	73.2	73.5	73.4	73.0		
	sed	(N rate) (interactions) N/A (varieties at same N rate)								

		0	**40**	**100**	**160**	**220**	**280**	**340**	**Mean**	**cv%**
High Mowthorpe 2004	Avalon	63.2	65.3	67.1	72.6	71.1	67.0	69.3	68.0	
	Einstein	66.1	66.4	70.3	72.8	70.5	71.2	67.9	69.3	
	Hereward	67.6	67.3	71.5	71.8	70.4	69.6	70.5	69.8	3.8
	Riband	63.6	65.3	68.7	70.5	68.3	69.9	69.4	68.0	
	Mean	65.1	66.0	69.4	71.9	70.1	69.4	69.3		
	sed	1.978 (N rate)	2.718 (interactions)	2.152 (varieties at same N rate)					0.814	
		0	**40**	**100**	**160**	**220**	**280**	**340**	**Mean**	**cv%**
Terrington 2005	Avalon	72.0	72.7	74.0	74.4	74.4	74.8	74.0	73.8	
	Malacca	71.2	72.2	73.1	74.1	75.2	75.2	74.7	73.7	
	Mercia	74.0	74.1	77.0	77.6	78.0	78.9	78.0	76.8	1.3
	Solstice	73.8	75.0	75.4	77.6	78.7	79.1	78.5	76.9	
	Mean	72.8	73.5	74.9	75.9	76.6	77.0	76.3		
	sed	0.586 (N rate)	0.916 (interactions)	0.813 (varieties at same N rate)					0.307	
		0	**40**	**100**	**160**	**220**	**280**	**340**	**Mean**	**cv%**
Rosemaund 2005	Avalon	74.7	74.7	75.3	77.6	77.4	78.1	77.6	76.5	
	Einstein	74.3	75.0	75.7	77.0	77.5	77.4	77.5	76.4	
	Mercia	75.0	76.3	77.0	78.5	79.0	79.2	79.5	77.8	1.0
	Xi19	75.2	74.4	74.9	76.9	77.8	77.0	77.1	76.2	
	Mean	74.8	75.1	75.7	77.5	77.9	77.9	77.9		
	sed	0.302 (N rate)	0.604 (interactions)	N/A (varieties at same N rate)					0.228	
		0	**40**	**100**	**160**	**220**	**280**	**340**	**Mean**	**cv%**
High Mowthorpe 2005	Avalon	72.0	72.0	73.1	73.7	73.2	72.7	73.1	72.8	
	Einstein	73.3	74.0	73.9	74.9	74.8	75.0	74.9	74.4	
	Mercia	73.9	74.8	75.3	75.6	76.5	76.0	75.8	75.4	0.8
	Xi19	71.8	72.8	72.9	73.8	73.6	72.6	73.1	73.0	
	Mean	72.7	73.4	73.8	74.5	74.5	74.1	74.2		
	sed	0.310 (N rate)	0.530 (interactions)	0.497 (varieties at same N rate)					0.188	

		0	40	100	160	220	280	340	Mean	cv%
Essex 2005	Avalon	74.0	75.5	73.5	74.6	74.5	74.3	73.9	74.3	1.1
	Malacca	73.7	74.1	73.4	73.8	73.8	73.9	72.8	73.6	
	Mercia	75.3	77.1	76.4	77.1	77.5	77.1	76.3	76.7	
	Solstice	76.0	76.6	77.0	77.9	77.4	76.8	75.6	76.8	
	Mean	74.7	75.8	75.1	75.9	75.8	75.5	74.6		
	sed	0.523 (N rate)		0.804 (interactions)		0.705 (varieties at same N rate)			0.267	

Appendix 3. Nopt for grain yield by parallel curve fitting (Design 1)

Site	Variety	Nopt kg/ha N (se in brackets)							
		3:1	4:1	5:1	6:1	7:1	8:1	9:1	10:1
Boxworth 2003	Malacca	207 (26)	196 (23)	185 (20)	175 (18)	165 (17)	157 (16)	148 (15)	140 (15)
	Mercia	192 (21)	181 (19)	172 (18)	162 (17)	154 (16)	146 (15)	138 (14)	131 (14)
	Riband	191 (20)	181 (18)	172 (17)	164 (16)	156 (15)	148 (15)	141 (14)	134 (14)
	Xi19	215 (28)	203 (24)	192 (21)	183 (19)	173 (17)	164 (16)	156 (15)	148 (15)
	Site	201 (11)	190 (11)	180 (11)	170 (11)	162 (12)	153 (12)	145 (12)	138 (12)
Boxworth 2004	Avalon	>300	>300	>300	241 (90)	190 (34)	161 (20)	142 (14)	127 (11)
	Malacca	>300	295 (181)	228 (50)	196 (26)	175 (17)	159 (13)	146 (11)	135 (9)
	Riband	177 (14)	163 (11)	152 (10)	142 (8)	135 (8)	127 (8)	121 (7)	115 (7)
	Solstice	>300	>300	271 (110)	221 (40)	193 (23)	174 (15)	159 (12)	146 (10)
	Site	>300	238 (42)	205 (18)	182 (11)	165 (9)	152 (9)	140 (9)	131 (8)
Terrington 2004	Hereward	253 (28)	242 (24)	232 (21)	222 (19)	212 (17)	203 (15)	194 (14)	184 (14)
	Mercia	213 (16)	204 (14)	196 (14)	188 (13)	180 (13)	172 (12)	164 (12)	157 (12)
	Riband	237 (23)	227 (20)	217 (18)	207 (16)	198 (15)	189 (14)	179 (13)	171 (13)
	Xi19	286 (51)	272 (42)	258 (36)	245 (30)	232 (26)	220 (22)	208 (19)	198 (17)
	Site	243 (15)	233 (12)	223 (10)	213 (9)	203 (9)	194 (9)	186 (9)	176 (10)
Rosemaund 2004	Einstein	183 (9)	179 (8)	174 (8)	170 (7)	165 (7)	161 (7)	157 (7)	152 (7)
	Mercia	147 (9)	141 (8)	135 (8)	128 (8)	122 (8)	116 (8)	110 (8)	104 (8)
	Option	152 (7)	147 (7)	143 (7)	138 (7)	134 (7)	130 (7)	125 (7)	121 (7)
	Riband	170 (8)	165 (8)	160 (8)	155 (7)	150 (7)	145 (7)	140 (7)	136 (7)
	Site	164 (6)	159 (6)	154 (7)	149 (7)	144 (7)	139 (7)	134 (8)	129 (8)
High Mowthorpe 2004	Avalon	252 (>opt)	243 (>opt)	234 (>opt)	225 (>opt)	215 (>opt)	206 (>opt)	197 (>opt)	188 (>opt)
	Einstein	255 (>opt)	247 (>opt)	240 (>opt)	233 (>opt)	225 (>opt)	218 (>opt)	210 (>opt)	203 (>opt)
	Hereward	261 (>opt)	252 (>opt)	243 (>opt)	234 (>opt)	225 (>opt)	217 (>opt)	208 (>opt)	199 (>opt)
	Riband	237 (>opt)	231 (>opt)	224 (>opt)	217 (>opt)	210 (>opt)	203 (>opt)	196 (>opt)	189 (>opt)
	Site	250 (>opt)	242 (>opt)	235 (>opt)	227 (>opt)	219 (>opt)	211 (>opt)	203 (>opt)	195 (>opt)

