October 2011
Cost £17.64

Project Report No. 483

Predicting grain protein to meet market requirements for breadmaking and minimise diffuse pollution from wheat production

by

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This is the final report of a 40 month project (RD-2005-3211) which started in April 2007. The work was funded by a Defra LINK project (£310,938; LK0990) and a contract for £110,005 from HGCA, with in-kind contributions from HGCA (£7,000), Bruker Optics (£82,651), Heygates Ltd (£4,462), Camgrain Stores Ltd (£54,525) and Fengrain Ltd (£54,525).

HGCA is the cereals and oilseeds division of the Agriculture and Horticulture Development Board.

CONTENTS

Abbreviations used:

AN	Ammonium nitrate
ANOVA	Analysis of Variance
BW	Boxworth
CBRI	Campden BRI
Coop	Farmer Cooperative
DM	Dry matter
DMHI	Dry matter harvest index
E	Early (sown)
EXP	Exponential
FL	Flowering
FT	Fourier Transform (algorithms)
FU	Foliar urea
GS	Growth stage
HI	Harvest Index
HH	Hand harvest
HM	High Mowthorpe
HFN	Hagberg Falling Number
L	Late (sown)
LAI	Leaf Area Index
Leco	Laboratory Instrument Company – a specific manufacturer of instruments for determination of N by the Dumas combustion method
LIN	Linear
LSD	Least significant difference
LTA	Long term average
MALNA	Managing late nitrogen applications to meet wheat protein market requirements: HGCA Project 2579 (Report No. 401)
MR	Milky ripe
N	Nitrogen
NHI	Nitrogen Harvest Index
NIR	Near Infra Red
Nobs	Number of observations
RMSD	Root mean square deviation
Rsd	Reproducibility standard deviation
Spwt	Specific weight
WP	Whole Plant

1. ABSTRACT

The aim of this project was to develop a system to aid decisions on the use of foliar sprays of urea during grain filling to boost grain protein of milling wheat crops.

Reference data totalling 1,210 measurements from six N response experiments and 246 commercial fields in East Anglia over three harvest years 2007-2009 augmented 219 data points from a previous project; these were used to calibrate Near Infra Red (NIR) assessments of moisture and nitrogen (N) in ears and whole plants at flowering and milky ripe (MR) stages. Plant N% at and after anthesis related clearly to grain N%, and hence to grain protein content at harvest. Relationships were better at the MR stage than at anthesis, and they were as good for ears alone as for whole plants. For high yielding varieties (e.g. Solstice, Einstein, Xi19) 2.0% ear N was indicative of grain with 2.28%N (13% protein), and differences from 2% ear N indicated equivalent differences in grain N%, hence 1.8% ear N related to ~12% grain protein. For low yielding varieties (e.g. Hereward) 1.8% ear N indicated 13% grain protein. Plant N could be analysed rapidly and directly by NIR (e.g. in a local laboratory) or by the Dumas method after posting samples to a remote laboratory. The predictive precision of both methods was similar. The Dumas method is widely used in many labs, so little extra capital investment may be necessary. The NIR method can be used for numerous applications, and can provide the quick turn-around required for fertiliser decisions. After testing and discarding semi-mechanistic models that took account of weather and yield forecasts, a 'best' grain protein forecasting system was developed. This system accounted for measured ear N at the MR stage, a variety factor to distinguish older varieties (e.g. Hereward) from modern higher yielding varieties, and a further factor that accounted for regional and rotational differences between trial conditions and farm conditions. Cost-benefit analysis of late urea spray strategies were conducted with or without 'best' predictions of grain protein, hence taking account of whether extra premium was expected due to a spray, and considering premium levels (plus possible deductions), expected grain production (yield x hectares) relating to the spray decision, and the cost of fertiliser (including application costs). Because of imprecision, results showed only a few circumstances in which a strategy of applying late N according to ear N analysis field-by-field and year-by-year proved better than strategies of never applying late N (when premiums are less than £20 per tonne) or always applying late N (when premiums are more than £20 per tonne). However, the benefits of ear N analysis improved when predictions were applied across a group of growers over a number of seasons (from £6 to £61/ha with different scenarios). Thus ear analysis should best be used strategically (several fields in one year, or several years on one farm), rather than tactically (for single fields in single seasons). Indeed, the farms studied here showed consistent differences in protein achievement; these may be inherent and unavoidable, or they may indicate persistent on-farm inaccuracies in N management. In either case, ear N analysis appears to offer a useful additional diagnostic tool, to augment measuring soil N and grain yield in support of good N management.

2. SUMMARY

2.1. Introduction

Foliar urea typically increases grain protein by 0.4 – 0.7% for every 40 kg/ha nitrogen (N) when applied at the milky ripe (MR) stage. The extra cost can be recouped through achieving the target grain protein (typically 13%) hence attracting extra premium payments; however, most crops have too little or too much protein for extra N to cause extra premium payments. Also, only 32% of N applied as foliar urea is recovered in the grain. The remainder is assumed to be lost, either volatilised as ammonia from the crop surface or leached as nitrate through the soil during the following winter. Given recent increases in the price of N, and heightening environmental concerns, it is increasingly important that inputs of foliar urea are used as efficiently as possible. The challenge for this project therefore was to facilitate improved decision-making on the use of late N for wheat by predicting its likely final grain protein content in time to avoid unnecessary applications. Growers currently can only do this crudely, based on previous farm performance.

2.1.1. Previous HGCA studies

The first MALNA LINK project (LK 0927/HGCA 2579; HGCA Report 401) demonstrated that the Matrix-I Near Infra Red (NIR) instrument from Bruker Optics could measure N and moisture in fresh (undried) samples of wheat at the MR stage. However, measurements of immature wheat and final grain protein in one year did not provide adequate calibrations to predict grain protein across sites and seasons because it appeared that variation in yield was of similar importance as variation in total N uptake in influencing final grain protein content.

Samples analysed from single N response experiments showed that a number of crop parameters (e.g. leaf greenness, total biomass, etc.) tended to correlate well with yield and/or final grain protein content. However, such relationships were less clear across a wide range of seasons and environments. An example of this was HGCA Project 1216 which used the chlorophyll meter (Precision-N tester); this gave good predictions of grain yield (based on measurements of flag leaves) within controlled N response experiments. However, the predictions failed when applied over a wider range of sites and environments.

Successful prediction methods for final grain protein are best tested using commercial crops with a wide range of soil types and environments. This approach was the core of the present project, and was achieved through engagement with the members of two grower led farmer Cooperatives (Coops): Fengrain and Camgrain.

2.1.2. Aim of project

The aims of the work described here were to:

a) conduct field experiments to extend the environments available to test forecasts of yield and final grain protein, and to provide plant material with a wide range of plant N concentrations for continuing development of NIR calibrations, and;
b) monitor a large number of commercial crops, in order to test the utility of the forecasting system, and also to provide plant material for extending the NIR calibrations, with a wider range of environmental influences but with a more limited range of N nutrition.

2.2. Materials and methods

2.2.1. Historic data sets

Data were available from the first MALNA project (HGCA Project Report No. 401), comprising 218 samples, spanning four harvest seasons from 2002-2005. The data included reference measurements (moisture and N determined by the Kjeldahl method) from ear and whole plant samples, harvested at the MR stage, and grain from harvest, but there were no data on crop biomass either at immature or harvest stages.

Data were also available from the HGCA Development project (data which underpinned the HGCA 'Wheat Growth Guide'; Volume III of HGCA Project Report No. 151) to guide the early conceptual development of the model, and understanding of wheat growth and N accumulation. The practical work in this project involved sampling 18 crops of Mercia winter wheat (6 sites x 3 field seasons) in order to define the typical patterns of growth and development of winter wheat in the UK.

2.2.2. Nitrogen response field experiments

Field experiments were carried out in each of three seasons to test N nutrition and geographic location (Cambridgeshire and Yorkshire, in all three seasons), sowing date (two seasons) and varietal effects. Sites, soils, varieties and treatments are shown in Summary Table 1. Applied N rates were adjusted based on soil N supply measured in spring (0-90 cm depth plus plant N uptake). Adjacent plots were drilled in duplicate for each treatment to give separate hand harvest and combine harvest plots, and a guard plot of a single variety was sown between each pair of treatment plots.

Summary Table 1. Site details for experiments at Boxworth, Cambridgeshire (BW) and High Mowthorpe, Yorkshire (HM) in harvest years 2007-2009.

Site, season and Field name	Soil	Sowing date(s)	Varieties[1]	Spring soil mineral N (kg/ha)	Applied N (kg/ha)
BW 2007 Pamplins North	chalky boulder clay	03/10/06 2/11/06	He, Xi	65	0, 110, 220, 270, 320
BW 2008 Bottom Brooks	chalky boulder clay	05/10/07 05/11/07	He, Xi	84	0, 75, 150, 225, 300
BW 2009 Brickyard Pond	chalky boulder clay	26/09/08	He, Xi, So, Ei	51	0, 110, 220, 270, 320
HM 2007 Elbow South	shallow silty clay loam over chalk	10/10/06 13/11/06	He, Xi	106	0, 90, 180, 230, 280
HM 2008 Whether Palin	shallow silty clay loam over chalk	04/10/07 06/11/07	He, Xi	100	0, 75, 150, 225, 300
HM 2009 Towthorpe	shallow silty clay loam over chalk	10/11/08	He, Xi, So, Ei	33	0, 140, 280, 320, 380

[1], Varieties: He, Hereward; Xi, Xi19; So, Solstice; Ei, Einstein

2.2.3. Commercial field sites

Fields were sampled from participating Coop members (Camgrain or Fengrain) in East Anglia in each of the three seasons. Choice of field, variety, soil type, N rate and other agronomic decisions were left to the grower. Participants were asked whether they were planning to use foliar urea, and if so, were provided with warning signs to place in field to mark the sample area, and as a reminder to switch off the sprayer so that this ‘study area’ remained untreated. At the end of the season, each grower completed a detailed questionnaire on previous and current cropping details including total N use.

2.2.4. Crop assessments

For both N response experiments and commercial crops samples were taken at flowering and MR stage. These were prepared for NIR scanning by a standard protocol in ADAS, Campden BRI or Coop labs. After scanning samples were recovered, dried, moisture content was recorded, and they were sent for N determination by the reference method (Dumas combustion procedure, using a ‘Leco’ instrument). Prior to combine harvesting, hand harvest (‘grab samples’) were taken for independent estimates of grain yield, total biomass per unit area, dry matter and N harvest indices. All plots from the ADAS N response trials were combine-harvested and yields recorded. Commercial crops were harvested by the growers, and yields were recorded from the combine or otherwise. Where possible, three grain samples were available from commercial field crops: the hand harvest sample taken by ADAS staff; a combine harvest sample from the sample area within the field (which would have no late N applied); a combine harvest sample representing the remainder of the field outside the sample area (which may, or may not have had late N applied). All N and protein results are reported on a 100% dry matter (DM) basis.

2.2.5. NIR calibrations

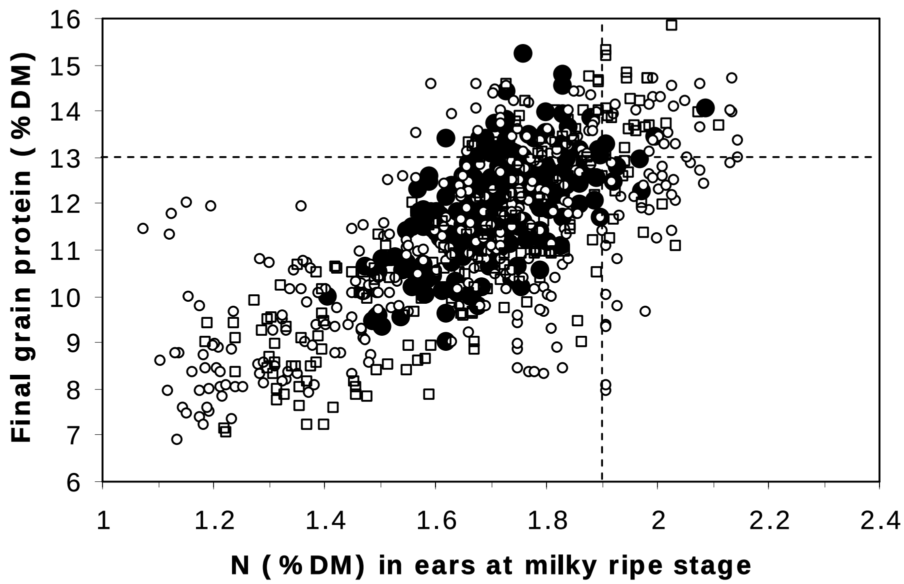
NIR predicts N and moisture in the immature plant by comparing spectra from scanned samples to measures using lab methods. In the present work, N (dry basis) and moisture in fresh plant material were matched with spectral data and added to the NIR calibration dataset developed in the first MALNA project. In addition to samples at MR, plant material was taken at flowering. Bruker Optics combined the dataset (now 2002-2009) to develop the updated NIR calibrations. These new calibrations were used to provide re-predicted values for N and moisture for the 2007- 2009 data, for use in the financial assessment of the best approach.

2.2.6. Approaches to forecasting final grain protein

Two approaches were tested for protein forecasting. Firstly, a semi-mechanistic model was developed to predict yield using the N and biomass measurements at MR, and integrating information on canopy size and senescence, radiation interception and DM growth, and DM partitioning to grain. Secondly, a statistical approach was taken whereby the full dataset was examined by regression analysis, giving best relationships between N and MC in immature plant material (both measured and NIR predicted) and final grain protein. The impacts of uncertainties associated with analysis and sampling were assessed, as was the inclusion of variety factors. Finally, financial cost-benefit analyses were carried out to determine the best forecasting strategy, taking into account the costs of investing in NIR equipment, the costs associated with N application and the potential benefits from achieving premia, as affected by the recorded yields but ignoring whether specific weight or Hagberg Falling Number targets were met. Strategies compared included those of the growers, one of always applying late N, and one of never applying late N.

2.3. Results and discussion

Overall, the relationship between final grain protein and ear N found in the first project held true in this project; ear N of ~1.9% indicated that the crop would achieve 13% grain protein (Summary Figure 1). However, there was much variation to be explained.



Summary Figure 1. Final grain protein (N x 5.7) plotted against ear N% at the milky ripe stage: Data from the previous MALNA project (□); current project field trials (○) and commercial crops (●).

2.3.1. Seasons and weather effects

A summary of data from the commercial crops is shown in Summary Table 2. The three seasons produced relatively low protein. For 5 of the 6 N response experiments only 43-88% of the long term average rainfall was experienced during the period 1st March to 31st May. However, a spring rainfall modifier (i.e. low rainfall = high protein) did not improve protein predictions.

Low temperatures during grain filling were a feature of these years, especially 2008, and were associated with increased grain yield, and hence resulted in diluted grain protein. However, it did not prove worthwhile to incorporate weather forecasts into a prediction system because of poor forecasting skill (the Met Office withdrew their seasonal forecasts during the project, due to criticism of their accuracy). Thus this project progressed on the basis that measurements of N in the plant, taken as near to harvest as possible (e.g. MR stage) would give the best chance of assessing the true N status of the crop, rather than through more mechanistic modelling.

Summary Table 2. Summary of grain protein, N uptake and N harvest index (NHI) for 246 commercial crops sampled from 2007 to 2009.

Season	G. protein sample area by ADAS (%DM)	G. protein sample area by grower (%DM)	G. protein whole field by grower (%DM)	Total N uptake (kg/ha)	Grain N offtake (kg/ha)	NHI (%)
2007						
Mean	12.4	12.4	12.7	291	199	69.0
Max	15.2	15.3	15.6	411	276	90.0
Min	10.1	10.1	9.9	160	105	45.8
Range	5.1	5.2	5.6	251	171	44.2
SD†	0.97	1.16	1.10	52.9	35.4	7.71
Nobs*	78	69	72	77	77	77
2008						
Mean	11.3	11.1	11.5	239	193	81.3
Max	13.5	12.7	13.3	327	257	87.5
Min	9.0	8.8	9.6	151	127	66.2
Range	4.5	3.9	3.7	176	130	21.2
SD	0.96	0.90	0.80	41.9	30.0	3.91
Nobs	80	74	71	80	80	80
2009						
Mean	12.2	12.0	12.4	270	195	72.6
Max	14.8	13.8	14.2	385	265	79.7
Min	10.0	9.9	10.7	170	127	61.7
Range	4.8	4.0	3.6	215	137	18.0
SD	0.93	0.86	0.63	48.3	32.1	3.66
Nobs	75	79	80	74	74	74

†, SD standard deviation; *, Number of observations

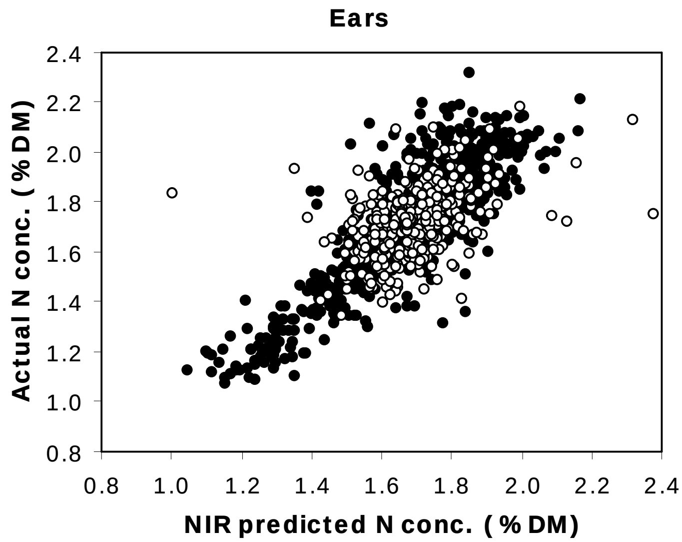
2.3.2. Comparison between field trials and commercial crops

Commercial farm samples had a smaller range of N in immature crop material, and in grain, than the field experiments (Summary Figure 1). While this was expected but not been demonstrated previously.

Of varieties accounting for more than 5% of the commercial crops, only Hereward had an average grain protein exceeding 12%. The best average ear N indicating 13% grain protein was 1.8% for Hereward, and 2.0% for modern varieties such as Solstice and Xi19.

2.3.3. NIR calibrations

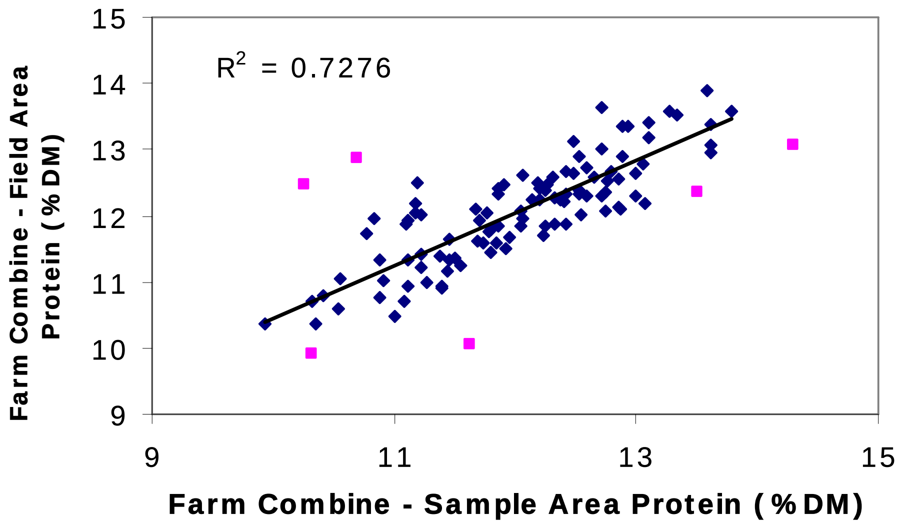
The first MALNA project built NIR calibrations on 219 immature plant samples (each of ears and whole plant, at MR stage only). These were from four seasons and only from field experiments on first wheats. The current project collected many more samples (1,210 each of ears and whole plant) representing samples both from flowering (566) and MR stage (604). Of the total, 450 were from commercial farm crops. Thus the calibrations here were based both on a wide range of N contents (by including under and over-fertilized crops from the experiments) as well as a wider range of soils, rotational positions and growing conditions seen in commercial practice. An example of NIR-predicted ear N is shown in Summary Figure 2.



Summary Figure 2. Nitrogen concentration in fresh ears measured by reference method (Dumas), plotted against N concentration predicted using an NIR calibration for data from field experiments (●) and commercial crops (○), 2007-2009.

Both the NIR and Leco measurements were affected by sampling and analytical errors. Several samples were required to increase certainty in N estimates, but this added cost. Surprisingly, errors in Leco were +/- 0.3% protein; thus single determinations of grain protein using the reference method could not reliably detect differences of 0.1% protein, a figure upon which deductions are made in commerce.

Analytical errors probably account for part of the variation in Summary Figure 1, and they limit our ability to predict grain protein from immature plants. However, within-field variability also increased this uncertainty significantly. Summary Figure 3 shows the measurements of grain protein in the whole field, compared to the sample area within that field (where no late FU was applied). Red points represent samples that could be excluded as outliers, but the remaining data are indicative of the statistical noise arising when spatial variation is added to analytical variation.



Summary Figure 3. Grain protein content (%DM) from field sample and whole field areas that did not receive late urea nitrogen, by analysis of samples from the farm combine (grower Cooperative data, 2007 to 2009).

2.3.4. Development of a forecasting system

Many 'mechanistic' models of wheat grain yield explicitly simulate many aspects of crop growth and environmental effects, but they have large prediction errors without calibration to site conditions. In this project, we developed a simpler semi-mechanistic model of grain yield, which was informed by measured total crop N and biomass at either flowering or MR.

The model first used default parameters to estimate biomass growth as a function of intercepted radiation and compared this to the measured biomass. The ratio of predicted and measured biomass was used to calculate a rate modifier for biomass gain, reflecting potential site-specific conditions and stressors (such as water and nutrients), that was then used to make a final prediction of grain yield. In this way the model used the field measurements to improve predictions and implicitly represent site effects. However, while a working model was developed successfully, its uncertainties were such that a statistical model proved more robust. Statistical models that were considered using either (i) whole plant or ears, (ii) measurements at flowering or MR, and (iii) the Leco reference or NIR methods for N content.

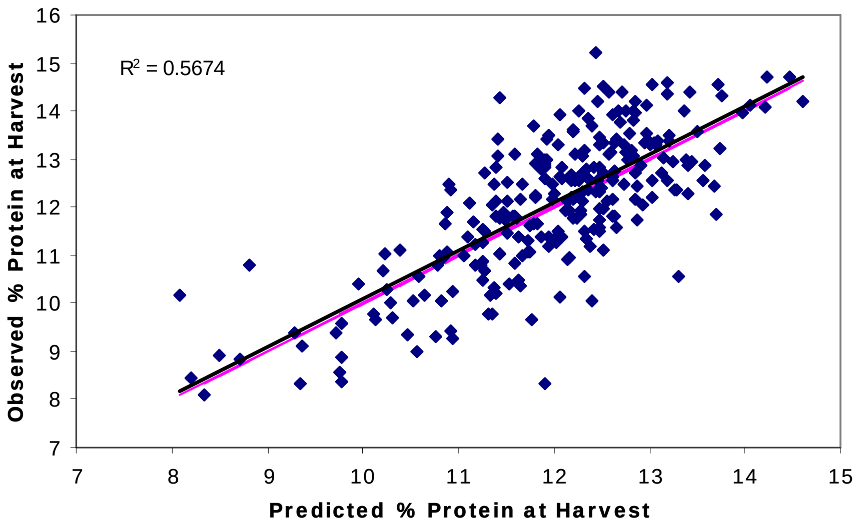
(i) The range of N contents in whole plant material was greater than in ears alone. Hence, whole plant data generally performed better in grain protein prediction. However, this advantage was marginal and, given the extra effort (hence cost) in taking large samples for analysis compared to the relative ease of sampling ears alone, a method based on ear analysis was preferred.

(ii) Assessments at the MR stage were preferred because they showed much stronger relationships with grain protein than those at flowering with both Leco and NIR analysis and at both BW and HM trial sites. Ideally, the grower would prefer earlier measurements to provide more time to plan the late foliar application. However statistical analysis showed measurements at MR had a clear advantage.

(iii) Predictions from NIR were comparable to those from Leco (as assessed by R^2). Because of its ease of use and ability to give instantaneous readings the best fit statistical model from the NIR data was developed using a proportion of the data from both the field trials and Coop data. However, for occasional users, the capital investment in a NIR instrument could be avoided by using Leco, and the model would remain much the same.

Two correction factors were also included: a 'Hereward' factor for the ear N to indicate 13% grain protein was lower for Hereward than higher yielding modern varieties, and a 'farm' factor because grain proteins for commercial crops were generally greater than from field experiments at comparable ear N%; this probably occurred because farm crops included second wheats and were only from East Anglia.

The predictive precision of the final best model with 260 crops combined from the Coop and field trials samples is illustrated in Summary Figure 4 (model tuned and tested on the same data). There was a small improvement in model performance over the first MALNA project (R^2 0.52 for predictions of experimental samples using Leco analysis). The R^2 of 0.57 is actually better than may first appear because it applies to farm as well as experimental crops, and to NIR predictions rather than the Leco method. When an additional 86 independent data points (other varieties not used to build the model, mainly Einstein) were added in order to validate the model, the R^2 was reduced to 0.45. The model also incorporates the uncertainties arising from relatively small samples of ears and grain which, although replicated within the sample area, only represented a small area of a whole field. If the number of ear or grain (or both) samples was increased, improvements might be seen, for example by amalgamating data from several fields or growers. An image of how the system might look in practice to the grower, in an Excel-based format is shown in Summary Figure 5.



Summary Figure 4. Predicted protein at harvest versus observed protein at harvest using a regression model with NIR ear data as the main predictor (n=260).

USER INPUT DATA >>	7.5	: Expected Yield (t/ha)
	24.0	: Cost of 40 kg/ha of Fertiliser N (£/ha)
	13.0	: Protein Bonus Threshold (%)
	15.00	: Protein Bonus (£/t)
	1.00	: Penalty (£/t) for reduction in protein each 0.1% below target
	1.72	: NIR Measured Immature Ear Nitrogen (%)
	NO	: Hereward type ?
	YES	: Commercial farm crop
MODEL OUTPUT DATA >>		
	12.2	: Predicted Harvest Grain Protein without late N (%)
	12.6	: Predicted Harvest Grain Protein with late N (%)
	52.78	: Net Monetary Benefit of Late Fertiliser (£/ha)
		: Decision (Green = Apply, Red = Do Not Apply)

Summary Figure 5. Example system in spreadsheet-based format.

2.3.5. Financial assessment

Because single predictions had wide confidence limits, the value of late N application strategies are best assessed by averaging over a number of crops. Different strategies were assessed by working out the average premium per hectare for all crops sampled due to achieving (or not) 13% protein (with a reduction of £1 per 0.1% down to 12.5%), less all costs. Assumed costs (where applicable) were £3.60 for ear sampling and analysis, £0.60 per kg urea N applied, and £7/ha for N application. Otherwise, actual yields and final protein contents (estimated from ADAS-taken preharvest grab samples) were assumed. Where necessary, assumed protein responses to 40 kg/ha urea N applied were +0.7% protein if final grain protein <12%, and +0.4% if >12% protein (earlier HGCA research showed a declining response to late FU as grain protein increased, and this was apparent in the growers data set in the present project). This procedure was used to adjust grain protein from crops of growers who did apply foliar urea.

After examining many strategies for protein prediction (detailed in the main report), it was clear that best strategies change with the price of N, and the premium for milling wheat. Five basic strategies are summarised here:

A. Grower practice; actual quantities of late N, as applied by each Coop grower,

B. A ‘perfect’ model; assumes the grain protein at harvest was predicted exactly, in time to guide late urea use - this represents the best any model can hope to achieve,

C. All applied; assumes all growers applied 40 kg N/ha late foliar urea N,

D. None applied; assumes no growers apply late N,

E. Best model; assumes all growers used the best-fit model (described above) based on ear analysis by NIR.

Although overall, the use of ear analysis by NIR and the statistical model performed well, giving benefits in the range £6 – 61/ha, disappointingly, this was not the best strategy unless the expected premium was about £20/t. At less than £20/t it proved better for no late N to be applied and at more than £20/t, it proved better for all crops to receive late N. There appeared to be few cases where the best-fit model (E) proved the most profitable strategy. A summary of costs, benefits and net benefits of the five strategies is presented in Summary Table 3.

Summary Table 3. Comparison of costs and benefits (£/ha) averaged across all 234 fields in the Coop group. Premium of £15/t at 13% grain protein decreasing by £1/t per 0.1% protein to 12.5%, a N fertiliser cost of £0.6/kg, spread cost of £7/ha and test cost of £3.60/ha.

		(£/ha)		
Strategy	**Total Cost of Urea N**	**Total Cost Of NIR System**	**Total value of premia**	**Net Benefit**
A Grower model	-£11.83	£0.00	£36.40	£24.58
B 'Perfect' model	-£6.77	-£3.60	£53.33	£42.95
C All apply late N	-£31.00	£0.00	£54.84	£23.84
D No-one applies late N	£0.00	£0.00	£31.32	£31.32
E Best fit model	-£17.24	-£3.60	£47.41	£26.57

As well as achieving 13% protein, the milling wheat premium also depends on meeting Hagberg Falling Number (HFN) and Specific Weight (Spwt) standards of 250 s and 76 kg/hl, respectively. Data from the HGCA wheat quality calculator show that the likelihood of achieving all three quality standards is low ~25% (5 to 50% over 2000 to 2010) for nabim Group 1 varieties. Any chance of failing to meet HFN and Spwt standards will reduce the net benefits of using late N (Summary Table 3). However, discussions during the project suggested that this tends to be grower specific i.e. some growers never have a problem meeting Spwt. Therefore, the results here should be adjusted for other quality criteria in the light of growers’ own experience.