Terrington 2005	Avalon	272 (44)	249 (31)	230 (23)	214 (18)	200 (15)	188 (13)	178 (12)	168 (11)
	Malacca	282 (50)	257 (34)	237 (25)	221 (19)	207 (16)	195 (14)	184 (12)	174 (11)
	Mercia	237 (23)	222 (18)	209 (15)	197 (13)	187 (11)	178 (11)	169 (10)	162 (9)
	Solstice	>340	302 (69)	272 (44)	249 (30)	230 (23)	214 (18)	201 (15)	188 (13)
	Site	278 (32)	253 (19)	234 (13)	218 (9)	204 (8)	192 (8)	181 (8)	172 (8)
Rosemaund 2005	Avalon	257 (27)	246 (24)	235 (21)	224 (20)	214 (18)	204 (17)	195 (17)	186 (16)
	Einstein	266 (24)	257 (21)	248 (19)	239 (18)	230 (17)	222 (16)	214 (15)	206 (15)
	Mercia	247 (25)	236 (22)	225 (20)	215 (19)	204 (18)	195 (17)	186 (16)	177 (16)
	Xi19	300 (47)	287 (40)	274 (34)	261 (29)	249 (27)	237 (23)	227 (21)	216 (19)
	Site	267 (17)	255 (14)	245 (12)	234 (11)	224 (11)	219 (11)	205 (12)	196 (12)
High Mowthorpe 2005	Avalon	241 (18)	227 (15)	215 (13)	203 (12)	192 (11)	182 (10)	172 (10)	164 (9)
	Einstein	262 (20)	249 (16)	237 (14)	226 (12)	215 (11)	205 (10)	196 (10)	187 (9)
	Mercia	229 (14)	217 (13)	206 (11)	195 (11)	185 (10)	176 (9)	168 (9)	160 (9)
	Xi19	264 (22)	249 (18)	236 (16)	223 (13)	212 (12)	201 (11)	191 (10)	182 (10)
	Site	249 (11)	235 (9)	223 (8)	211 (7)	201 (8)	191 (8)	181 (8)	173 (8)
Essex 2005	Avalon	0	0	0	0	0	0	0	0
	Malacca	0	0	0	0	0	0	0	0
	Mercia	0	0	0	0	0	0	0	0
	Solstice	0	0	0	0	0	0	0	0
	Site								
Mean (old)		225	215	205	192	181	171	162	154
Mean (modern)		258	246	229	215	203	192	183	174

Note: Means exclude Essex 2005

Appendix 4. Nopt for grain yield by individual curve fitting (Design 1)

Site	Variety	Nopt kg/ha N (se in brackets)							
		3:1	4:1	5:1	6:1	7:1	8:1	9:1	10:1
Boxworth 2003	Malacca	208 (40)	199 (32)	190 (25)	181 (21)	172 (17)	164 (14)	156 (13)	148 (12)
	Mercia	189 (20)	176 (18)	165 (18)	155 (18)	149 (19)	138 (18)	130 (18)	123 (18)
	Riband	186 (33)	174 (29)	163 (29)	153 (29)	145 (29)	137 (29)	129 (28)	123 (27)
	Xi19	214 (75)	206 (64)	198 (55)	190 (47)	182 (42)	174 (38)	167 (35)	159 (32)
Boxworth 2004	Avalon	>300	>300	252 (174)	216 (37)	189 (16)	169 (13)	152 (12)	138 (12)
	Malacca	263 (117)	233 (52)	211 (28)	194 (18)	179 (15)	166 (15)	155 (15)	145 (15)
	Riband	178 (41)	156 (22)	141 (18)	130 (17)	121 (16)	113 (16)	107 (15)	101 (14)
	Solstice	>300	>300	249 (86)	215 (29)	192 (15)	175 (11)	161 (10)	149 (9)
Terrington 2004	Hereward	252 (124)	241 (100)	231 (81)	222 (65)	212 (52)	203 (42)	194 (34)	185 (28)
	Mercia	212 (22)	201 (17)	190 (14)	180 (13)	171 (13)	163 (13)	154 (13)	143 (13)
	Riband	236 (>opt)	226 (>opt)	217 (>opt)	208 (>opt)	199 (>opt)	191 (>opt)	182 (>opt)	174 (>opt)
	Xi19	265 (231)	256 (223)	247 (216)	238 (208)	230 (200)	221 (193)	212 (185)	203 (177)
Rosemaund 2004	Einstein	183 (147)	180 (145)	178 (142)	175 (140)	172 (137)	168 (135)	165 (132)	162 (130)
	Mercia	140 (12)	133 (19)	126 (8)	120 (7)	113 (7)	107 (7)	101 (7)	95 (7)
	Option	153 (>opt)	148 (>opt)	144 (>opt)	139 (>opt)	135 (>opt)	131 (>opt)	127 (>opt)	122 (>opt)
	Riband	169 (22)	159 (16)	151 (13)	143 (12)	136 (12)	129 (12)	123 (12)	117 (12)
High Mowthorpe 2004	Avalon	252 (>opt)	242 (>opt)	233 (>opt)	224 (>opt)	214 (>opt)	204 (>opt)	195 (>opt)	186 (>opt)
	Einstein	256 (>opt)	250 (>opt)	244 (>opt)	238 (>opt)	232 (>opt)	226 (>opt)	219 (>opt)	213 (>opt)
	Hereward	261 (>opt)	251 (>opt)	241 (>opt)	231 (>opt)	222 (>opt)	212 (>opt)	203 (>opt)	193 (>opt)
	Riband	235 (>opt)	228 (>opt)	220 (>opt)	213 (>opt)	206 (>opt)	198 (>opt)	191 (>opt)	184 (>opt)
Terrington 2005	Avalon	>340	>340	249 (81)	216 (32)	194 (20)	178 (16)	165 (15)	154 (15)
	Malacca	314 (284)	271 (98)	243 (50)	222 (30)	205 (22)	191 (19)	179 (19)	169 (19)
	Mercia	233 (13)	223 (12)	215 (11)	206 (11)	198 (11)	191 (11)	184 (12)	177 (12)
	Solstice	>340	>340	283 (89)	254 (45)	232 (26)	214 (18)	199 (15)	184 (14)
Rosemaund 2005	Avalon	292 (150)	259 (69)	234 (38)	215 (25)	198 (21)	184 (20)	172 (20)	161 (20)

	Einstein	264 (83)	256 (72)	247 (62)	239 (53)	232 (46)	224 (40)	216 (34)	209 (30)
	Mercia	247 (40)	236 (31)	225 (25)	214 (20)	204 (16)	194 (13)	185 (11)	176 (10)
	Xi19	283 (>opt)	274 (>opt)	266 (>opt)	258 (>opt)	249 (>opt)	241 (>opt)	233 (>opt)	224 (>opt)
High Mowthorpe 2005	Avalon	243 (18)	226 (15)	212 (13)	199 (12)	187 (11)	176 (10)	166 (10)	157 (9)
	Einstein	254 (35)	246 (30)	237 (26)	229 (22)	221 (19)	213 (17)	206 (14)	198 (13)
	Mercia	228 (19)	213 (15)	199 (14)	187 (13)	177 (14)	167 (14)	158 (14)	149 (13)
	Xi19	258 (29)	247 (23)	236 (18)	226 (14)	216 (12)	207 (10)	198 (9)	189 (8)
Essex 2005	Avalon	0	0	0	0	0	0	0	0
	Malacca	0	0	0	0	0	0	0	0
	Mercia	0	0	0	0	0	0	0	0
	Solstice	0	0	0	0	0	0	0	0
Mean (old)		230	218	200	186	175	165	156	147
Mean (modern)		254	244	228	216	205	196	187	178

Note: Means exclude Essex 2005

Appendix 5. Yield at Nopt (Yopt) by parallel curve fitting (Design 1)

Site	Variety	Yopt (t/ha N)							
		3:1	4:1	5:1	6:1	7:1	8:1	9:1	10:1
Boxworth 2003	Malacca	6.94	6.90	6.85	6.80	6.73	6.67	6.60	6.52
	Mercia	7.03	6.99	6.95	6.90	6.85	6.79	6.72	6.65
	Riband	6.78	6.74	6.70	6.66	6.61	6.55	6.49	6.42
	Xi19	7.30	7.26	7.21	7.16	7.09	7.02	6.96	6.88
Boxworth 2004	Avalon	>7.39	>7.39	>7.39	7.08	6.75	6.53	6.37	6.23
	Malacca	>9.16	9.14	8.84	8.66	8.53	8.41	8.30	8.19
	Riband	8.91	8.86	8.81	8.75	8.71	8.65	8.60	8.54
	Solstice	>10.01	>10.01	9.98	9.70	9.52	9.38	9.25	9.13
Terrington 2004	Hereward	9.28	9.24	9.20	9.14	9.08	9.01	8.93	8.84
	Mercia	8.57	8.54	8.50	8.46	8.41	8.35	8.28	8.22
	Riband	8.98	8.95	8.90	8.85	8.79	8.72	8.64	8.56
	Xi19	9.94	9.89	9.83	9.76	9.67	9.58	9.48	9.38
Rosemaund 2004	Einstein	10.63	10.62	10.59	10.57	10.54	10.51	10.47	10.43
	Mercia	7.95	7.93	7.90	7.86	7.82	7.78	7.73	7.67
	Option	9.56	9.54	9.53	9.50	9.47	9.44	9.40	9.37
	Riband	9.76	9.75	9.73	9.70	9.67	9.63	9.59	9.55
High Mowthorpe 2004	Avalon	5.33	5.30	5.26	5.22	5.16	5.09	5.02	4.94
	Einstein	6.60	6.57	6.54	6.51	6.46	6.41	6.35	6.28
	Hereward	5.87	5.84	5.80	5.76	5.70	5.64	5.57	5.49
	Riband	6.11	6.09	6.06	6.03	5.99	5.94	5.88	5.82
Terrington 2005	Avalon	8.35	8.27	8.19	8.10	8.01	7.92	7.83	7.74
	Malacca	8.97	8.89	8.80	8.71	8.62	8.53	8.44	8.34
	Mercia	8.45	8.40	8.34	8.28	8.21	8.15	8.07	8.00
	Solstice	>9.89	9.79	9.65	9.53	9.40	9.28	9.17	9.05