The poorer performance of the best-fit model (strategy E) compared to ‘group action’ (all apply or no-one apply) arose largely because of the accumulated uncertainties associated with sampling and analyses for single fields. This points to the value of whole field sensing, such as with spectral reflectance. Otherwise, it is highly likely that ‘group action’ in sharing ear analysis results and associated data would improve the certainty of ‘group’ predictions. Hence, although there were no high protein years to test here, it seems very likely that growers acting together (either nationally, regionally or more locally) should be able to use ear analysis to detect whether to expect low, moderate of high grain protein for their area in each season. Since much grain protein variation is seasonal, this could be an effective new prediction strategy.

2.3.6. Potential external effects of a forecasting system

Behaviour of the growers (for the 205 fields were complete records were available) was broadly in line with national survey data (British Survey of Fertiliser Practice, 2009), with 41% applying an average of 37 kg/ha late N. As might be expected in low protein years, more growers would have been recommended by the best-fit model to add late foliar urea (56%) than actually did in practice. About 42% of these applications would have been responsible for achieving premiums, compared to 16% with existing farmer strategy, so best-fit prediction method could be more effective to a group than to individual farmers. Assuming it would be equally effective in a high protein year, it may be expected that more growers would be discouraged from unnecessary N use.

Overall, the best strategy was that no-one applies late N unless the expected premium was over £20/t. It may be expected that this would also be the best strategy in a high protein year, given that still only a minority of crops would benefit from extra protein. However, the needs of the milling industry would be compromised by such a strategy due to a reduced supply of high protein wheat. This conclusion raises important questions about whether the 13% protein target for breadmaking wheat works to the overall benefit of the industry, since in the three years of study here it led many growers to waste N, and since the average grower stood to lose financially from applying late N.

2.4. Conclusions and recommendations

This project highlighted some reasons why previous forecasting systems have failed in commercial practice and it has shown the increasing difficulty of achieving 13% protein in modern high yielding varieties. Specific conclusions are as follows:

1) Robust, updated NIR calibrations are now available for N and moisture in immature plant material, including whole crop and ears collected at flowering as well as at MR,
2) The best grain protein forecasts were not improved by spring rainfall data, by forecasts of weather during grain filling, or by yield forecasts,
3) The best model used ear measurements taken at MR stage, plus a variety factor to distinguish variety yield potential, and a ‘farm’ factor,
4) The Dumas reference and NIR methods of measuring ear N performed similarly; NIR was simpler and faster to use on fresh plant material,
5) Plant N and grain protein varied less in commercial crops than in N response trials whilst sampling errors were greater; hence farm N measures were uncertain,
6) Data collection from farms showed that many growers could keep better records of yield and grain protein, which would improve N management over time,
7) The best protein prediction method showed no benefit for individual crops, but significant benefits could accrue if predictions were applied across a group of fields, or over a number of seasons,
8) Farms showed consistent differences in protein achievement; these may be inherent and unavoidable, or they may indicate persistent on-farm inaccuracies in N management. In either case, ear N analysis appears to offer a useful additional diagnostic tool, to augment measurements of soil N and grain N in supporting good N management,
9) N response trials in three low protein seasons showed that modern high yielding varieties required >290 kg/ha applied N in 13 out of 14 instances to achieve 13% final grain protein, much more than was applied by growers (233 kg/ha). Further experience of ear N analysis is desirable in high protein years,
10) Full exploitation of group actions to forecast grain protein might require results to be kept confidential, so that prices were not affected; the full value of protein forecasts will only become clear after a system is deployed commercially,
11) Given the difficulties of achieving 13% protein in high yielding wheat varieties. while staying within environmental limits for N applications, in many cases, the best approach was not to apply late N,
12) Financial benefits both for growers and for the public can be seen to accrue from implementing a decision support system based on forecasting final grain protein, to target late N use; this might require the milling industry to offer larger premiums to ensure continuing availability of breadmaking wheat with 13% grain protein.

The following recommendations for further study are made:

1) Ear N analysis should be tested (in research and commercially) over a wider range of seasons, to include a ‘high protein’ year,
2) Work is required to develop in field-sensing systems for late crop N status, which could be tractor or satellite mounted and could average results over large areas,
3) Work is needed to relate variability in crop N status across a field with yield and grain protein for those same fields at harvest. This should be possible using modern on-combine yield monitoring, in-line protein determination by NIR, and satellite positioning,
4) Given the uncertainties in grain protein measurements, particularly when based on Dumas, commercial deductions for differences in grain protein of 0.1% may need to be reconsidered by the industry,
5) The industry should reconsider whether the 13% protein target could be reduced or avoided, since it encourages wasteful N fertiliser use, which in many cases is of no benefit to growers, and which deters breeders from increasing yield potential.

3. TECHNICAL DETAIL

3.1. Introduction

3.1.1. Aims and objectives

The aim of the present project was to improve decision making with respect to applications of fertiliser nitrogen to milling wheat, using a crop modelling approach combined with Near Infra Red (NIR) sensing of crop nitrogen (N) content.

The specific objectives were to:

I. Develop a model to predict final grain yield and protein content,

II. Test the model with growers and grain Cooperatives (Coops) using commercial crops,

III. Provide a reference dataset with which to test the physiological aspects of any model,

IV. To validate and improve previous NIR calibrations for N% and moisture in immature material and grain, and

V. Validate overall grain yield and grain protein forecasting model.

3.1.2. Background

Late applied foliar urea (FU) is successful in raising grain protein, such that for the average grower, the cost of the extra N is paid for by the premium received on achieving a target, typically 13% grain protein assuming that other quality parameters i.e. HFN and specific weight, are also reached (Turley *et al*., 2001).

However, urea is taken up relatively inefficiently by the crop canopy. Dampney and Salmon (1990) showed that on average less than 40% of N applied as foliar urea was recovered in the grain. The remaining 60% (*ca*. 8,000 tonnes of N) is assumed to reach the soil where it could be leached during the following winter, or be volatilised from the crop surface and lost to the atmosphere. Moreover, it is known that for many wheat crops, grain protein at harvest may often be adequate to meet the premium, without the application of additional FU (Sylvester-Bradley, 1990). Given recent increases in the price of N, there is increasing scrutiny of inputs such as FU. Unfortunately, growers currently have no way of assessing the N status of their crops, in order to target fertiliser decisions, and specifically identify those crops where extra N may not be needed. Therefore a robust system, which will accurately predict the requirement for additional late applied N (principally FU), is required.

Inefficient use of fertiliser N by crops (excess applications of fertiliser or poor uptake by the crop) is a major source of diffuse pollution, leading to leaching of nitrate over winter. This is of special concern where a large proportion of milling wheat is grown in a Nitrate Vulnerable Zone. About one third (663,000 ha) of the total (1,990,000 ha; HGCA, 2004) winter wheat grown in the UK, is grown for purposes of milling and breadmaking. For these markets, the industry has a requirement for high grain protein content (13%) in the best milling samples, and there is a financial incentive (a premium paid) for growers who can reach this level of grain protein. Consequently, about half the winter wheat for breadmaking (*ca*. 332,000 ha; British Fertiliser Survey) receives an additional application of N late in the season in the form of FU during early grain filling. FU is typically applied at a rate of 40 kgN/ha, representing 13,280 tonnes/annum of N during grain filling.

Foliar urea applied at the milky ripe (MR) stage is typically reported to increase grain protein by 0.4 – 0.7% for every 40 kg N/ha (HGCA, 1998). In a study by Dampney *et al*., 2006 applications of 40 kgN/ha foliar urea applied at GS70-75 gave an average protein increase of 0.66%, with the rate of response tending to be slightly lower as the yield increased.

For crops that are already set to reach the 13% premium at harvest, this late application is unnecessary both financially and as an environmental risk. Furthermore, there are occasions when the protein level of the crop is so low that the late N will still be insufficient to reach the threshold. The challenge therefore is to improve decision making, by predicting the likely final grain protein content of the crop in time to prevent unnecessary late applications of fertiliser.

However achieving the milling wheat premium is also dependent on meeting Hagberg Falling Number (HFN) and Specific Weight Standards (Spwt) of 250 s and 76 kg/hl respectively. Analysis of information in the HGCA Wheat Quality Calculator (www.hgca.com) shows that for all nabim 1 Group wheats (nationally) on average between 2003 and 2008 only 48% of surveyed results met both the HFN and Spwt standards ranging between 30 to 70% between years. Data from the HGCA Wheat Quality Calculator also illustrates that the likelihood of achieving all three quality standards was low ~ 30% (10 to 50% over 2003 to 2008) for nabim Group 1 varieties.

Previous HGCA funded work

The MALNA LINK project (LK 0927/HGCA 2579) demonstrated successfully that the Matrix-I NIR from Bruker Optics is a robust system that can be used to measure N and moisture in fresh (undried) samples of wheat. While the previous MALNA project envisaged that the measurements of immature wheat protein and final grain protein made in one year would provide calibrations to predict grain protein across sites and seasons, there are a number of reasons why this approach would not be robust enough to be used in commercial practice:

In general, high yield potential tends to dilute grain N%, and therefore, it is believed that some prediction of yield is also required, in order to accurately predict grain N%. Total N uptake by winter wheat can vary between *ca*. 200 and 300 kg/ha (+/-20%; HGCA Wheat Growth Guide, 1st edition;

Sylvester-Bradley *et al*., 1997), and the grain yield for a single variety can vary between 7.4 and 10.6 t/ha (+/-18%). Therefore from this data set with Mercia winter wheat, variation in yield appears to be of similar importance as variation in total N uptake, as a factor influencing final grain protein content, assuming that nitrogen harvest index (NHI) remains constant.

3.1.3. Modelling approaches

Empirical models based on weather and other variables

There are a number of approaches based on empirical models, which attempt to correlate yield and protein concentrations to weather variables, measured over a wide range of sites and seasons. For the purposes of predicting yield, a combination of five parameters (photothermal quotient in October, rainfall in November, rainfall in May, low min. temperatures in June and wind speed in July) in a multiple regression, explained 70% of the variation in wheat yields (Sylvester-Bradley *et al*., 2005). For the purposes of predicting grain protein, a model using the variables cultivar, N application, periods of winter and spring rainfall and summer temperature, accounted for 70% of the variation in grain protein by the end of May (Smith and Gooding, 1999).

It is acknowledged that such empirical models generally work best as forecasting systems where the environment is typically dominated by one major variable (e.g. drought), whereas in a more complex environment of the UK, with more fine-tuning of inputs, such models are less useful. While they are useful in providing forecasts for average performance across a region (which may be very valuable data for millers and the grain trade) they are not useful for an individual grower to make husbandry decisions, field by field. At the local scale, important variables such as disease pressure, soil type, or high residual soil N supply (e.g. from previous applications of farmyard manure) might need to be incorporated into any prediction system. Data from the HGCA Wheat Growth Guide also showed considerable variation in N uptake (and losses from above ground DM) after flowering, and this would further complicate an estimation of final grain protein from knowledge of plant N content at flowering and final yield.

Complex simulation models

A complex simulation model for wheat growth (Sirius) exists. This has recently been studied in detail by Sylvester-Bradley *et al*. (Defra project AR0909) using an integrated data set comprising 205 sets of observations collated from experiments conducted by ADAS and the University of Nottingham in the 1990’s. Sirius uses daily weather, soil and husbandry conditions as inputs, and is also reported to be useful for decisions on N nutrition. However, in terms of accuracy, large deviations in predicting grain yield were found (> +/-1 t/ha). It was concluded that in environments where variation in yield is low (i.e. this is likely to be the case on an individual field or location for a well managed milling wheat crop in the UK), Sirius is more likely to be useful for comparing strategies for growing wheat (e.g. examining the effects of sowing dates on yield potential), rather than in practical management. It is unlikely to be useful for making fine-tuning decisions regarding late N applications on a local level.

Simulation models such as Sirius have been built on a detailed physiological basis containing many parameters, most of which are not necessarily related to those features of the crop which a grower would use to make agronomic decisions within the growing season. Therefore, it has long been argued that a ‘parsimonious’ approach to modelling is required, which more closely links the most important variables that influence growth and development, with those that will influence a growers agronomic decisions. This project aimed to take a parsimonious approach without the need for a complex simulation model, using measurements and observations which could be made by the grower during the flowering to early grain filling period, to predict grain yield and grain protein concentration.

3.1.4. Lessons learnt from previous protein prediction studies

When samples are analysed from within tightly controlled, N response experiments, a number of crop parameters (e.g. leaf greenness, total biomass etc) tend to correlate well with yield and/or final grain protein content (e.g. Lopez-Bellido *et al*., 2004; see further discussion below). However, such relationships tend to break down when applied across a wide range of seasons and environments. An example of this was HGCA project 1216, which used the chlorophyll meter (Precision-N tester). The chlorophyll meter gave good predictions of grain yield (based on measurements of flag leaves) within controlled N response experiments. However, the predictions failed when applied over a wider range of sites and environments.

Therefore it is clear that models to predict final grain protein must be tested using samples from commercial crops, taken from a wide range of soil types and environments. This approach was the core of the present proposal, and was achieved through engagement with the members of Fengrain and Camgrain.

3.1.5. Previous approaches to forecasting grain protein

Smith and Gooding (1996) studied the relationships between wheat quality in HGCA surveys and daily temperature, rainfall and N application. They found that grain protein was negatively correlated with spring rainfall (5th March - 27th May) but positively correlated with early summer rainfall (28th May - 8th July), and was positively correlated with summer temperature. Increased temperature is known to hasten senescence and reduce the length of grain filling, which tends to reduce dry matter accumulation, while N accumulation in the grain is less affected by temperature in the UK. Temperature can also affect N availability indirectly as it increases N mineralization in soil, and a significant, but variable quantity of N can be taken up by the wheat crop post-anthesis.

A negative influence of spring rainfall means that a wet spring tends to decrease grain protein; the initial hypothesis being that the conditions being conducive to early N uptake will tend to also increase yield and hence, lead to a net dilution in grain proteins. Rainfall later in the season would tend to increase availability of N to the crop during grain filling, when N can be more directly translocated to the ear, rather than being incorporated into stem storage. Smith and Gooding did acknowledge a contradiction in the literature (citing Taylor and Gilmour, 1971 working in New South Wales) in that late rainfall can also be hypothesised to maintain leaf greeness and prolong photosynthesis and grain filling, hence diluting grain protein. However, both varieties and agronomy have changed so much since the 1960s that it would be unwise to assume such relationships hold fast today.

In a further refinement of their model, Smith and Gooding (1999) showed that a simple model based on variety, N application and two climatic factors, winter and spring rainfall could predict 70% of the variation in grain protein by the end of May. As with their earlier model, spring rainfall (4^{th} March – 26^{th} May) was negatively associated with grain protein content. After the end of May, high temperature was again the main factor, positively influencing grain protein. Considering the effect of spring rainfall further, they cited work of Powlson *et al*. (1992) who showed that spring rainfall could be associated with loss of N, presumably because rainfall shortly after application of N fertiliser leached the N below the rooting zone. The model developed by Smith and Gooding (1999) showed only varied success at predicting grain protein at different sites, indicating that different soil types should be treated differently in order to be able to predict local effects These authors acknowledged the work of Benzian and Lane (1986) who suggested that estimates of soil texture and wetness could significantly improve weather-based models for predicting grain protein.

Lopez-Bellido *et al*. (2004) studied variation in N concentration and chlorophyll (which is related to N concentration) in a series of eight N response experiments at Rothamsted with the variety Hereward (over the harvest years 1993-2001). Their work utilised the Minolta SPAD meter which estimates chlorophyll concentration in individual leaves. A 13% grain protein level required an N concentration of 2% in whole shoots and 4% in flag leaves at anthesis, and required a critical SPAD reading of 52.4. The advantage of the SPAD readings are that they are not destructive and are fast to make, although in Lopez-Bellido's work measurements were made on 90 leaves in each treatment! Lopez-Bellido *et al*. concluded that the SPAD meter had potential for predicting grain N requirements but that further work was needed to establish SPAD calibrations for other wheat varieties under UK conditions. Other workers have also reported the utility of the SPAD meter e.g. Matsunaka *et al*. (1997). The SPAD meter has since been evaluated in the field by agronomists in the Eastern region, but has not shown consistent responses across commercial crops (Jamie Mackay, personal communication). Part of the problem may lie in a poor relationship between chlorophyll and N status across different varieties and/or seasons, as anticipated by the

Rothamsted workers, and could in part be due to different mobility patterns of N in contrasting soils, as alluded to by Benzian and Lane.

The work of Smith and Gooding (1999) showed that although 70% of the variation in grain protein could be predicted by the end of May, there is still time to influence grain protein through agronomic intervention. Moreover, Lopez-Bellido *et al*. (2004) showed that measurements of N and/or chlorophyll in the flag leaf could be used to predict grain protein. However, such approaches inevitably suffer because, for a specific crop, an unexpectedly high or low yield can respectively decrease or increase the final grain protein. Therefore, the ability to also forecast yield may add extra predictive power to any model for grain protein, based on early season estimates or weather and/or N status.

3.1.6. Previous approaches to yield forecasting

Mechanistic models of wheat yield of varying complexity include Sirius, which calculates biomass production from photosynthetically active radiation, (Jamieson *et al*., 1998), AFRCWHEAT2 (Weir *et al*., 1984), CERES-Wheat (Ritchie and Otter, 1985) and APSIM (McCown *et al*. 1996; Keating *et al.* 2003). These models vary in the detail of the description of the phenology of crop growth and in the detail of their requirements for daily weather, soil and husbandry data. Sylvester-Bradley *et al*. (2005) compared the relative performance of these models and despite the complexity of the models, accuracy in predicting grain yield was still found to be greater than +/- 1 t/ha. Testing several simulation models against yields from UK agricultural experiments, Landau et al. (1998) reported prediction errors of between 2.2 and 3 t/ha for AFRCWHEAT2, CERES predicted very low yields with a bias of -2.6t/ha and SIRUS predicted high values with a possible bias of 2.1 t/ha. For all the models the root mean squared error of model grain predictions exceeded 2 t/ha. The models whilst all applied to the same data also showed low correlations between each other. Although Landau *et al*.'s analysis was strongly contended (Jamieson et al., 1999; Landau et al., 1999) it is, nevertheless, the case that despite two decades of intensive development (e.g. *ref to APSIM, DESSAC, etc.*), no crop simulation model has yet gained acceptance by growers for their decision support.

Porter *et al*. (1993) compared AFRCWHEAT2, CERES and SWHEAT for 5 experiments with two variety types in non-limiting conditions in New Zealand. The absolute error in prediction grain yield averaged over the 5 crops was 12% of that observed for CERES-wheat and 15% for AFRCWHEAT2 for the variety Avalon. The SWHEAT model did not perform as well for either of two varieties. Model predictions compared to 283 globally observed yields using the model CERES-wheat, demonstrated that the model was able to explain about 60% of the variation (Ritchie and Otter, 1985).

These models have struggled to predict the rather subtle variation in UK wheat yields (compared to larger, global, moisture-driven yield variation), especially when there are other factors at play in these experiments such as disease, weed and pest control, lodging and harvest conditions (Landau *et al*., 1999) which the models are not designed to capture. Thus, modelling work in the UK has demonstrated the importance of fine-scale variation or unmodelled factors in predicting UK wheat yields for individual fields. Coupled with their more detailed data requirements and the time required to apply them, these more complex crop physiology-based models become prohibitive to use in situations where there are many sites to model. In this project, there are many farms in the grower group with different soil conditions growing different varieties.

In contrast, Landau *et al*. (1998) developed a more parsimonious multi-regression model of wheat yield in the UK. Key environmental variables influencing yield included rainfall before and after anthesis, during grain filling and in the spring, and a temperature-driven duration of grain filling.

Sylvester-Bradley (1991) also argued that a parsimonious approach to yield modelling is required in which models are developed that use parameters which relate to the crop features a grower would used to make an agronomic decision and that can be easily identified and measured at timely points in the growing season.

Measured N and biomass could be collected at MR and flowering in using the Matrix-I NIR instrument from Bruker Optics. The prediction of the protein by forecasting biomass and N increments and its re-distribution at harvest using measureable field data could therefore be achieved either by using a simpler physically based model, or by using a ‘black-box’ approach for example a regression model as first demonstrated in used in the first MALNA LINK project (HGCA Report No. 401). The additional benefits of an approach where the nitrogen content of the whole plant or ear can be measured at flowering or MR, is that the uncertainty associated with modelling the crop development from the point of sowing is removed.

A major issue for any approach is that the estimation of protein requires the ratio of grain N and yield to be determined. Both parameters have inherent errors in their measurement. Errors are associated with the measured N and biomass at MR or flowering, as well as the model estimates of the grain increment and N uptake and redistribution over the grain filling period. It is easy to see that once yield is divided into N content that the errors in one or both estimates can seriously affect the final estimate of the grain protein

3.1.7. Approaches in current project

The potential strength of the Matrix-I NIR system, currently unrealised, is that by combining an estimate of fresh weight per unit area, and moisture (by NIR), an estimate of biomass accumulation can be derived. Coupled with a measurement of N% in the plant (also possible by NIR), a realistic estimate of N uptake (kg/ha) is achievable. This has not been possible before using low cost, rapid sensing techniques. Using benchmarks for estimates of N uptake at a specific growth stage (from the HGCA Wheat Growth Guide, 1997) and N harvest index, it would then be possible to estimate final grain N at harvest. The modelling approach will rely on quick and easy measurements a grower can make, based only on the most important parameters influencing yield potential and estimates of N partitioning during the grain filling period.

The aims of the practical work in the current project were to:

a) provide a series of field experiments to extend the range of environments available to test models for forecasting yield and final grain protein, and at the same time to provide plant material containing a wide range of plant N concentrations, for continuing development of NIR calibrations, and;

b) monitor a large number of commercial crops, in order to test the utility of the forecasting system, and also to provide plant material for extending the NIR calibrations, with a wider range of environmental influences, but with a more limited range of N nutrition (contrasting with those encountered in N response experiments where most of the environmental variation other than the effect of N, is minimised).

3.2. Materials and methods

3.2.1. Description of historic data sets

MALNA 1

Data from the first MALNA project (Project Report No. 401; Bhandari *et al*., 2006), comprised 219 samples, spanning four harvest seasons from 2002-2005. The data included reference measurements (moisture and N determined by Kjeldahl) from ear and whole plant samples, harvested at the MR stage, and grain from harvest. There were no data on crop biomass at either immature stage or pre-harvest.

HGCA 'Development' project

Data were made available from the HGCA Development project (data which underpinned the HGCA 'Wheat Growth Guide'; Volume III of HGCA Project Report No. 151) to guide the early conceptual development of the model, and understanding of wheat growth and N accumulation. The practical work in this project involved sampling 18 crops of Mercia winter wheat (6 sites x 3 field seasons) in order to define the typical patterns of growth and development of winter wheat in the UK.

3.2.2. Field experimentation 2007-2009

In order to extend the range of environments, field experiments were carried out in each of three seasons. These provide a test of environmental effects, specifically N nutrition and geographic location (all three seasons), sowing date (two seasons) and varietal effects. The soil type at Boxworth was a chalky boulder clay (on ADAS farm in 2007, on an adjacent farm of same soil type in 2008 and 2009), and the soil type at the High Mowthorpe site was a shallow silty clay loam over chalk (on ADAS farm in 2007 and 2008, and nearby at Towthorpe in 2009).

Sites, varieties and treatments are shown in Table 1. Applied N rates were adjusted based on the soil mineral N measured in the spring (0-90cm depth), plus a measure of plant N uptake.

Table 1. Site experimental details for Boxworth (BW) and High Mowthorpe (HM) 2007-2009 harvest years.

Site, season and Field name	Sowing date(s)	Varieties[1]	Spring soil mineral N (kg/ha)	Applied N rates (kg/ha)
BW 2007 Pamplins North	03/10/06 2/11/06	He, Xi	65	0, 110, 220, 270, 320
BW 2008 Bottom Brooks	05/10/07 05/11/07	He, Xi	84	0, 75, 150, 225, 300
BW 2009 Brickyard Pond	26/09/08	He, Xi, So, Ei	51	0, 110, 220, 270, 320
HM 2007 Elbow South	10/10/06 13/11/06	He, Xi	106	0, 90, 180, 230, 280
HM 2008 Whether Palin	04/10/07 06/11/07	He, Xi	100	0, 75, 150, 225, 300
HM 2009 Towthorpe	10/11/08	He, Xi, So, Ei	33	0, 140, 280, 320, 380

[1], Varieties: He, Hereward; Xi, Xi19; So, Solstice; Ei, Einstein

Plots were established using an Øyjord drill with a 12 m plot length. Adjacent plots were drilled in duplicate for each treatment to give separate hand harvest (HH) and combine harvest (CH) plots, and a guard plot of a single variety was sown between each pair of treatment plots.

3.2.3. Growth analysis - Immature samples

The date of flowering was recorded for each variety at each site, using the recommended fertiliser N rate treatment to assess flowering date. When anthers were visible on 50% of the spikes, this was recorded as date of flowering (GS61). Samples were taken for growth analysis at two immature stages: flowering (FL), MR stage.

Sampling area

Samples were taken from the HH plots. The samples were taken using 2 x 0.25 m^2 quadrats from the centre line of each plot, to give a total bulked sample of 0.5 m^2 per plot for each treatment. Quadrats were placed in a representative area of the plot, where possible placing the quadrat diagonal to the direction of drilling, and excluding the outer two rows of each plot from the quadrat area. At least 1m was left between successive quadrat samples, and between the samples taken at different sampling times (FL and MR stages). All the above ground material within the quadrat area including any dead and dying material was harvested using sharp pointed scissors to cut off plants at the soil surface

Laboratory growth analysis

Yield component analysis was carried out as follows: When the sample was returned to the lab, the whole fresh weight of the sample was recorded, and approximately a 1 kg representative sub-sample removed for growth analysis. At High Mowthorpe, after recording the weight of the whole sample, and making a record of any diseases present the sub-samples (1 kg) were labelled, sealed in plastic bags and couriered overnight to Campden BRI.

At Boxworth and Campden BRI (on receiving the HM samples), the sub-sample was divided into (i) one third for ‘whole plant’ sub-sample and (ii) two thirds for an ‘ear’ sub-sample. These were treated separately as follows:

(i) The whole plant sub-sample was chopped into 3-4 cm lengths, and mixed thoroughly. The chopped sample was scanned using the Matrix-I NIR as described below, and then after scanning, the chopped sub-sample dried to constant weight at 80 ^{o}C, the weight recorded before sending to the labs for N determination.

(ii) The number of fertile shoots in the ear sub-sample was recorded, and then the ears cut from the stems. The fresh weights of the straw and ear sub-samples were recorded, and the ears chopped into 3-4 cm lengths. The ear sub-sample was then scanned using the Matrix-I NIR as described below, and the (chopped) sub-sample of ears placed in a drying oven and dried to constant weight at 80 ^{o}C. Following drying, the weight was recorded and the sample sent for N analysis (by Dumas combustion).

The samples were scanned as instructed under NIR operating instructions (Section 3.2.4).

Growth analysis - Pre-harvest samples

In addition to sampling at the two immature stages, a sample was taken just prior to harvest (within 2 days of the anticipated harvest date). A area of 0.5 m^2 per plot was selected using a quadrat and all the plants cut-off at ground level and the sample placed in a paper sack. In the lab, total ear number, ear, straw and chaff dry matter were recorded. The ears were threshed, the seed recovered and used to determine grains/ear, harvest index and finally after sending samples of grain and straw+chaff for N determination, N harvest index was estimated.

3.2.4. Commercial growers studies 2007-2009

To provide a range of samples representative of commercial practice, fields were sampled from participating Coop members (Camgrain or Fengrain) in East Anglia, in each of the three field seasons. Choice of field, variety, soil type, N rate and other agronomic decisions were left to the grower. Participants were asked whether they were planning to use foliar urea, and if so, were provided with warning signs to place in field to mark out the sample area, and asked to switch off the sprayer so that a section of the field remained untreated (the ‘study area’).

To anonymise the identifiers, each field was given a unique code in the form:
[farm ID].[field ID].

The [farm ID] remained constant for a particular grower throughout the three years of the study. Each year the second part of the code changed so no field code could ever be duplicated as follows:
2007; [farm ID].1 to …..[farm ID].4
2008; [farm ID].5 to …..[farm ID].8
2009; [farm ID].9 to …..[farm ID].12

Immature sampling

Samples were taken at both flowering and MR stages. Growers were provided with a detailed sampling protocol. In 2007, the protocol was based on sampling 5 x 50 cm lengths of rows (area sampled varied between growers, based on actual row spacing, but typically 0.313 m^2 for 12.5 cm average row width). In 2008 and 2009, sample areas at the immature stages were harvested from each field using a quadrat (total 0.4 m^2). A metal quadrat was manufactured for each participant and supplied by ADAS prior to sampling. Detailed sampling protocols are given in Annexes 1 and 2.