Rosemaund 2005	Avalon	7.98	7.95	7.90	7.84	7.77	7.70	7.62	7.53
	Einstein	9.39	9.36	9.32	9.27	9.21	9.15	9.08	9.01
	Mercia	7.78	7.74	7.69	7.64	7.56	7.49	7.42	7.33
	Xi19	8.88	8.83	8.78	8.70	8.63	8.54	8.45	8.35
High Mowthorpe 2005	Avalon	9.90	9.85	9.80	9.73	9.66	9.59	9.50	9.42
	Einstein	11.61	11.57	11.51	11.45	11.38	11.31	11.23	11.14
	Mercia	10.09	10.05	10.00	9.94	9.88	9.81	9.74	9.66
	Xi19	11.35	11.30	11.24	11.17	11.10	11.02	10.93	10.85
Essex 2005	Avalon	7.31	7.31	7.31	7.31	7.31	7.31	7.31	7.31
	Malacca	6.91	6.91	6.91	6.91	6.91	6.91	6.91	6.91
	Mercia	7.26	7.26	7.26	7.26	7.26	7.26	7.26	7.26
	Solstice	8.28	8.28	8.28	8.28	8.28	8.28	8.28	8.28
Mean (old)		8.09	8.05	8.01	7.94	7.87	7.79	7.72	7.64
Mean (modern)		9.09	9.05	8.98	8.90	8.82	8.74	8.66	8.58

Note: Means exclude Essex 2005

Appendix 6. Grain protein content at Nopt from parallel curve fitting (Design 1)

		Grain protein (%)							
Site	**Variety**	**3:1**	**4:1**	**5:1**	**6:1**	**7:1**	**8:1**	**9:1**	**10:1**
Boxworth 2003	Malacca	13.62	13.51	13.38	13.24	13.07	12.93	12.74	12.56
	Mercia	13.36	13.22	13.09	12.93	12.79	12.63	12.47	12.32
	Riband	13.17	13.07	12.97	12.86	12.74	12.60	12.46	12.32
	Xi19	13.53	13.39	13.23	13.09	12.92	12.75	12.59	12.42
Boxworth 2004	Avalon	>14.10	>14.10	>14.10	14.10	13.61	13.34	13.16	13.01
	Malacca	>13.21	13.21	12.66	12.28	12.00	11.78	11.60	11.45
	Riband	11.07	10.94	10.85	10.78	10.73	10.67	10.64	10.60
	Solstice	>13.01	>13.01	13.01	12.65	12.31	12.02	11.77	11.54
Terrington 2004	Hereward	12.85	12.80	12.75	12.68	12.60	12.52	12.41	12.28
	Mercia	12.59	12.54	12.49	12.43	12.36	12.29	12.20	12.11
	Riband	11.98	11.94	11.89	11.83	11.75	11.67	11.55	11.43
	Xi19	12.48	12.34	12.18	12.01	11.82	11.64	11.44	11.26
Rosemaund 2004	Einstein	11.21	11.12	11.01	10.92	10.80	10.70	10.60	10.48
	Mercia	11.37	11.25	11.13	10.98	10.86	10.74	10.61	10.49
	Option	10.27	10.18	10.11	10.02	9.95	9.88	9.79	9.71
	Riband	10.48	10.36	10.24	10.12	9.99	9.86	9.72	9.61
High Mowthorpe 2004	Avalon	14.23	14.13	14.01	13.87	13.70	13.53	13.33	13.12
	Einstein	13.19	13.14	13.09	13.02	12.93	12.84	12.72	12.60
	Hereward	13.26	13.14	13.01	12.87	12.73	12.59	12.44	12.28
	Riband	12.11	11.98	11.83	11.67	11.51	11.34	11.18	11.01
Terrington 2005	Avalon	12.77	12.56	12.33	12.10	11.86	11.63	11.42	11.20
	Malacca	12.91	12.66	12.40	12.14	11.88	11.64	11.39	11.16
	Mercia	12.31	12.08	11.85	11.63	11.43	11.24	11.04	10.88
	Solstice	>12.90	12.90	12.64	12.36	12.07	11.78	11.52	11.24

Rosemaund 2005	Avalon	13.54	13.43	13.29	13.13	12.95	12.76	12.56	12.35
	Einstein	12.76	12.66	12.56	12.44	12.31	12.18	12.05	11.90
	Mercia	13.13	12.97	12.80	12.62	12.41	12.22	12.02	11.81
	Xi19	13.17	13.07	12.96	12.82	12.66	12.48	12.31	12.10
High Mowthorpe 2005	Avalon	12.71	12.62	12.51	12.38	12.24	12.08	11.90	11.74
	Einstein	11.61	11.57	11.51	11.45	11.37	11.28	11.18	11.07
	Mercia	11.98	11.86	11.74	11.59	11.44	11.29	11.15	10.99
	Xi19	11.99	11.82	11.68	11.52	11.39	11.24	11.11	10.99
Essex 2005	Avalon	13.09	13.09	13.09	13.09	13.09	13.09	13.09	13.09
	Malacca	12.94	12.94	12.94	12.94	12.94	12.94	12.94	12.94
	Mercia	13.05	13.05	13.05	13.05	13.05	13.05	13.05	13.05
	Solstice	12.43	12.43	12.43	12.43	12.43	12.43	12.43	12.43
Mean (old)		**12.45**	**12.33**	**12.20**	**12.19**	**12.02**	**11.87**	**11.71**	**11.56**
Mean (modern)		**12.53**	**12.50**	**12.39**	**12.22**	**12.05**	**11.89**	**11.73**	**11.57**

Note: Means exclude Essex 2005

Appendix 7. Alveograph data

Boxworth 2003

		Fertiliser N applied (kg/ha N)								
Variate	Variety	0	40	100	150	200	250	300	Mean	cv%
W	Malacca	119.7	125.3	142.7	184.0	207.0	196.7	221.7	171.0	9.8
	Xi19	102.7	101.3	141.7	171.7	191.0	201.3	183.3	156.1	
	Mean	111.2	113.3	142.2	177.8	199.0	199.0	202.5		
	sed	9.61 (N rate) 13.34 (interactions) 13.07 (varieties at same N rate)							4.94	
P/L	Malacca	0.48	0.52	0.51	0.45	0.40	0.45	0.42	0.46	27.0
	Xi19	0.40	0.39	0.43	0.45	0.48	0.35	0.44	0.42	
	Mean	0.44	0.45	0.47	0.45	0.44	0.40	0.43		
	sed	0.057 (N rate) 0.089 (interactions) 0.097 (varieties at same N rate)							0.037	
Pmax	Malacca	41.7	46.3	47.3	55.0	56.0	57.3	59.0	51.8	12.9
	Xi19	38.7	38.0	47.3	53.7	58.7	53.7	53.0	49.0	
	Mean	40.2	42.2	47.3	54.3	57.3	55.5	56.0		
	sed	2.99 (N rate) 4.80 (interactions) 5.32 (varieties at same N rate)							2.01	
L	Malacca	88.0	91.0	102.3	124.3	140.0	128.3	142.7	116.7	15.0
	Xi19	97.7	98.7	112.3	122.3	126.0	151.3	121.7	118.6	
	Mean	92.8	94.8	107.3	123.3	133.0	139.8	132.2		
	sed	7.62 (N rate) 12.70 (interactions) 14.37 (varieties at same N rate)							5.43	
G	Malacca	20.8	21.2	22.4	24.8	26.3	25.2	26.6	23.9	7.8
	Xi19	22.0	22.0	23.6	24.5	25.0	27.4	24.5	24.1	
	Mean	21.4	21.6	23.0	24.7	25.6	26.3	25.5		
	sed	0.80 (N rate) 1.34 (interactions) 1.52 (varieties at same N rate)							0.58	
P200	Malacca	50.7	46.7	50.0	48.7	50.0	52.3	50.0	49.8	5.5
	Xi19	42.0	42.7	45.0	46.7	47.3	48.0	50.7	46.0	
	Mean	46.3	44.7	47.5	47.7	48.7	50.2	50.3		
	sed	1.76 (N rate) 2.32 (interactions) 2.14 (varieties at same N rate)							0.81	