Sample processing

On receipt at the Coop laboratory, crop samples were removed from the bag. Excess moisture was shaken off and if the sample was taken in rain, it was blotted dry using paper towelling. The whole sample weight was recorded and a representative sub-sample of approximately 1 kg for used for scanning (the reminder discarded). The 1 kg sample was divided into roughly (i) one third (350 g) for whole plant subsample, and (ii) two thirds (650 g) for the ear sub-sample, making sure each had a label. These were treated separately as follows:

(i) the WP subsample was chopped into pieces 4-5 cm in length, including the ears. The chopped sample was mixed well to ensure stem, leaves and ear portions are well mixed. The chopped sample was scanned using the Matrix-I NIR as described below.

(ii) the weight of the ear sub-sample was recorded before cutting off the ears, then counting and recording the number of ears. The ears were saved and the leaves and stems discarded. All the ears in the sub sample were chopped into 2-3 pieces each, and used to fill the NIR cell. The samples were scanned as instructed under NIR operating instructions (Section 3.2.5).

Pre-harvest sampling

Just prior to combine harvesting by the grower, ADAS staff visited each field and collected a representative sample of crop from the study area for the purpose of carrying out destructive growth analysis. In 2007, this represented an average area of 0.72 m^2 from each field sampling area (range 0.5 to 1 m^2; exact procedure varied between fields, using either fixed metal quadrats, or the row length method). In 2008 and 2009, a total of 1 m^2 was sampled in each case (4 x 0.25 m^2 quadrats). Samples were cut off at ground level and place into potato sacks prior to analysis.

Combine harvesting

Participants were asked to collect three samples if possible: (i) a sample from within the study area which in all cases would be untreated with urea, (ii) a sample from just outside the study area (this would be as close as possible to representing a sample from the study area but <u>with</u> late foliar N applied[*]), and (iii) a combine harvested sample representative of the whole field (again treated with late foliar N*).

[*] where applied by the grower

3.2.5. Laboratory protocols; crop processing and NIR scanning

In the present project further development of the NIR protocol took place, adapting the instrument to make additional calibration and background measurements. The Matrix-I NIR machine required a warm up period of at least 10 mins before beginning sample processing. If not carried out routinely, the machine automatically prompted the user to make these measurements again. These were:

1. Weekly PQ test,
2. Daily check on reference flour sample,
3. Background check every 3 hours.

On arrival, samples were checked to ensure that the sampler had sealed the bags well, to avoid moisture loss. If not processing immediately, samples were left in a cool room, and out of direct sunlight. Alternatively, samples were stored in a fridge or cold store at 4 ^{o}C if available the aim being to process within 24 h of receipt.

Each sub-sample of ears or whole plant (prepared as described above) was scanned three times, emptying the chamber between scans, and re-mixing the scanned material with the remainder of the chopped sub-sample before adding back to the chamber and re-scanning.

ADAS sites

A separate protocol was developed for the NIR scanning which covered start-up and running of the equipment and computer. Each sample was given a unique ID indicating site (BW, HM), form (WP or ears, E), the date on which it was sampled, and the plot number.

Coop stores

A separate protocol was developed for the NIR scanning which covered start-up and running of the equipment and computer. Each sample was given a unique numeric ID code as described above, form (WP or ears, E) and the date on which it was sampled.

After scanning the Coop samples, a sample of both whole plant and ears were placed in a sealed plastic bag with a label, and place in a fridge prior to collection by ADAS. The sample was subsequently dried and sent for Leco N determination.

Nitrogen determination (ADAS and Coop sites)

Nitrogen in grain and dried whole plant and ear samples were determined using the Dumas combustion method, either at Campden BRI, or at NRM UK Ltd. Grain N was converted to protein using the conversion factor N x 5.7 and all results reported on a 100% dry matter (DM) basis.

3.2.6. Development of NIR calibrations

At the end of each season of sampling, the four Matrix-I NIR machines were returned to Bruker Optics. The data were recovered, and matched with the immature plant N and moisture data, and added into the calibrations from the previous year.

3.2.7. Other data

Meteorological data relating to individual field trials was derived from daily weather data collected at the ADAS sites. To pursue a simplified yield model temperature, rainfall and solar radiation on a daily basis are important drivers. However, these variables were not available at the farmer grower's sites. Consideration was given when assessing the format of any mechanistic model and the benefits of a physically based model versus an empirically based model of protein of the ease of accessibility of weather data and financial implications of purchasing weather data in any future operational system.

Data from the HGCA annual protein survey were downloaded from www.hgca.com, and UK national grain yields from the UN Food and Agriculture Organization (http://faostat.fao.org/site/339/default.aspx).

3.2.8. Statistical analysis

Field experiments

Results were analysed by ANOVA within each site using the Genstat (v12; Anon 2008) statistical package. In 2007 and 2008, a split plot design was used, with the 2 sowing dates allocated randomly to main plots within the blocks (replicates), and variety and N treatments full randomised within the main plots. In 2008, a fully randomised plot design was used with variety and N treatments fully randomised within blocks. N response curves for yield were fitted to each of the N timing treatments using standard 'Linear plus Exponential' functions (Sylvester-Bradley *et al.*, 2008). Nitrogen optima for grain yield were determined using a break- even ratio of 6:1 (grain price assumed to be £97/t, Ammonium nitrate (34.5% N) price £200/t). N response curves for other variables (grain N, ear and whole plant N% at flowering and MR stages) were fitted to each of the N timing treatments using standard Linear (%N = A + B x N) or exponential (%N=A+B x R^N) functions.

Analytical data

Laboratory measurements of N in the immature plant were compared to NIR predicted data following development of the appropriate calibrations by Bruker Optics, and incomplete pairs of data and outliers are removed using Cooks distances calculated using the Statistica Version 9.1, Copyright Statsoft, Inc. 1984-2010) software package. Potential outliers are identified as follows in equation 1:

$$D_i \geq \frac{4}{n-(k+1)} \qquad \text{(equation 1)}$$

Where D_i = Cooks distance and, *n* is the number of samples and *k* is the number of predictors.

Assessing model performance

The Root Mean Squared Deviation (RMSD; equation 2) was also calculated for both models, which represents the mean deviation of predicted values with respect to observed ones (Pineiro *et al*., 2008):

$$RMSD = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(\hat{y}_i - y_i\right)^2} \qquad \text{(equation 2)}$$

Where *n* = number of samples; $\hat{y}$ = predicted sample and y = observed sample.

3.2.9. Modelling – yield and protein forecasting

Semi-mechanistic model

Firstly, a semi-mechanistic model was developed to predict grain yield. The model was initialised with an estimate of the total crop biomass (above ground) and N content from measurements at either anthesis (GS 61) or MR (GS 73). The crop leaf area index at this time was estimated from the N content (30 kg N per unit LAI; Scott *et al*., 1994). The model was then based on a phenological description of plant development up to and after the measurement time, driven by measurements of daily measurements of air temperature. Time to plant vernalisation and plant emergence was calculated according to Kirby (1992). The rate of leaf emergence and the final number of leaves was defined by the corrected functions of Baker *et al*. (1980) and Kirby (1992) to define the total thermal time to anthesis. The intermediate first node and flag leaf growth stages were defined according to Kirby and Weightman (1992). These stages were used to profile crop height that varies from 0.05 m at emergence to 0.65 m at anthesis (HGCA, 1997). The canopy area was profiled from sowing date to anthesis through thermal time according to Gillett *et al*. (1999).

A daily radiation budget was calculated according to Allen *et al*. (1994) and the canopy radiation interception was calculated using an extinction coefficient of 0.45. Biomass was accumulated using a default radiation use efficiency value of 2.4 g MJ^{-1}, and an assumption that 0.45 of the intercepted radiation is photosynthetically active. A proportion of the total biomass was lost each day to represent respiration, in proportion to air temperature (Hay and Walker, 1989). The biomass increment was further reduced due to late sowing and required a further adjustment for variety from the HGCA Recommended List. The default radiation use efficiency was modified on the second iteration of the model according to the ratio of predicted and measured crop biomass on the first iteration.

The development and maximum size of the canopy was not directly adjusted for water stress, although a daily soil water balance was calculated according to Bailey and Spackman (1988). The daily energy balance was used to calculate the average difference between the canopy and air temperature. When the daily maximum air temperature plus the canopy difference exceeded 30 ^{o}C then biomass accumulation was reduced to zero to represent heat stress.

Post anthesis, the canopy leaf area index declined linearly to zero after 500 ^{o}C plus one phyllocron accumulated air temperature (Jamieson *et al*., 1998). The radiation use efficiency also declined linearly to represent the falling leaf N content. All new biomass accumulated post anthesis was assumed to support grain development. During this period, 25% of the total stem and leaf biomass at anthesis was also transferred to the grain, and exploratory versions of the model allowed for estimation of grain protein, using a fixed N harvest coefficient. It should be noted that the model did not predict the impact of lodging or disease which also affected some of the trials and co-operative sites.

The semi-mechanistic model was driven using daily weather records for ADAS Boxworth for the years 2003 and 2004 (Malna 1 Dataset); and for the years 2007 and 2008 (Trials Dataset for the current project; Section 3.2.7). The reference Leco methodology was used to measure crop N content at the MR stage, and biomass was estimated by quadrat sampling.

Statistical model

The second modelling approach attempted to simply relate measurements of N in the immature crop (ears or whole plant) at flowering or MR stages, to final grain proteins using a regression analysis approach. The available raw data came from both N response experiments (Section 3.2.2) and commercial crops (Section 3.2.4). The immature data were available both as the original reference data (Leco N analysis), or as NIR predictions at the end of the project based on the calibrations referred to above (Section 3.2.6). Various modifiers were assessed, for instance moisture content of immature plants (which might allow adjustment, if for example the crop had not been sampled at the precisely the correct growth stage) and these are described further in the Results section 3.3.5.

3.2.10. Financial assessment

In developing the model to predict protein at harvest, consideration should also be made as to how this prediction would be used in making a decision whether or not to apply late foliar nitrogen to the crop. Therefeore, the protein prediction therefore needs to be embedded with a financial assessment of the factors influencing that decision.

Grower costs and benefits

In order to scope out the benefit of using a modelling tool to predict grain protein, the estimated Farmer Costs (C) were discussed and set out as follows in order to provide a basis against which the any model could be assessed throughout the project. Of course, none of the costs set out below are fixed or necessarily accurate to date but were considered a realistic estimate for this project.

Firstly an estimate of the operational test costs were set out as follows:

1. Capital cost and maintenance of the NIR machine:
   Estimated as £40k @ 7% Depreciation = £8k per year;
   If a machine is purchased by a grower group for example which supports 100 Farmers, each with 100 ha, the cost of supporting the NIR machine = £0.80 per ha/year
2. The cost of each test: £8 per sample (for one 10 ha field);
3. The cost of a qualified advisor if required to interpret the NIR results and advise is estimated as £20 per sample (for one 10 ha field).

Secondly, the Costs (C) to the farmer of adding the late application of foliar N are made. The farmer costs are associated with the purchase and spreading of fertiliser.

1. Assuming fertiliser @ £0.60 per kg N = £24/ha for first 40 kg N as Urea;
2. Spreading (diesel, time etc.) = £7/ha (Nix, 2009);
   Total Cost: £34.60 per ha (or £31/ha without test overhead)

It is important to note that there has been great variability in fertiliser prices over the past 10 years. Fertiliser cost is an important factor affecting whether it is financially beneficial to add the late foliar N in the hope of pushing the protein above the 13% premium threshold.

Thirdly an estimate of the Benefit (B) to farmers was set out. The financial benefit of using a NIR/model based system is the opportunity to get the milling wheat premium: The milling wheat premium is very variable even on a monthly basis and subject to supply and demand. For example, milling wheat was priced at £19.60/t more than feed wheat for the week ending July 2nd 2010, increasing to £31.60/t greater that feed week for the week ending 10th September 2010 (Farmers

Weekly). For the purposes of the baseline illustration, an agreed typical value for the past few years is used:

1. £15/t for achieving 13% protein;
2. Penalty of £1 for 0.1% protein increments down to 12.5%

Effects of late foliar N on grain protein

From a series of historic field trials the effects on protein of extra N applied as ammonium nitrate (AN) or foliar urea spray at GS75 (MR) have been reviewed. Given that in the 1990s, grain protein was expressed at 86%DM (dry matter) basis, the responses reported below have been corrected to 100%DM to make them easily comparable with the data collected in the present project. Foliar urea has demonstrated greater increases in protein for the same quantity of N than AN. Dampney and Salmon (1990) report an increase in protein of 0.63% (DM basis) at GS75 for 30 kg/ha foliar urea applied. HCGA (1997) reported that a foliar spray of 40 kg/ha N as a urea solution applied during milk development (GS70-79) increased grain protein on average by 1.05% (DM basis). Dampney *et al*. (2006) for 3 sites report an average rate of protein response to 40 kg/ha of late N of 0.66% (DM basis), mean yield 9.34 t/ha (85% DM basis), compared to an earlier HGCA research project (Dampney *et al*., 1995) with a 1.07% protein response, mean yield 7.15 t/ha. In a second series in the same project, Dampney *et al*. (1995) looked at the timing of a standard 40 kg/ha of N applied at GS 70-79, and the response was lower at 0.83% (DM basis). Increase in grain protein content from 30 kg/ha extra N applied foliar urea was shown to vary according to the grain protein content by Dampney *et al*. (1995) with an average 0.83% increase for proteins below 12.2%, 0.78% increase for proteins between 12.2-14% and 0.47% protein increase (DM basis) for harvest proteins over 14%.

To summarise the experiments above, the average rate of protein response to 30-40 kg/ha late foliar urea is between 0.4 and 0.8% protein.

3.3. Results

3.3.1. Crop performance, description of data sets

Main features of growing seasons 2007-2009

Locations of sites samples are shown in Figure 1.

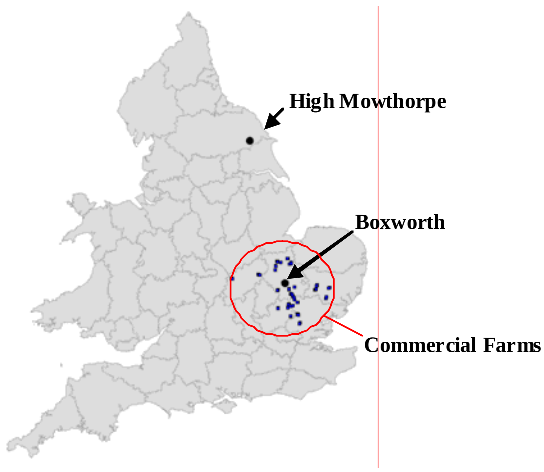


Figure 1. Locations of trial sites at Boxworth and High Mowthorpe and the spread of commercial farms in the grower Cooperative in East Anglia.

Monthly averages for maximum and minimum daily temperatures and rainfall totals through the growing seasons at Boxworth and High Mowthorpe can be found in Table A1, Annex 3). All three study seasons were unusual in that they had relatively dry springs compared to the long term average (LTA). It can be seen from Table 2 that the rainfall for the period from the beginning of March until the end of May was dry; in 5 of the 6 site seasons combinations, rainfall was only 43-88% of the LTA. Even in 2007 at Boxworth, which had rainfall of 104% of the LTA, the site experienced a very dry spring with only 1.4 mm of rainfall in April. The reason for the high rainfall figure in 2007 was that it started raining at the end of May, and continued through flowering and grain filling. The summers of both 2007 and 2008 were high rainfall years for much of the country, with severe and widespread flooding.

Table 2. Spring rainfall at Boxworth and High Mowthorpe sites 2007-2009 compared to long term average (LTA).

Site/season	Mar-April Rainfall		Mar-May Rainfall	
	(mm)	(% LTA)	(mm)	(% LTA)
Boxworth				
2007	35.0	36.7	152.0	104.0
2008	66.1	69.3	122.3	83.6
2009	43.0	45.1	64.0	43.8
40 year LTA	95.4		146.0	
High Mowthorpe				
2007	41.6	37.2	108.3	66.3
2008	120.6	107.8	143.6	87.9
2009	63.4	56.7	113.6	69.5
40 year LTA	111.9		163.4	

The other features of the seasons under study were the relatively cool summers, meaning that grain filling was long and resulting proteins low. The data in Table 3 are presented for the Boxworth site, together with the average grain protein contents from the HGCA survey and UK national yields from FAO. Boxworth is used here as being representative of the east Anglian region and of the commercial growers who took part in the study. It can be seen that the period of study encompassed three low protein years, whereas the preceding 3 years in particular were high temperature and high protein years. In particular, 2008 can be seen as the highest yielding year, with the lowest grain protein recorded during the period 2001-2009. Notwithstanding the very hot period in 2003-2006, the July maximum daily temperatures for all 3 years during the period of study were lower than the 40 year LTA, with 2008 also notable for low daily maximum temperatures in June.

Table 3. Average daily temperatures for June and July at ADAS Boxworth during the seasons 2007-2009, compared to short and long term averages, and grain protein and yields for GB Group 1 wheats.

Season	Air temperature (^{o}C)				GB wheats	
	June max	June min	July max	July min	Grain protein* (%DM)	Grain yield† (t/ha)
Historic						
2001	20.7	8.7	24.5	12.3	13.1	7.1
2002	20.6	9.9	22.8	11.1	13.0	8.0
2003	21.4	10.2	22.8	12.2	13.7	7.8
2004	22.9	11.6	24.0	12.3	13.5	7.8
2005	23.4	11.0	23.7	13.2	13.6	8.0
2006	23.1	10.9	29.4	13.9	13.5	8.0
Long term averages						
3 yr (2004-06)	23.1	11.1	25.7	13.1	13.5	7.9
6 yr (2001-06)	22.0	10.4	24.5	12.5	13.4	7.8
40 yr (1970-2009)	19.8	9.5	22.4	11.6		
Present study						
2007	21.5	10.8	21.7	11.7	12.8	7.2
2008	18.4	10.2	21.3	12.3	12.0	8.3
2009	19.7	10.2	20.9	12.2	12.7	7.9
Average for study period						
3 yr (2007-2009)	19.9	10.4	21.3	12.1	12.5	7.8

*, Grain protein from www.hgca.com, GB Group 1 wheats only

†, Grain yield (at 85%DM) from FAOstat, UN Food and Agriculture Organization

3.3.2. ADAS Field experiments

Final yields and grain proteins

Grain yields at the economic optimum N rate in each trial are shown in Table 4 and grain proteins in Table 5. The data show a similar pattern to that seen in the UK national yields with 2007 being the lowest yielding year, and generally low grain protein content in all three years.

The high protein and low yield of Hereward is clear compared to Xi19, as is the effect of very high yields being reflected in low proteins, for instance at High Mowthorpe in 2009. Late sowing tended to reduce yield and increase grain protein content in 2007 and 2008. Further data are shown in Annex 4: Late sowing decreased the predicted N rate required to achieve 13% protein by between 30 and 130 kg/ha for Hereward and between zero and 90 kg/ha for Xi19. Across all sites and seasons, the modern varieties Einstein, Xi19 and Solstice had predicted N rates of >290 kg/ha in

13 out of 14 instances, whereas Hereward only had 3 instances out of 10 where >290 kg/ha was required to achieve 13% grain protein.

Table 4. Grain yields (t/ha, 85%DM) at economic optimum N rate in each trial determined by curve fitting.

Site/season	Variety x sowing date			
	Hereward-E	**Hereward-L**	**Xi19-E**	**Xi19-L**
HM2007	7.78	4.60	8.18	5.69
BW2007	7.67	*	8.09	5.77
HM2008	7.90	6.85	7.93	6.02
BW2008	9.52	9.76	10.52	10.18
	Variety			
	Einstein	**Hereward**	**Solstice**	**Xi19**
HM2009	11.38	5.61	11.32	11.57
BW2009	10.00	8.91	8.83	10.00

* curve fitting not possible

E, Early sowing; L, Late sowing

Table 5. Grain protein content (% DM basis, Nx5.7 by Dumas) at economic optimum N rate in each trial determined by curve fitting.

Site/season	Variety x sowing date			
	Hereward-E	**Hereward-L**	**Xi19-E**	**Xi19-L**
HM2007	12.26	12.54	11.91	11.86
BW2007	11.46	*	11.00	11.74
HM2008	12.54	13.34	11.12	11.46
BW2008	11.17	11.12	11.00	*
	Variety			
	Einstein	**Hereward**	**Solstice**	**Xi19**
HM2009	10.49	12.03	11.74	12.20
BW2009	12.26	12.43	12.48	11.97

* curve fitting not possible

E, Early sowing; L, Late sowing

The full data set from which the fitted curves are taken can be viewed in Annex 4, including the slope coefficients for the respective curves. Slopes were chosen based on those curves which explained the major proportion of the variation. In most cases, grain yield response to applied N followed the typical linear plus exponential functions, except for BW2007 where there was particularly bad lodging in the wet summer, and the late sowing date suffered from competition with blackgrass (Annex, Fig. A6).

The response of grain protein to increasing N rate varied between sites and seasons, sometimes following a quadratic function (8 instances) and more often a linear function (15 instances). Given the importance of measurements of N in immature plant material for the purpose of predicting final grain protein, curves were also fitted to investigate the relationships between ear or plant N% and N rate.

There was no consistent pattern with the following numbers for each type of curve (where fitted). The type of curves fitted are summarised here and the coefficients are presented in full in Annex 4:

Relationship with N rate:	Linear+ exponential	Quadratic	Linear
Flowering Ear N%	2	16	5
Flowering Whole plant N%	0	16	7
Milky Ripe Ear N%	0	18	4
Milky Ripe Whole plant N%	0	16	8

The types of curves fitted was not wholly random; some years had more instances of linear relationships than quadratic e.g. the very high yielding crop at HM2009 (Annex Fig. A5), and also BW2008 (Annex Fig. A7), whereas other sites demonstrated predominantly quadratic functions for the relationships between measured parameters and N rate e.g. BW2009 (Annex Fig. A8). Using the economic optimum N rate (from the grain yield response to applied N; Annex 4), and the equations to the fitted curves, the N% in the immature material could be predicted at the optimum N rate. Finally, the fitted curves could also be used to predict the N concentration in immature material at the N rate which would have been expected give a 13% final grain protein. These fitted N rates are also shown in Annex 4.

There were three important observations arising from the data in Table 6:
Firstly, the difference in the actual N content in immature plant between the minimum N% (typically at the zero N rate applied) and the highest N content measured in each trial, was wider in whole plant material (0.68-0.98) than it was in ears (0.28-0.54). This observation might imply that whole plant material provides a better basis to use as a predictive measure of final grain protein, assuming that the form of material has no effect on the precision of taking the measurements.

The full data are presented in Annex 5, and are summarised across sites, seasons and sowing dates in Table 6. It should be noted that there were generally more observations for Hereward and Xi19 (10 each) than Einstein and Solstice (2 each). Secondly, it can be seen that for the MR ears (the fraction used as the material of choice in the first MALNA project for the purpose of predicting final grain protein) the N content predicted to give 13% grain protein was 1.9%, agreeing with the data in the previous project. Thirdly, it can be seen that for MR ears, Hereward had a lower threshold (1.81%) than Xi19 (2.03%) for predicting 13% final grain protein, with 1.9% effectively being an average of the two.

Table 6. Nitrogen content in immature material averaged across sites, seasons and sowing dates for 4 varieties predicted at the economic optimum N rate, or at the N rate which would have given 13% final grain protein (for full dataset see Annex 4).

	Hereward	Xi19	Einstein	Solstice	Average
Flowering ear					
N% at opt N	1.83	1.84	1.56	1.71	1.80
N% at 13% grain protein	1.90	2.03	*	1.76	1.95
Max N% measured†	1.88	1.96	1.71	1.80	1.89
Min N% measured†	1.46	1.52	1.43	1.41	1.48
Range (max-min)	0.42	0.44	0.28	0.39	0.41
Flowering whole plant					
N% at opt N	1.73	1.70	1.61	1.66	1.70
N% at 13% GP	1.92	2.07	*	1.79	1.98
Max N% measured	1.98	1.98	1.83	1.92	1.96
Min N% measured	1.01	1.00	0.93	0.97	1.00
Range (max-min)	0.97	0.98	0.90	0.96	0.97
Milky Ripe ears					
MR Ear (N%) at opt N	1.74	1.79	1.62	1.67	1.75
MR Ear (N%) at 13% GP	1.81	2.03	*	1.75	1.91
Max N% measured	1.83	1.88	1.70	1.75	1.83
Min N% measured	1.35	1.38	1.20	1.20	1.34
Range (max-min)	0.48	0.50	0.51	0.54	0.50
Milky Ripe Whole plant					
MR WP (N%) at opt N	1.34	1.46	1.34	1.37	1.39
MR WP (N%) at 13% GP	1.62	1.08	*	1.48	1.26
Max N% measured	1.65	1.67	1.49	1.54	1.64
Min N% measured	0.98	0.97	0.82	0.86	0.95
Range (max-min)	0.73	0.76	0.68	0.68	0.73

* not possible to predict either because of inability to fit curve or because 13% protein was not reached in the trial.

†, maximum and minimum value derived from means of data from ANOVA

Total biomass and partitioning

Growth analysis was carried out just prior to harvest for all sites except HM2007. Total biomass and total N uptake were strongly influenced by applied N rate, but differences between sowing dates or variety were rarely significant and there were few interactions. The full data set is presented in Annex 6 for reference. Total dry matter (biomass) when averaged across treatments within each site and season was broadly related to grain yield (Figure 2) with BW2007 being the main outlier, where lodging reduced grain yields.

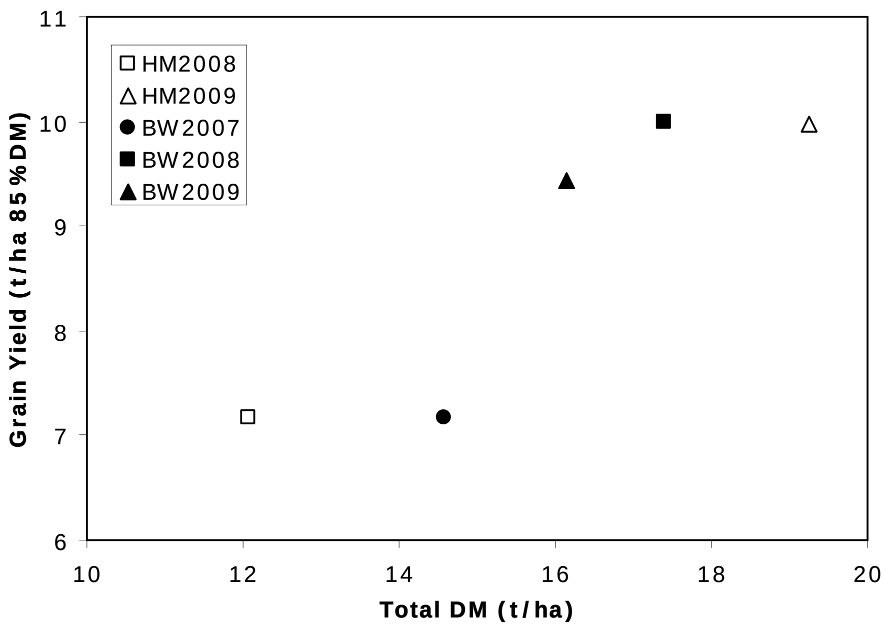


Figure 2. Relationship between combine harvested grain yield at the economic optimum, and total dry matter from growth analysis, for 5 site x season combinations (data points are averaged across variety and sowing dates at each location).

The dry matter and nitrogen harvest indices (DMHI and NHI) were also measured at harvest. Again, sowing date had little effect (only being significantly lower in the early sowing at BW2007) and variety also had little effect, with Hereward having lower DMHI at BW2008, HM2008 and BW2009. The difference between varieties was less apparent with N partitioning, with Hereward only having a significantly lower NHI in one location, BW2008 (full data set in Annex 6), which explains why it tends to have higher grain protein. Because of the small size of the varietal effect, this is not considered further here. In contrast, N applications significantly affected DMHI and NHI in 7 out of 10 experiments were growth analysis was carried out.

The responses to applied N are summarised in Tables 7 and 8 (individual variety x sowing date data are presented in Annex 6). However although the N effect was usually significant, the direction of the response was not consistent: Generally the second applied N rate (after zero N) increase harvest index and the response then plateaued. However, at BW2007 there was no effect of N rate on DMHI (Table 7). Although there were some broad trends for instance high NHI in the high yielding crops (HM2009, BW2008 and BW2009) and low NHI in BW2007 there was no consistent relationship which could be used as the basis for improving forecasts of grain protein content.

Table 7. Effect of N rate on dry matter harvest index (averaged across varieties and sowing dates) for 5 site x season locations 2007-2009.

Site and season	Applied N level					Sig.†	LSD (5%)
	1	2	3	4	5		
BW2007							
N rate (kg/ha)	0	110	220	270	320		
DMHI (%)	47.0	49.8	47.1	42.3	48.5	ns	8.38
BW2008							
N rate (kg/ha)	0	75	150	225	300		
DMHI (%)	46.1	46.8	51.2	51.6	50.5	***	2.61
BW2009							
N rate (kg/ha)	0	110	220	270	320		
DMHI (%)	48.1	50.9	52.6	50.7	51.3	***	2.30
HM2008							
N rate (kg/ha)	0	75	150	225	300		
DMHI (%)	47.1	51.0	53.2	52.4	53.2	***	1.92
HM2009							
N rate (kg/ha)	0	140	280	320	380		
DMHI (%)	53.7	56.8	58.1	57.7	58.2	***	2.06

†, Significance: ns, not significant; *, $p<0.05$; ***, $p<0.001$

NHI was higher than DMHI and also showed a strong response to applied N (Table 8.). Again the effect was not consistent: At HM2008 and HM2009 there was no significant effect of applied N on NHI; at the other sites where the N effect was significant, at BW2007 and BW2009, NHI decreased in response to applied N, while at BW2009, NHI increased in response to applied N.