Boxworth 2004

Variate	Variety	Fertiliser N applied (kg/ha N)							Mean	cv%
		0	40	100	150	200	250	300		
W	Solstice	131.0	137.7	138.7	146.7	130.7	156.0	163.7	143.5	9.7
	sed	11.39 (N rate)								
P/L	Solstice	0.67	0.57	0.57	0.44	0.32	0.40	0.38	0.48	12.0
	sed	0.0467 (N rate)								
P	Solstice	56.3	54.3	54.0	51.0	43.3	51.3	52.7	51.9	9.5
	sed	4.01(N rate)								
L	Solstice	83.3	95.7	95.3	117.3	138.3	128.0	139.3	113.9	5.6
	sed	5.23 (N rate)								
G	Solstice	20.4	21.8	21.7	24.1	26.2	25.2	26.3	23.7	2.9
	sed	0.55 (N rate)								
IE	Solstice	41.0	40.7	42.0	42.0	40.3	42.7	42.0	41.5	5.4
	sed	1.84 (N rate)								

High Mowthorpe 2004

Variate	Variety	Fertiliser N applied (kg/ha N) 0	40	100	160	220	280	340	Mean	cv%
W	Einstein	107.0	90.3	113.7	144.0	140.3	147.0	169.7	130.3	15.6
	sed	16.55 (N rate)								
P/L	Einstein	0.83	1.01	1.01	1.15	1.18	1.34	1.35	1.12	30.4
	sed	0.279 (N rate)								
P	Einstein	55.3	51.0	59.0	76.3	74.0	80.7	86.7	69.0	12.7
	sed	7.17 (N rate)								
L	Einstein	66.7	53.7	66.3	67.3	63.0	60.7	68.7	63.8	23.9
	sed	12.46 (N rate)								
G	Einstein	18.1	16.2	17.9	18.3	17.6	17.3	18.3	17.7	11.8
	sed	1.70 (N rate)								
IE	Einstein	35.0	39.0	36.7	34.0	36.7	34.3	34.7	35.8	9.0
	sed	2.62(N rate)								

Rosemaund 2004

		Fertiliser N applied (kg/ha N)								
Variate	**Variety**	**0**	**40**	**100**	**160**	**220**	**280**	**340**	**Mean**	**cv%**
W	Einstein	70.3	87.0	109.7	123.7	162.7	170.0	203.0	132.3	10.6
	sed	11.50 (N rate)								
P/L	Einstein	1.18	1.44	1.32	0.87	0.86	0.93	0.69	1.04	
	sed	0.252 (N rate)								29.6
P	Einstein	45.7	56.0	61.0	56.0	64.0	67.3	67.0	59.6	13.5
	sed	6.57 (N rate)								
L	Einstein	42.7	40.0	46.3	65.0	77.3	76.7	98.0	63.7	17.9
	sed	9.30 (N rate)								
G	Einstein	14.5	14.0	15.1	17.9	19.5	19.5	22.0	17.5	9.2
	sed	1.31 (N rate)								
IE	Einstein	27.0	13.7	47.0	46.7	50.0	49.7	51.7	40.8	28.8
	sed	9.60 (N rate)								

Terrington 2004

Variate	Variety	Fertiliser N applied (kg/ha N)							Mean	cv%
		0	40	100	150	200	250	300		
W	Hereward	73.3	77.0	145.0	165.7	165.0	124.7	179.3	132.9	26.9
	Xi19	56.0	63.3	93.7	113.3	134.7	163.7	145.3	110.0	
	Mean	64.7	70.2	119.3	139.5	149.8	144.2	162.3		
	sed	18.91 (N rate)	26.69 (interactions)	26.64 (varieties at same N rate)					10.07	
P/L	Hereward	0.46	0.46	0.31	0.36	0.43	0.45	0.38	0.41	18.3
	Xi19	0.37	0.54	0.65	0.67	0.50	0.68	0.67	0.58	
	Mean	0.42	0.50	0.48	0.51	0.47	0.57	0.52		
	sed	0.102 (N rate)	0.115 (interactions)	0.074 (varieties at same N rate)					0.028	
P	Hereward	51.0	33.3	40.7	49.3	53.3	42.7	50.0	45.8	25.5
	Xi19	27.0	35.0	43.7	53.0	50.0	64.3	60.0	47.6	
	Mean	39.0	34.2	42.2	51.2	51.7	53.5	55.0		
	sed	8.74 (N rate)	11.12 (interactions)	9.73 (varieties at same N rate)					3.68	
L	Hereward	70.0	72.3	137.3	140.0	134.3	99.7	136.0	112.8	20.0
	Xi19	73.0	66.0	70.0	83.3	97.7	98.3	91.3	82.8	
	Mean	71.5	69.2	103.7	111.7	116.0	99.0	113.7		
	sed	13.83 (N rate)	17.86 (interactions)	15.98 (varieties at same N rate)					6.04	
G	Hereward	18.5	18.8	26.0	26.3	25.7	22.0	26.0	23.3	10.3
	Xi19	19.0	18.0	18.6	20.2	21.8	22.0	21.1	20.1	
	Mean	18.7	18.4	22.3	23.3	23.8	22.0	23.5		
	sed	1.59 (N rate)	2.05 (interactions)	1.82 (varieties at same N rate)					0.69	
IE	Hereward	45.0	42.3	48.7	45.3	43.0	44.3	50.3	45.6	15.2
	Xi19	34.7	33.3	40.7	35.3	36.3	42.4	40.0	37.5	
	Mean	39.8	37.8	44.7	40.3	39.7	43.4	45.2		
	sed	3.18 (N rate)	4.85 (interactions)	5.17 (varieties at same N rate)					1.95	

Rosemaund 2005

Variate	Variety	Fertiliser N applied (kg/ha N)							Mean	cv%
		0	40	100	160	220	280	340		
W	Einstein	82.0	75.0	121.0	172.0	191.3	221.7	221.0	154.9	17.6
	Xi19	81.3	70.3	90.7	188.7	215.7	253.3	251.7	164.5	
	Mean	81.7	72.7	105.8	180.3	203.5	237.5	236.3		
	sed	16.19 (N rate) 22.89 (interactions) N/A (varieties at same N rate)							8.65	
P/L	Einstein	1.38	1.46	1.21	0.98	0.54	0.58	0.54	0.96	32.0
	Xi19	0.68	0.75	0.89	0.76	0.89	0.88	0.93	0.83	
	Mean	1.03	1.11	1.05	0.87	0.72	0.73	0.73		
	sed	0.165 (N rate) 0.233 (interactions) N/A (varieties at same N rate)							0.088	
P	Einstein	49.7	51.0	60.3	67.7	58.3	63.7	61.3	58.9	12.9
	Xi19	39.7	38.0	47.0	64.7	75.0	78.3	81.0	60.5	
	Mean	44.7	44.5	53.7	66.2	66.7	71.0	71.2		
	sed	4.43 (N rate) 6.27 (interactions) N/A (varieties at same N rate)							2.37	
L	Einstein	42.3	36.3	51.0	70.0	110.3	114.0	120.0	77.7	21.3
	Xi19	59.3	51.7	53.7	86.3	84.7	97.0	88.0	74.4	
	Mean	50.8	44.0	52.3	78.2	97.5	105.5	104.0		
	sed	9.37 (N rate) 13.25 (interactions) N/A (varieties at same N rate)							5.01	
G	Einstein	14.2	13.3	15.8	18.6	23.4	23.7	24.2	19.0	10.3
	Xi19	17.1	15.9	16.3	20.7	20.4	21.8	20.9	19.0	
	Mean	15.7	14.6	16.1	19.7	21.9	22.7	22.5		
	sed	1.13 (N rate) 1.60 (interactions) N/A (varieties at same N rate)							0.61	
IE	Einstein	16.0	14.7	50.7	53.7	51.7	55.3	55.0	42.4	22.9
	Xi19	44.7	43.3	45.0	54.3	54.4	57.7	57.7	51.0	
	Mean	30.3	29.0	47.8	54.0	53.1	56.5	56.4		
	sed	6.17 (N rate) 8.73 (interactions) N/A (varieties at same N rate)							3.30	