3.3.3. Performance of commercial farm crops

Growth analysis carried out during, and at the end of the season allowed an estimate of grain yield and DM partitioning within the farm crops. Table 9 summarises the key parameters of growth at the MR stage and at final harvest across the 245 fields sampled. Average grain yields of the commercial crops in the three study years (10.8, 11.5, 10.7 t/ha) show the same trend to the GB yields shown in Table 3 (7.2, 8.3, 7.9 t/ha) with 2008 being the highest yielding year.

Table 8. Effect of N rate on nitrogen harvest index (averaged across varieties and sowing dates) for 5 site x season locations 2007-2009.

Site and season	Applied N level					Sig.†	LSD (5%)
	1	2	3	4	5		
BW2007							
N rate (kg/ha)	0	110	220	270	320		
NHI (%)	65.1	59.2	56.9	55.8	53.3	***	4.36
BW2008							
N rate (kg/ha)	0	75	150	225	300		
NHI (%)	83.4	82.1	83.5	80.4	75.6	***	1.80
BW2009							
N rate (kg/ha)	0	110	220	270	320		
NHI (%)	73.4	79.4	79.7	80.5	79.3	***	2.65
HM2008							
N rate (kg/ha)	0	75	150	225	300		
NHI (%)	71.0	72.4	72.4	73.1	71.5	Ns	2.99
HM2009							
N rate (kg/ha)	0	140	280	320	380		
NHI (%)	77.5	78.2	77.7	77.1	76.0	Ns	2.45

†, Significance: ns, not significant; ***, p<0.001

Table 9. Summary of dry matter (DM) production, partitioning, grain yield and harvest index (HI) for 245 commercial crops sampled from 2007-2009.

Year	M. Ripe Ear DM (t/ha)	M. Ripe WP DM (t/ha)	Straw DM (t/ha)	Chaff DM (t/ha)	G. yield (t/ha, 85% DM)	Total DM (t/ha)	DM HI (%)
2007							
Mean	7.2	18.2	7.4	2.1	10.8	18.6	49.7
Max	11.4	29.6	11.7	2.9	14.4	25.7	80.4
Min	3.9	10.5	3.8	1.3	6.7	11.7	32.4
Range	7.5	19.1	7.9	1.6	7.8	14.1	48.0
SD†	1.59	3.91	1.75	0.33	1.89	3.16	5.93
N	78	78	76	77	77	77	77
2008							
Mean	7.5	18.9	6.9	2.1	11.5	18.7	52.1
Max	10.8	24.4	9.4	2.6	14.6	23.0	58.7
Min	4.9	13.2	4.1	1.5	7.5	13.1	45.7
Range	5.9	11.3	5.3	1.1	7.1	9.9	12.9
SD	1.26	2.37	1.13	0.23	1.55	2.43	2.62
N	83	83	81	80	81	81	80
2009							
Mean	7.0	16.1	5.8	5.8	10.7	20.7	53.9
Max	11.0	21.7	8.3	8.3	13.8	27.9	60.0
Min	4.5	4.7	3.2	3.2	7.5	13.4	46.0
Range	6.5	16.9	5.1	5.1	6.3	14.5	14.0
SD	1.41	3.16	1.09	1.09	1.46	3.18	2.72
N	83	83	74	74	74	74	74

†, SD Standard deviation

The reason for the higher yields for the study crops may be partly due to overestimates from growth analysis (typically, because growth analysis ignores tramlines and headland losses) but may also reflect the fact that these East Anglian crops are genuinely high yielding crops compared to the national average. One important observation is that in 2007, the crops were more variable, with a wider range of yields and harvest indices. The very low harvest indices in 2007 were probably representative of lodged crops.

Relationships between vegetative dry matter and final grain yield

As one aim of the study was to search for predictors of yield, the ear and whole plant DM was also measured. There was no useful statistical relationship between these parameters and grain yield at the MR stage (Figure 3), or at the flowering stage (data not shown).

For the data in Figure 3, if a linear regression was fitted, the respective R^2 values would be: Ear DM, 0.29; WP DM, 0.29; total DM, 0.56). The fact that total DM is based in part on the grain yield measurement (i.e. the variables are not truly independent) and still has such a low R^2 illustrates the difficulties of using biomass estimates to predict yield. For full dataset see Annex 9. Average grain protein contents for 2007-2009 also followed the national trends (12.8, 12.0, 12.7%; Table 3) with the hand harvested samples from the sample area (those untreated with later foliar N) having proteins of 12.4, 11.0 and 11.8%, and the growers' whole field samples (some of which were treated with late foliar N) having proteins of 12.6, 11.5 and 12.4% (Table 10).

The data in Table 10 confirm the observations of three low protein years, with 2008 being the lowest of the three, the season which also showed the highest N harvest index. For full data set see Annex 8.

Despite the relatively low average grain proteins, a number of growers achieved 13% protein or above. For the samples collected from the sample areas (areas within fields untreated with late foliar N) over the three seasons, 77% of growers (ADAS sample) and 59% (own sample) achieved 12.5% protein, while 16% of growers (both ADAS, and grower-collected samples) achieved 13% protein. For the whole field sample (which include 110 fields to which late foliar N had been applied) 38% of crops achieved 12.5% protein but only 18% achieved 13% protein.

Total N uptake for the commercial crops (average 267 kg/ha, Table 10; Annex 8) over the three year of study was higher than recorded in the field trials: The total N uptake in each field trial (averaged across the top three N rates) was 221 kg/ha (full data set in Annex 6). In the commercial crops, these may be slight overestimates of total N uptake because as noted earlier, growth analysis can overestimate DM production which is an important component when calculating total N uptake. However, the differences between sites within a year, are of more interest, with the range in N uptake being almost as large as the mean in 2007 (251 vs 291 kg/ha).

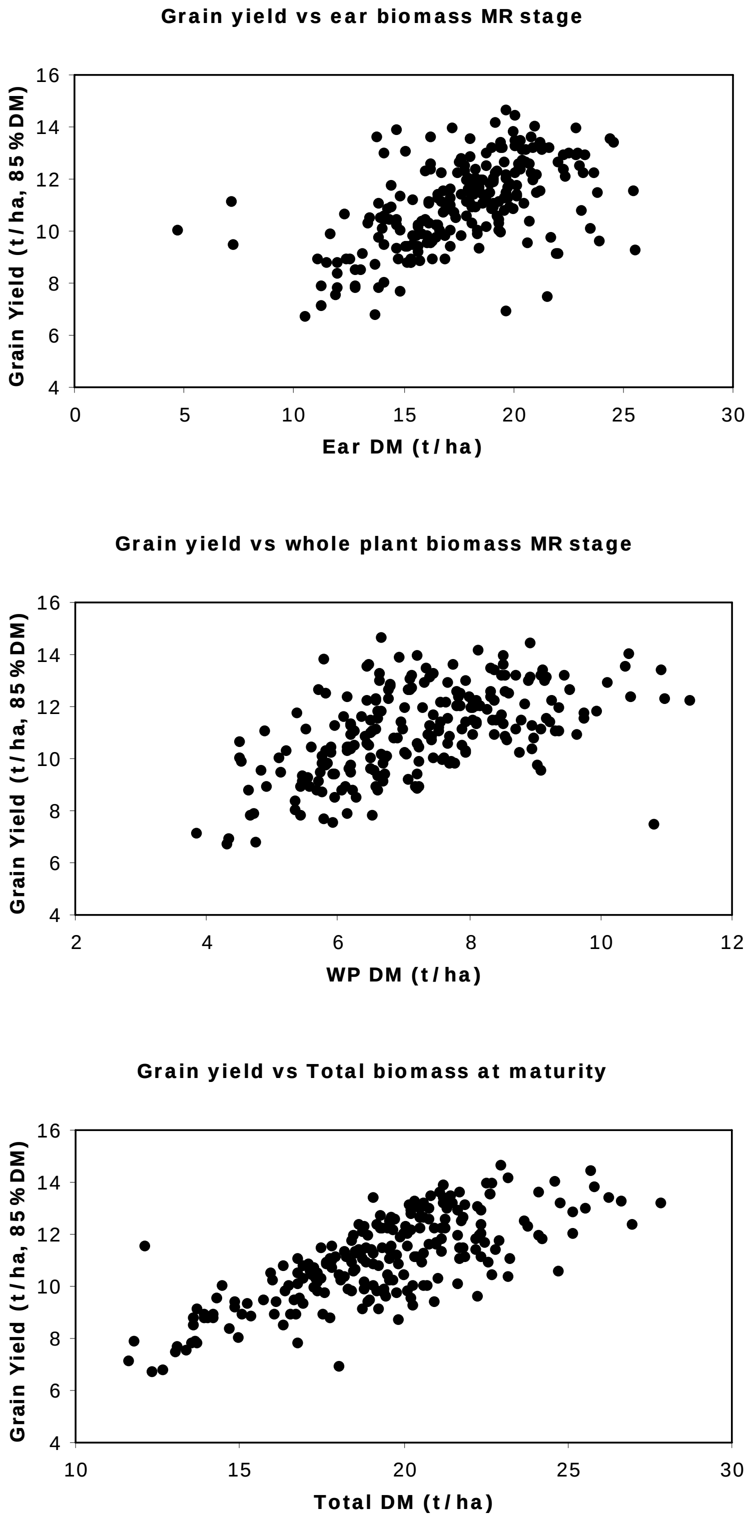


Figure 3. Relationships between grain yield and ear and whole plant dry matter at milky ripe stage, and total biomass at harvest, for 245 commercial crops sampled in 2007-2009.

Table 10. Summary of grain protein, N uptake and N harvest index (NHI) for 246 commercial crops sampled from 2007-2009.

Season	G. protein sample area by ADAS (% DM)	G. protein sample area by grower (% DM)	G. protein whole field by grower (% DM)	Total N uptake (kg/ha)	Grain N offtake (kg/ha)	NHI (%)
2007						
Mean	12.4	12.4	12.7	291	199	69.0
Max	15.2	15.3	15.6	411	276	90.0
Min	10.1	10.1	9.9	160	105	45.8
Range	5.1	5.2	5.6	251	171	44.2
SD†	0.97	1.16	1.10	52.9	35.4	7.71
N	78	69	72	77	77	77
2008						
Mean	11.3	11.0	11.5	239	193	81.3
Max	13.5	12.7	13.3	327	257	87.5
Min	9.0	0.0	9.6	151	127	66.2
Range	4.5	12.7	3.7	176	130	21.2
SD	0.96	1.57	0.80	41.9	30.0	3.91
N	80	75	71	80	80	80
2009						
Mean	12.2	11.9	12.4	270	195	72.6
Max	14.8	13.8	14.2	385	265	79.7
Min	10.0	0.0	10.7	170	127	61.7
Range	4.8	13.8	3.6	215	137	18.0
SD	0.93	1.59	0.63	48.3	32.1	3.66
N	75	80	80	74	74	74

†, SD standard deviation

A summary of the variety means for grain protein, of the 213 crops where variety name was known, is shown in Table 11. Solstice and Xi19 accounted for 70% of the crops studied with an average grain protein content of 12.0 and 11.4%, respectively with no late foliar N applied. Hereward and Soissons, the more widely grown high protein wheats had average grain proteins of 12.6 and 12.8% respectively. Some varieties like Magister and the unnamed RAGT variety which showed very high proteins (>13%) were only grown in single years and the data should be treated with caution.

Table 11. Average grain protein for varieties, where known, for commercial crops from 2007-2009 (NB: samples represent crops which had no late foliar N applied).

Variety	Grain protein (% DM)	Number of observations	Variety as proportion of total (%)
Alchemy	11.4	1	0.5
Battalion	11.6	3	1.4
Cordiale	11.2	13	6.1
Einstein	11.8	15	7.0
Gladiator	10.2	4	1.9
Hereward	12.6	12	5.6
Magister	14.0	2	0.9
Malacca	13.3	4	1.9
RAGT†	13.4	2	0.9
Soissons	12.8	8	3.8
Solstice	12.0	121	56.8
Welford	13.1	1	0.5
Xi19	11.4	27	12.7
	Total	213	100

†, Non-RL variety

Immature crop samples were also collected and analysed for their N content. These data are shown in Table 12.

As seen in the ADAS field trials, the range of N contents was generally greater in whole plant than it was in ear material. However, this was not always the case; the pattern was less clear for samples taken at flowering compared to the MR stage.

Straw and chaff contain only about 25% of the total N in the plant, but 48% of the DM, hence N concentrations are low in these fractions. Of particular note was the low N content in chaff and straw in 2008 (the highest yielding year).

Table 12. Summary of N content in immature material at flowering and milky ripe stage, and in the straw and chaff at harvest for 246 commercial crops sampled from 2007-2009.

Season	Flower. Ear N (% DM)	Flower. WP N (% DM)	M. Ripe Ear N (% DM)	M. Ripe WP N (% DM)	Straw and Chaff N (% DM)
2007					
Mean	1.63	1.61	1.71	1.55	0.97
Max	1.89	2.27	1.88	1.94	1.73
Min	0.78	1.27	1.53	1.21	0.62
Range	1.11	1.00	0.35	0.73	1.11
SD	0.186	0.232	0.086	0.172	0.220
N	40	40	78	78	78
2008					
Mean	1.61	1.50	1.66	1.31	0.50
Max	2.13	2.12	1.83	1.83	0.94
Min	1.34	0.00	1.41	0.98	0.34
Range	0.79	2.12	0.42	0.86	0.60
SD	0.124	0.274	0.096	0.141	0.120
N	83	83	83	83	81
2009					
Mean	1.70	1.41	1.79	1.41	0.64
Max	2.18	2.30	2.09	1.73	0.93
Min	1.56	1.04	1.61	0.99	0.46
Range	2.18	2.30	0.48	0.75	0.47
SD	0.488	0.444	0.093	0.146	0.090
N	85	85	85	85	75

Effect of late foliar N

By asking the grower to take samples both from the sampling area and from the whole field, it was possible to assess the benefit from applying later foliar N (as urea), in those instance where late N was applied. Over the three years of study, where data were available, 95 plots received late foliar N, with rates applied varying between 20 and 100 kg/ha. Most commonly where late foliar N was applied, growers applied 40-49 kg/ha, although a large number applied less than 40, which brought the overall average rate of N applied to 37 kg/ha. On average, the grain protein in the whole field area was 0.1% higher than in the sample area with no late N, and 0.6% higher with late N (Table 13).

Table 13. Grain proteins (N x 5.7) for samples collected by participating growers from sample area and whole field in 194 crops 2007-2009, where amount of late N applied was known, and grain samples had been collected by grower.