Terrington 2005

Variate	Variety	Fertiliser N applied (kg/ha N)							Mean	cv%
		0	40	100	160	220	280	340		
W	Malacca	75.7	85.0	119.3	197.0	262.7	284.7	282.7	186.7	9.6
	Solstice	81.7	86.7	114.7	171.7	250.3	276.3	290.0	181.6	
	Mean	78.7	85.8	117.0	184.3	256.5	280.5	286.3		
	sed	10.58 (N rate) 14.72 (interactions) 14.47 (varieties at same N rate)							5.47	
P/L	Malacca	1.17	1.07	1.25	1.17	0.97	0.74	0.82	1.03	14.9
	Solstice	1.64	1.31	1.40	0.93	0.70	0.67	0.78	1.06	
	Mean	1.40	1.19	1.33	1.05	0.84	0.70	0.80		
	sed	0.132 (N rate) 0.160 (interactions) 0.127 (varieties at same N rate)							0.048	
P	Malacca	46.8	47.3	61.3	78.7	87.0	81.7	83.3	69.5	7.8
	Solstice	56.3	52.3	64.7	67.3	79.7	78.0	81.7	68.6	
	Mean	51.6	49.8	63.0	73.0	83.3	79.8	82.5		
	sed	3.71 (N rate) 4.84 (interactions) 4.40 (varieties at same N rate)							1.66	
L	Malacca	39.7	45.0	51.0	70.7	90.3	110.7	113.0	74.3	12.8
	Solstice	34.7	40.3	46.7	76.7	99.3	119.3	108.0	75.0	
	Mean	37.2	42.7	48.8	73.7	94.8	115.0	110.5		
	sed	9.20 (N rate) 10.73 (interactions) 7.81 (varieties at same N rate)							2.95	
G	Malacca	13.9	14.9	15.8	18.7	21.1	23.4	23.4	18.7	5.7
	Solstice	13.1	14.1	15.1	19.4	22.1	24.3	23.1	18.7	
	Mean	13.5	14.5	15.5	19.0	21.6	23.8	23.3		
	sed	1.00 (N rate) 1.18 (interactions) 0.87 (varieties at same N rate)							0.33	
IE	Malacca	0.0	34.0	32.0	53.7	54.7	37.7	55.3	38.2	44.4
	Solstice	0.0	31.3	45.7	50.3	53.7	54.0	58.0	41.9	
	Mean	0.0	32.7	38.8	52.0	54.2	45.8	56.7		
	sed	7.46 (N rate) 12.69 (interactions) 14.52 (varieties at same N rate)							5.49	

Appendix 8. Raw data and ANOVA (Design 2)

Grain yield (t/ha @ 85% DM)

Site and base N rate (kg/ha N)	Late N strategy	Rate of late N (kg/ha) 0	40	80	120	Mean	Significance (p<0.05)
Boxworth 2003	Control	6.88					
(xxx)	AN at GS39		7.02	6.85	6.90	6.92	
	Foliar urea 10%		7.00	7.22	6.87	7.03	AN at GS39 vs Rest ns
	Foliar urea 20%		6.99	6.64	6.89	6.84	Foliar urea 10% vs 20% ns
	AN + urea 10%		7.09	6.98	6.93	7.00	Foliar urea vs AN+urea ns
	AN + urea 20%		7.14	7.06	6.94	7.04	
	Mean		7.05	6.95	6.91		
	sed		0.091 (N rates)	0.204 (interactions)		0.118	
	cv %		4.2				
Terrington 2003	Control	10.64					
	AN at GS39		10.83	10.66	10.65	10.71	
	Foliar urea 10%		10.49	10.20	10.26	10.32	AN at GS39 vs Rest <0.05
	Foliar urea 20%		10.14	10.26	10.35	10.25	Foliar urea 10% vs 20% ns
	AN + urea 10%		10.48	10.69	10.75	10.64	Foliar urea vs AN+urea <0.05
	AN + urea 20%		10.41	10.90	10.51	10.61	
	Mean		10.47	10.54	10.50		
	sed		0.101 (N rates)	0.226 (interactions)		0.130	
	cv %		3.0				
Rosemaund 2003	Control	8.35					
	AN at GS39		7.62	8.72	8.55	8.30	
	Foliar urea 10%		8.32	8.40	8.33	8.35	AN at GS39 vs Rest ns
	Foliar urea 20%		8.45	8.21	8.24	8.30	Foliar urea 10% vs 20% ns
	AN + urea 10%		8.63	8.33	8.32	8.43	Foliar urea vs AN+urea ns
	AN + urea 20%		8.49	8.57	8.39	8.48	
	Mean		8.30	8.45	8.37		
	sed		0.108 (N rates)	0.242 (interactions)		0.140	
	cv %		4.1				

Boxworth 2004	Control	9.57					
	AN at GS39		9.97	9.96	9.82	9.92	
	Foliar urea 10%		9.69	9.78	9.83	9.77	AN at GS39 vs Rest ns
	Foliar urea 20%		9.64	9.78	9.93	9.78	Foliar urea 10% vs 20% ns
	AN + urea 10%		9.59	9.74	9.94	9.75	Foliar urea vs AN+urea ns
	AN + urea 20%		9.84	9.97	10.07	9.96	
	Mean		9.75	9.85	9.92		
	sed		0.084 (N rates)	0.188 (interactions)		0.108	
	cv %			2.7			
Terrington 2004	Control	9.95					
	AN at GS39		9.98	10.07	10.01	10.02	
	Foliar urea 10%		10.20	9.56	10.10	9.96	AN at GS39 vs Rest ns
	Foliar urea 20%		10.04	10.09	10.00	10.04	Foliar urea 10% vs 20% ns
	AN + urea 10%		10.11	10.15	10.24	10.17	Foliar urea vs AN+urea <0.05
	AN + urea 20%		9.91	10.51	10.38	10.27	
	Mean		10.05	10.08	10.15		
	sed		0.094 (N rates)	0.210 (interactions)		0.121	
	cv %			2.9			
Rosemaund 2004	Control	9.56					
	AN at GS39		9.88	9.68	9.70	9.75	
	Foliar urea 10%		9.49	9.56	9.65	9.56	AN at GS39 vs Rest ns
	Foliar urea 20%		9.71	9.35	9.67	9.58	Foliar urea 10% vs 20% ns
	AN + urea 10%		9.75	9.74	9.91	9.80	Foliar urea vs AN+urea >0.05
	AN + urea 20%		9.80	9.67	9.67	9.71	
	Mean		9.73	9.60	9.72		
	sed		0.065 (N rates)	0.145 (interactions)		0.084	
	cv %			2.1			

High Mowthorpe 2004	Control	6.33					
	AN at GS39		6.73	6.14	6.56	6.48	
	Foliar urea 10%		6.54	6.13	6.15	6.27	AN at GS39 vs Rest ns
	Foliar urea 20%		6.76	6.43	6.38	6.52	Foliar urea 10% vs 20% ns
	AN + urea 10%		6.22	6.33	6.75	6.43	Foliar urea vs AN+urea ns
	AN + urea 20%		6.32	6.51	6.27	6.37	
	Mean		6.52	6.31	6.42		
	sed		0.139 (N rates)	0.310 (interactions)		0.179	
	cv %			6.8			
Essex 2005	Control	11.19					
	AN at GS39		11.18	11.39	11.29	11.29	
	Foliar urea 10%		11.17	11.12	11.14	11.14	AN at GS39 vs Rest ns
	Foliar urea 20%		11.15	10.92	11.09	11.05	Foliar urea 10% vs 20% <0.05
	AN + urea 10%		11.29	11.41	11.31	11.34	Foliar urea vs AN+urea <0.05
	AN + urea 20%		11.18	11.04	11.21	11.14	
	Mean		11.19	11.18	11.21		
	sed		0.068 (N rates)	0.153 (interactions)		0.089	
	cv %			1.9			
High Mowthorpe 2005	Control	11.67					
	AN at GS39		11.96	11.88	11.98	11.94	
	Foliar urea 10%		11.55	11.47	11.01	11.34	AN at GS39 vs Rest <0.05
	Foliar urea 20%		11.60	11.49	11.40	11.50	Foliar urea 10% vs 20% <0.05
	AN + urea 10%		11.65	11.66	11.60	11.64	Foliar urea vs AN+urea <0.05
	AN + urea 20%		11.86	11.86	11.65	11.79	
	Mean		11.73	11.67	11.53		
	sed		0.067 (N rates)	0.150 (interactions)		0.086	
	cv %			1.8			

Grain protein (at 100% DM)

Site and base N rate (kg/ha N)	Late N strategy	Rate of late N (kg/ha)					Significance (p<0.05)
		0	40	80	120	Mean	
Boxworth 2003	Control	13.95					
(xxx)	AN at GS39		14.54	14.76	14.92	14.74	
	Foliar urea 10%		15.01	15.36	15.99	15.45	AN at GS39 vs Rest <0.05
	Foliar urea 20%		14.85	15.25	15.97	15.36	Foliar urea 10% vs 20% ns
	AN + urea 10%		14.58	15.12	15.20	14.96	Foliar urea vs AN+urea <0.05
	AN + urea 20%		14.78	15.13	15.39	15.10	
	Mean		14.75	15.13	15.49		
	sed		0.063 (N rates)	0.140 (interactions)		0.081	
	cv %		1.3				
Terrington 2003	Control	8.73					
	AN at GS39		10.09	9.45	9.71	9.75	
	Foliar urea 10%		9.76	10.61	11.35	10.57	AN at GS39 vs Rest <0.05
	Foliar urea 20%		9.97	10.34	10.96	10.43	Foliar urea 10% vs 20% ns
	AN + urea 10%		9.92	10.26	10.78	10.32	Foliar urea vs AN+urea <0.05
	AN + urea 20%		9.25	10.55	10.28	10.03	
	Mean		9.80	10.24	10.62		
	sed		0.193 (N rates)	0.433 (interactions)		0.250	
	cv %		6.1				
Rosemaund 2003	Control	12.00					
	AN at GS39		12.54	12.80	13.27	12.87	
	Foliar urea 10%		13.54	13.25	14.85	13.88	AN at GS39 vs Rest <0.05
	Foliar urea 20%		12.91	13.81	14.18	13.63	Foliar urea 10% vs 20% ns
	AN + urea 10%		12.97	13.60	14.62	13.73	Foliar urea vs AN+urea ns
	AN + urea 20%		13.00	13.77	14.58	13.78	
	Mean		13.00	13.44	14.30		
	sed		0.232 (N rates)	0.519 (interactions)		0.300	
	cv %		5.5				

Boxworth 2004	Control	12.64					
	AN at GS39		12.95	13.10	13.28	13.11	
	Foliar urea 10%		13.44	13.95	14.01	13.80	AN at GS39 vs Rest <0.05
	Foliar urea 20%		13.54	13.31	14.04	13.63	Foliar urea 10% vs 20% ns
	AN + urea 10%		13.14	13.31	13.50	13.31	Foliar urea vs AN+urea <0.05
	AN + urea 20%		13.32	13.45	13.48	13.42	
	Mean		13.28	13.42	13.66		
	sed		0.107 (N rates)	0.239 (interactions)		0.138	
	cv %			2.5			
Terrington 2004	Control	11.96					
	AN at GS39		12.61	12.47	12.73	12.60	
	Foliar urea 10%		12.47	13.00	13.72	13.06	AN at GS39 vs Rest <0.05
	Foliar urea 20%		12.53	12.91	13.95	13.13	Foliar urea 10% vs 20% ns
	AN + urea 10%		12.33	13.04	13.07	12.81	Foliar urea vs AN+urea <0.05
	AN + urea 20%		12.48	12.83	12.95	12.75	
	Mean		12.48	12.85	13.28		
	sed		0.138 (N rates)	0.308 (interactions)		0.178	
	cv %			3.4			
Rosemaund 2004	Control	10.78					
	AN at GS39		11.84	12.00	12.47	12.10	
	Foliar urea 10%		11.70	11.98	12.98	12.22	AN at GS39 vs Rest ns
	Foliar urea 20%		11.59	12.30	13.02	12.30	Foliar urea 10% vs 20% ns
	AN + urea 10%		11.53	12.28	13.34	12.38	Foliar urea vs AN+urea ns
	AN + urea 20%		11.83	12.43	13.04	12.43	
	Mean		11.70	12.20	12.97		
	sed		0.157 (N rates)	0.351 (interactions)		0.203	
	cv %			4.1			

High Mowthorpe 2004	Control	12.34					
	AN at GS39		13.44	13.54	14.01	13.66	
	Foliar urea 10%		13.41	13.51	14.28	13.73	AN at GS39 vs Rest ns
	Foliar urea 20%		13.38	13.62	14.32	13.78	Foliar urea 10% vs 20% ns
	AN + urea 10%		13.34	13.78	14.68	13.93	Foliar urea vs AN+urea ns
	AN + urea 20%		13.45	13.84	13.72	13.67	
	Mean		13.40	13.66	14.20		
	sed		0.128 (N rates)	0.286 (interactions)		0.165	
	cv %			3.0			
Essex 2005	Control	13.47					
	AN at GS39		14.02	14.01	13.74	13.92	
	Foliar urea 10%		14.24	14.75	15.11	14.70	AN at GS39 vs Rest <0.05
	Foliar urea 20%		13.79	14.18	14.82	14.26	Foliar urea 10% vs 20% ns
	AN + urea 10%		13.81	14.29	14.59	14.23	Foliar urea vs AN+urea ns
	AN + urea 20%		13.97	14.59	14.55	14.37	
	Mean		13.97	14.36	14.56		
	sed		0.119 (N rates)	0.267 (interactions)		0.154	
	cv %			2.7			
High Mowthorpe 2005	Control	11.19					
	AN at GS39		11.77	11.93	11.98	11.89	
	Foliar urea 10%		12.13	12.33	13.22	12.56	AN at GS39 vs Rest <0.05
	Foliar urea 20%		11.80	12.24	12.77	12.27	Foliar urea 10% vs 20% ns
	AN + urea 10%		12.00	12.47	12.27	12.45	Foliar urea vs AN+urea <0.05
	AN + urea 20%		12.03	12.07	12.57	12.22	
	Mean		11.94	12.21	12.56		
	sed		0.094 (N rates)	0.209 (interactions)		0.121	
	cv %			2.4			

Grain N offtake (kg/ha N)

Site and base N rate (kg/ha N)	Late N strategy	Rate of late N (kg/ha) 0	40	80	120	Mean	Significance (p<0.05)
Boxworth 2003	Control	143.0					
(xxx)	AN at GS39		152.1	150.8	153.6	152.2	
	Foliar urea 10%		156.6	165.1	163.8	161.8	AN at GS39 vs Rest <0.05
	Foliar urea 20%		154.6	150.9	164.1	156.6	Foliar urea 10% vs 20% ns
	AN + urea 10%		154.0	157.4	156.9	156.1	Foliar urea vs AN+urea ns
	AN + urea 20%		157.2	159.3	159.3	158.6	
	Mean		154.9	156.7	159.5		
	sed		2.02 (N rates)	4.52 (interactions)		2.61	
	cv %		4.1				
Terrington 2003	Control	163.1					
	AN at GS39		191.8	176.6	181.9	183.4	
	Foliar urea 10%		179.6	189.8	204.3	191.2	AN at GS39 vs Rest ns
	Foliar urea 20%		178.1	186.3	199.2	187.8	Foliar urea 10% vs 20% ns
	AN + urea 10%		182.4	192.5	203.4	192.8	Foliar urea vs AN+urea ns
	AN + urea 20%		169.3	201.8	189.5	186.9	
	Mean		180.2	189.4	195.7		
	sed		4.41(N rates)	9.87 (interactions)		5.70	
	cv %		7.6				
Rosemaund 2003	Control	149.3					
	AN at GS39		142.1	166.4	169.3	159.2	
	Foliar urea 10%		167.8	165.9	184.4	172.7	AN at GS39 vs Rest <0.05
	Foliar urea 20%		162.7	169.1	174.2	168.6	Foliar urea 10% vs 20% ns
	AN + urea 10%		166.8	168.8	181.4	172.3	Foliar urea vs AN+urea ns
	AN + urea 20%		164.5	175.9	183.3	174.6	
	Mean		160.8	169.2	178.5		
	sed		3.38 (N rates)	7.55 (interactions)		4.36	
	cv %		6.4				

Boxworth 2004	Control	180.36					
	AN at GS39		192.55	194.49	194.29	193.78	
	Foliar urea 10%		194.14	203.46	205.32	200.97	AN at GS39 vs Rest ns
	Foliar urea 20%		194.61	194.03	207.91	198.85	Foliar urea 10% vs 20% ns
	AN + urea 10%		187.87	193.23	199.88	193.66	Foliar urea vs AN+urea ns
	AN + urea 20%		195.46	200.01	202.26	199.24	
	Mean		192.93	197.04	201.93		
	sed		2.16 (N rates)	4.83 (interactions)		2.79	
	cv %			3.5			
Terrington 2004	Control	177.4					
	AN at GS39		187.5	187.3	190.0	188.3	
	Foliar urea 10%		190.0	185.4	206.7	194.0	AN at GS39 vs Rest <0.05
	Foliar urea 20%		187.7	194.2	208.0	196.6	Foliar urea 10% vs 20% ns
	AN + urea 10%		185.9	197.5	199.5	194.3	Foliar urea vs AN+urea ns
	AN + urea 20%		184.5	200.9	200.6	195.4	
	Mean		187.1	193.0	201.0		
	sed		2.73 (N rates)	6.11 (interactions)		3.53	
	cv %			4.5			
Rosemaund 2004	Control	180.9					
	AN at GS39		205.2	203.7	212.3	207.1	
	Foliar urea 10%		194.7	200.9	219.5	205.0	AN at GS39 vs Rest ns
	Foliar urea 20%		197.4	201.7	221.0	206.7	Foliar urea 10% vs 20% ns
	AN + urea 10%		197.3	209.7	231.8	212.9	Foliar urea vs AN+urea <0.05
	AN + urea 20%		203.3	210.7	221.0	211.7	
	Mean		199.6	205.3	221.1		
	sed		2.98 (N rates)	6.67 (interactions)		3.85	
	cv %			4.6			

High Mowthorpe 2004	Control	116.4					
	AN at GS39		134.4	123.9	137.4	131.9	
	Foliar urea 10%		130.9	123.4	130.8	128.4	AN at GS39 vs Rest ns
	Foliar urea 20%		135.0	130.7	136.1	133.9	Foliar urea 10% vs 20% ns
	AN + urea 10%		123.7	130.0	148.0	133.9	Foliar urea vs AN+urea ns
	AN + urea 20%		126.9	134.5	128.1	129.9	
	Mean		130.2	128.5	136.1		
	sed		2.97(N rates)	6.65 (interactions)		3.84	
	cv %			7.3			
Essex 2005	Control	224.8					
	AN at GS39		233.6	238.0	231.2	234.3	
	Foliar urea 10%		237.1	244.6	251.0	244.2	AN at GS39 vs Rest <0.05
	Foliar urea 20%		229.5	230.9	245.2	235.2	Foliar urea 10% vs 20% <0.05
	AN + urea 10%		232.5	243.3	246.1	240.6	Foliar urea vs AN+urea ns
	AN + urea 20%		232.8	240.2	243.1	238.7	
	Mean		233.1	239.4	243.3		
	sed		2.52 (N rates)	5.64 (interactions)		3.26	
	cv %			3.4			
High Mowthorpe 2005	Control	194.8					
	AN at GS39		210.0	211.3	214.1	211.8	
	Foliar urea 10%		208.6	210.9	217.2	212.2	AN at GS39 vs Rest ns
	Foliar urea 20%		204.2	209.7	217.1	210.3	Foliar urea 10% vs 20% ns
	AN + urea 10%		208.5	216.8	212.1	212.5	Foliar urea vs AN+urea ns
	AN + urea 20%		212.8	213.5	218.3	214.9	
	Mean		208.8	212.5	215.8		
	sed		1.94 (N rates)	4.35 (interactions)		2.51	
	cv %			2.9			

Nitrogen recovery (% of N applied)

Site and base N rate (kg/ha N)	Late N strategy	Rate of late N (kg/ha) 0	40	80	120	Mean	Significance (p<0.05)
Boxworth 2003	Control						
(xxx)	AN at GS39		25.3	10.3	9.7	15.1	
	Foliar urea 10%		36.2	29.6	18.1	28.0	AN at GS39 vs Rest <0.05
	Foliar urea 20%		30.5	10.6	18.3	19.8	Foliar urea 10% vs 20% ns
	AN + urea 10%		29.9	19.2	12.7	20.6	Foliar urea vs AN+urea ns
	AN + urea 20%		37.6	21.9	13.2	24.6	
	Mean		31.9	18.4	14.4		
	sed		3.45 (N rates)	7.71 (interactions)		4.45	
	cv %	50.6					
Terrington 2003	Control						
	AN at GS39		71.5	16.8	15.6	34.7	
	Foliar urea 10%		41.1	33.3	34.3	36.2	AN at GS39 vs Rest ns
	Foliar urea 20%		37.3	28.9	30.1	32.1	Foliar urea 10% vs 20% ns
	AN + urea 10%		48.2	36.7	33.6	39.5	Foliar urea vs AN+urea ns
	AN + urea 20%		15.4	48.4	22.0	28.6	
	Mean		42.7	32.8	27.1		
	sed		9.46 (N rates)	21.16 (interactions)		12.22	
	cv %	87.5					
Rosemaund 2003	Control						
	AN at GS39		-17.9	21.4	16.7	6.7	
	Foliar urea 10%		46.4	20.9	29.3	32.2	AN at GS39 vs Rest <0.05
	Foliar urea 20%		33.6	24.8	20.8	26.4	Foliar urea 10% vs 20% ns
	AN + urea 10%		43.8	24.5	26.8	31.7	Foliar urea vs AN+urea ns
	AN + urea 20%		38.1	33.4	26.1	32.5	
	Mean		28.8	25.0	23.9		
	sed		6.68 (N rates)	14.94 (interactions)		8.62	
	cv %	81.6					

Boxworth 2004	Control						
	AN at GS39		30.5	17.7	11.6	19.9	
	Foliar urea 10%		34.5	28.9	20.8	28.0	AN at GS39 vs Rest ns
	Foliar urea 20%		35.6	17.1	23.0	25.2	Foliar urea 10% vs 20% ns
	AN + urea 10%		18.8	16.1	16.3	17.0	Foliar urea vs AN+urea ns
	AN + urea 20%		37.7	24.6	18.2	26.8	
	Mean		31.4	20.9	18.0		
	sed		3.73 (N rates)	8.34 (interactions)		4.82	
	cv %			50.4			
Terrington 2004	Control						
	AN at GS39		25.3	12.4	10.5	16.1	
	Foliar urea 10%		31.5	10.0	24.4	22.0	AN at GS39 vs Rest ns
	Foliar urea 20%		25.8	21.0	25.5	24.1	Foliar urea 10% vs 20% ns
	AN + urea 10%		21.2	25.1	18.4	21.6	Foliar urea vs AN+urea ns
	AN + urea 20%		17.8	29.4	19.4	22.2	
	Mean		24.3	19.6	19.6		
	sed		4.85 (N rates)	10.85 (interactions)		6.26	
	cv %			72.4			
Rosemaund 2004	Control						
	AN at GS39		60.8	28.5	26.2	38.5	
	Foliar urea 10%		34.5	25.0	32.2	30.6	AN at GS39 vs Rest ns
	Foliar urea 20%		41.2	26.0	33.5	33.6	Foliar urea 10% vs 20% ns
	AN + urea 10%		41.1	36.0	42.4	39.8	Foliar urea vs AN+urea ns
	AN + urea 20%		56.0	37.2	33.5	42.2	
	Mean		46.7	30.5	33.6		
	sed		5.12 (N rates)	11.45 (interactions)		6.61	
	cv %			43.8			

High Mowthorpe 2004	Control						
	AN at GS39		44.8	9.3	17.4	23.9	
	Foliar urea 10%		36.2	8.7	12.0	18.9	AN at GS39 vs Rest ns
	Foliar urea 20%		46.5	17.9	16.3	26.9	Foliar urea 10% vs 20% ns
	AN + urea 10%		18.1	16.9	26.3	20.5	Foliar urea vs AN+urea ns
	AN + urea 20%		26.1	22.6	9.7	19.5	
	Mean		34.3	15.1	16.4		
	sed		4.26 (N rates)	9.53 (interactions)		5.50	
	cv %			61.4			
Essex 2005	Control						
	AN at GS39		21.9	16.5	5.3	14.6	
	Foliar urea 10%		30.6	24.7	21.8	25.7	AN at GS39 vs Rest ns
	Foliar urea 20%		11.6	7.6	17.0	12.0	Foliar urea 10% vs 20% ns
	AN + urea 10%		19.3	23.0	17.7	20.0	Foliar urea vs AN+urea ns
	AN + urea 20%		19.8	19.2	15.2	18.1	
	Mean		20.6	18.2	15.4		
	sed		4.75 (N rates)	10.62 (interactions)		6.13	
	cv %			83.0			
High Mowthorpe 2005	Control						
	AN at GS39		37.9	20.6	16.1	24.9	
	Foliar urea 10%		34.5	20.2	18.6	24.4	AN at GS39 vs Rest ns
	Foliar urea 20%		23.4	18.6	18.6	20.2	Foliar urea 10% vs 20% ns
	AN + urea 10%		34.2	27.5	14.4	25.4	Foliar urea vs AN+urea ns
	AN + urea 20%		44.9	23.4	19.6	29.3	
	Mean		35.0	22.1	17.5		
	sed		3.00 (N rates)	6.70 (interactions)		3.87	
	cv %			38.2			

Specific weight (kg/hl)

Site and base N rate (kg/ha N)	Late N strategy	Rate of late N (kg/ha) 0	40	80	120	Mean	Significance (p<0.05)
Boxworth 2003	Control	76.3					
(xxx)	AN at GS39		76.7	77.1	75.8	76.5	
	Foliar urea 10%		77.1	77.1	76.5	76.9	AN at GS39 vs Rest ns
	Foliar urea 20%		76.8	76.4	76.0	76.4	Foliar urea 10% vs 20% ns
	AN + urea 10%		76.3	77.0	76.0	76.4	Foliar urea vs AN+urea ns
	AN + urea 20%		76.7	76.6	76.8	76.7	
	Mean		76.7	76.8	76.2		
	sed		0.26 (N rates)	0.59 (interactions)		0.34	
	cv %		1.1				
Terrington 2003	Control	63.3					
	AN at GS39		65.9	63.7	65.0	64.9	
	Foliar urea 10%		65.0	64.9	64.4	64.8	AN at GS39 vs Rest ns
	Foliar urea 20%		65.5	65.5	62.3	64.4	Foliar urea 10% vs 20% ns
	AN + urea 10%		65.4	67.8	63.7	65.6	Foliar urea vs AN+urea ns
	AN + urea 20%		64.2	63.2	64.1	63.8	
	Mean		65.2	65.0	63.9		
	sed		1.47 (N rates)	3.29 (interactions)		1.90	
	cv %		7.2				
Rosemaund 2003	Control	77.3					
	AN at GS39		77.9	77.9	78.3	78.0	
	Foliar urea 10%		77.6	77.2	77.5	77.4	AN at GS39 vs Rest ns
	Foliar urea 20%		78.0	77.4	77.5	77.6	Foliar urea 10% vs 20% ns
	AN + urea 10%		78.1	77.2	74.9	76.7	Foliar urea vs AN+urea ns
	AN + urea 20%		77.6	78.2	77.0	77.6	
	Mean		77.8	77.6	77.0		
	sed		0.38 (N rates)	0.86 (interactions)		0.50	
	cv %		1.6				

Boxworth 2004	Control	75.6					
	AN at GS39		75.8	75.9	75.7	75.8	
	Foliar urea 10%		76.1	75.7	75.4	75.7	AN at GS39 vs Rest ns
	Foliar urea 20%		75.8	75.9	76.0	75.9	Foliar urea 10% vs 20% ns
	AN + urea 10%		76.0	75.8	76.1	76.0	Foliar urea vs AN+urea >0.05
	AN + urea 20%		76.1	75.9	76.0	76.0	
	Mean		76.0	75.8	75.8		
	sed		0.10 (N rates)	0.23 (interactions)		0.13	
	cv %			0.4			
Terrington 2004	Control	69.0					
	AN at GS39		67.0	70.7	69.8	69.2	
	Foliar urea 10%		70.4	68.7	67.4	68.8	AN at GS39 vs Rest ns
	Foliar urea 20%		67.5	70.0	68.9	68.8	Foliar urea 10% vs 20% ns
	AN + urea 10%		68.7	70.6	66.4	68.6	Foliar urea vs AN+urea ns
	AN + urea 20%		69.6	68.3	67.6	68.5	
	Mean		68.7	69.7	68.0		
	sed		1.12 (N rates)	2.49 (interactions)		1.44	
	cv %			5.1			
Rosemaund 2004	Control	75.0					
	AN at GS39		76.2	75.3	76.4	76.0	
	Foliar urea 10%		75.5	75.5	74.9	75.3	AN at GS39 vs Rest <0.05
	Foliar urea 20%		75.9	74.9	75.5	75.4	Foliar urea 10% vs 20% ns
	AN + urea 10%		75.3	75.9	75.6	75.6	Foliar urea vs AN+urea ns
	AN + urea 20%		75.9	75.8	75.9	75.9	
	Mean		75.8	75.5	75.6		
	sed		0.23 (N rates)	0.51 (interactions)		0.29	
	cv %			1.0			

High Mowthorpe 2004	Control	69.2					
	AN at GS39		72.1	72.2	71.9	72.1	
	Foliar urea 10%		72.0	70.4	70.2	70.9	AN at GS39 vs Rest ns
	Foliar urea 20%		70.8	71.2	70.9	71.0	Foliar urea 10% vs 20% ns
	AN + urea 10%		71.4	71.0	71.0	71.1	Foliar urea vs AN+urea ns
	AN + urea 20%		71.4	71.3	69.4	70.7	
	Mean		71.5	71.2	70.7		
	sed		0.77 (N rates)	1.72 (interactions)		1.00	
	cv %			3.4			
Essex 2005	Control	77.1					
	AN at GS39		74.7	74.9	75.4	75.0	
	Foliar urea 10%		75.3	76.3	76.2	76.0	AN at GS39 vs Rest <0.05
	Foliar urea 20%		75.6	77.2	76.8	76.5	Foliar urea 10% vs 20% ns
	AN + urea 10%		76.5	75.4	77.5	76.5	Foliar urea vs AN+urea ns
	AN + urea 20%		74.9	76.9	74.9	75.6	
	Mean		75.4	76.2	76.2		
	sed		0.57 (N rates)	1.27 (interactions)		0.74	
	cv %			2.4			
High Mowthorpe 2005	Control	75.3					
	AN at GS39		76.7	75.8	75.2	75.9	
	Foliar urea 10%		75.7	76.1	74.7	75.5	AN at GS39 vs Rest ns
	Foliar urea 20%		75.7	75.7	75.6	75.7	Foliar urea 10% vs 20% ns
	AN + urea 10%		75.1	75.9	75.2	75.4	Foliar urea vs AN+urea ns
	AN + urea 20%		75.3	75.8	75.5	75.5	
	Mean		75.7	75.9	75.3		
	sed		0.33 (N rates)	0.73 (interactions)		0.42	
	cv %			1.4			