Amount of late N applied (kg/ha)	Grain protein sample area (% DM)	Grain protein whole field (% DM)	Protein difference (% DM)	No. of obs.
Nil	12.0	12.1	+0.1	99
20-36	11.8	12.3	+0.5	33
40-49	11.8	12.5	+0.6	57
50-100	11.1	11.8	+0.7	5

In broad terms, growers were correct in identifying the group which showed the highest grain proteins in the sample area (12.0%) and would be less likely to need late N, and conversely, applied the largest amount of urea to the group which showed the lowest proteins untreated (11.1%). However, given the magnitude of the sampling errors involved, these differences cannot be considered significant. The average increase in grain protein amongst the untreated crops between sample area and whole field showed a fairly even distribution as follows: crops where there was a reduction in protein (47%); crops where late N had no effect (9%); crops where an increase in protein was seen (44%). The corresponding values for crops treated with late foliar N were: reduction in protein content 19%, no effect 4% and increase 77%. The numbers of crops which exceeded the 13% grain protein threshold is considered further in the modelling section.

It should be noted that given the uncertainty in measurements of N using the reference methodology (ca. ±0.3% protein for single determinations). Therefore, small differences in protein content should be treated with caution where there are small sample numbers (e.g. the 50-100 kg/ha applied group where n=5; Table 13).

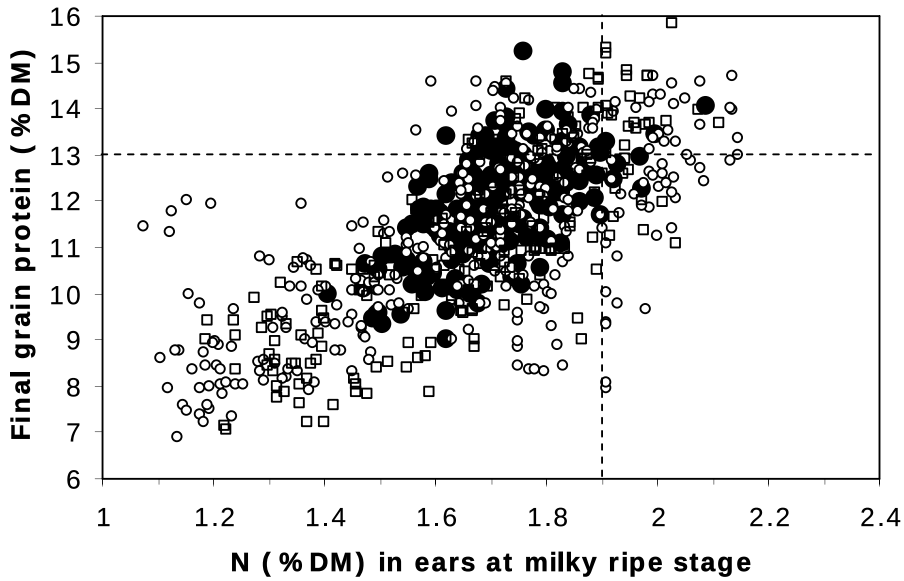


Figure 4. Final grain protein (N x 5.7) plotted against ear N% at the milky ripe stage: Data from the previous MALNA project (□); current project field trials (○) and commercial crops (●).

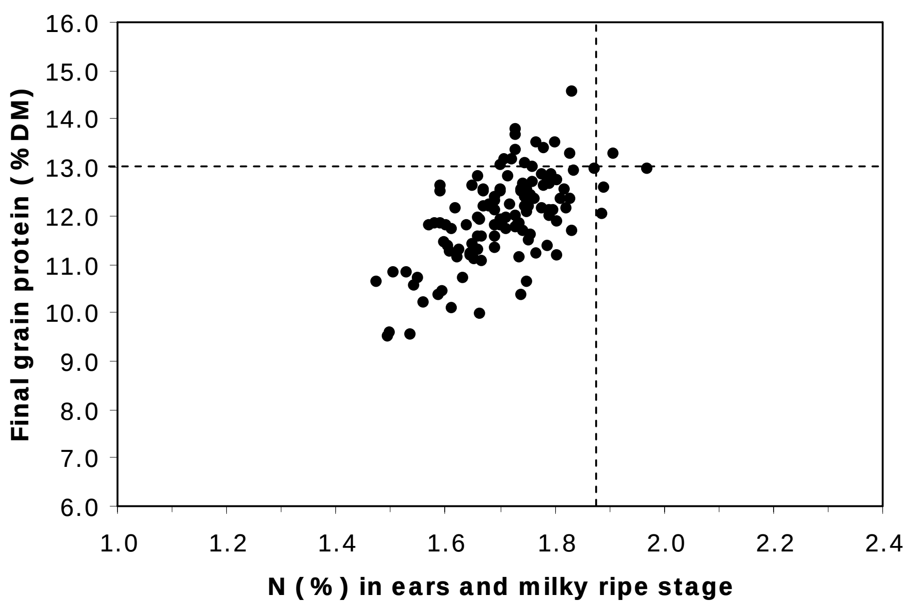


Figure 5. Final grain protein (N x 5.7) plotted against ear N% at the milky ripe stage for commercial crops of Solstice 2007-2009.

Relationships between N in immature plants and final grain protein

Figure 4 shows final grain protein (samples collected by ADAS, no late N applied) plotted against N% in the ears at MR stage (the relationship identified in the previous MALNA project). The data show that the field experiments in 2007-2009 had a similar range in ear N concentrations as the material studied in the previous project, but that the commercial samples exhibited a narrower range in ear N and grain protein. The cross hairs show the position of 13% grain protein, and the ear N value of 1.9% (see Table 6 and related discussion). Although not apparent from the diagram because of superimposition of data points, the farm crops appeared to have higher protein at a given level of ear N than did the samples field experiments. This is considered later in the modelling section

It was of interest to see whether a single variety gave a clearer example of the relationship between final grain protein and ear N. As Solstice made up 57% of the commercial crops studied, the data for this variety are shown in Figure 5. As above, the cross hairs show the position of 13% grain protein and the ear N value of 1.87% in this case.

3.3.4. Development of NIR calibrations

In each season, samples were taken from both farm crops and field trials, fresh samples scanned using the Matrix-I NIR equipment, and reference measurements made of N content in the DM, and moisture content. Calibrations were then built by Bruker Optics for both ears and whole plant material, adding the new data (up to 1210 data points for each) from the present project, into the calibrations developed in the previous project (219 samples). Of most interest, are the calibrations for N%, for which performance is shown in Figure 6 for ears, and Figure 7 for whole plant material. As with the reference data, the samples from commercial crops presented a much narrow range of predicted N% values than those from N response experiments.

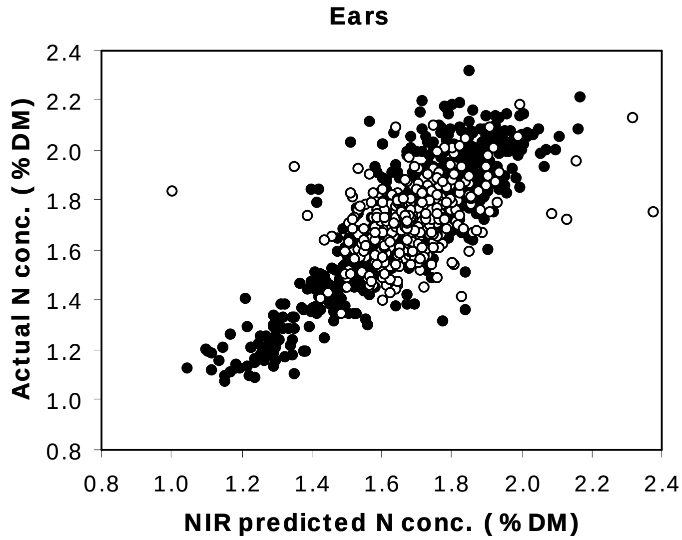


Figure 6. Nitrogen concentration in fresh ears measured by reference method (Dumas combustion), plotted against N concentration predicted using an NIR calibration for data from field experiments (●) and commercial crops (○), 2007-2009.

The data in figures 6 and 7 combine both flowering and MR samples, from which a single predictive calibration was built. The different data sets are shown in more details in Annex 10. Essentially the flowering and MR data overly each other in the scatter plots, but the flowering data tended to be more variable than the MR samples, both for ears (Fig. A9) and whole plant (Fig. A12).

These data support those from the field experiments, in that the whole plant material has a wider range of N content than does ears, and this is also reflected in the NIR predictions.

Calibrations for predicting moisture content in ears and whole plant were also developed. Plots showing actual vs predicted moisture content are presented for ears (Figure 8) and whole plant (Figure 9). The full data set presented by individual field trials, and separate plant components is shown in Annex 9.

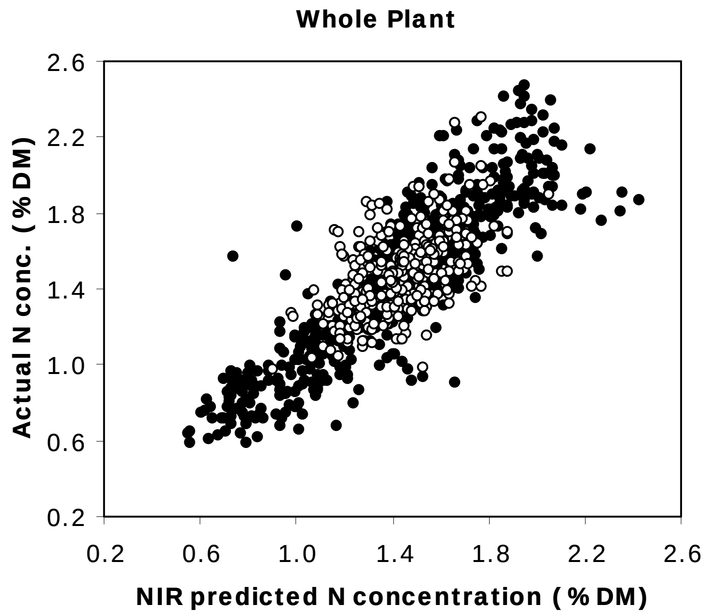


Figure 7. Nitrogen concentration in fresh whole plant measured by reference method (Dumas combustion), plotted against N concentration predicted using an NIR calibration for data from field experiments (●) and commercial crops (○), 2007-2009.

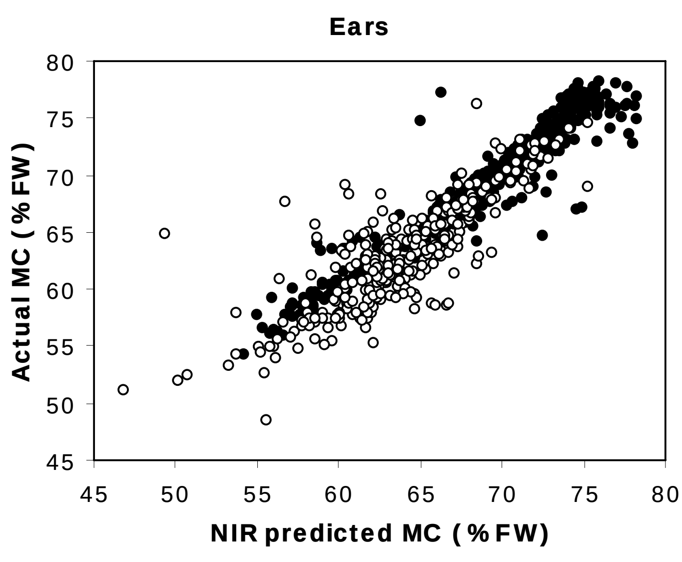


Figure 8. Moisture content (MC) of fresh ears measured by reference method (oven drying), plotted against MC predicted using an NIR calibration for data from field experiments (●) and commercial crops (○), 2007-2009.

Moisture content is potentially important, because the NIR calibration for N needs to account for moisture when expressing the N content on a dry basis. Also, it is possible that together with fresh weight, MC could be used to estimate total biomass and hence, yield (if total DM at flowering or MR could be used as predictors of yield). Finally in the case of ears, moisture could be used as a surrogate measure of crop maturity, in order to adjust the ear N measurements in a simple empirical method. In contrast to the position with N, it was found that the range in moisture content was slightly greater (range 55-80%) in ears than in whole plant (60-80%).

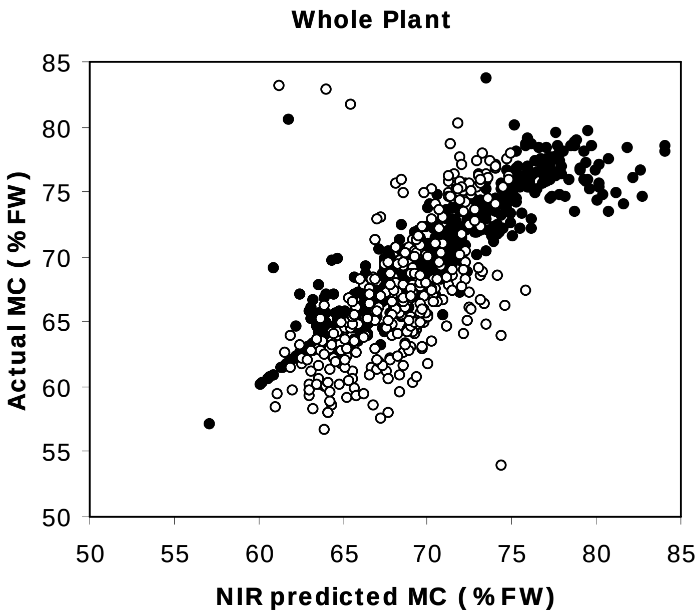


Figure 9. Moisture content (MC) of fresh whole plant measured by reference method (oven drying), plotted against MC predicted using an NIR calibration for data from field experiments (●) and commercial crops (○), 2007-2009.

3.3.5. Modelling approaches using reference data

Semi-mechanistic model

The first modelling approach examined in this project scoped out the development of a semi-mechanistic model that would explicitly predict final harvest yield and thus take into account grain protein dilution by yield in each year. The hypothesis was that taking into account the grain yield and expected N uptake would provide a means of providing a robust forecasting system. Central to this approach would be the necessity to estimate biomass and N increments and model their re-distribution, using measurable field data as model inputs.

For the model performance with field experiment data illustrated in Figure 10a, for n= 60 the standard deviation on the prediction error (observed – predicted) is 0.51 tonnes/ha with the average prediction error 0.55 tonnes/ha $\pm$ 0.13. For the model illustrated in Figure 10b, for n= 60 the standard deviation on the prediction error (observed – predicted) is 0.55 tonnes/ha with the average prediction error 0.47 tonnes/ha ± 0.14. For the model illustrated in Figure 10c, for n= 58 the standard deviation on the prediction error (observed – predicted) is 0.86 tonnes/ha with the average prediction error 0.22 tonnes/ha ± 0.21. For the model illustrated in Figure 10d, n= 58, the standard deviation on the prediction error (observed – predicted) is 0.86 tonnes/ha with the average prediction error 1.4 tonnes/ha ± 0.22.

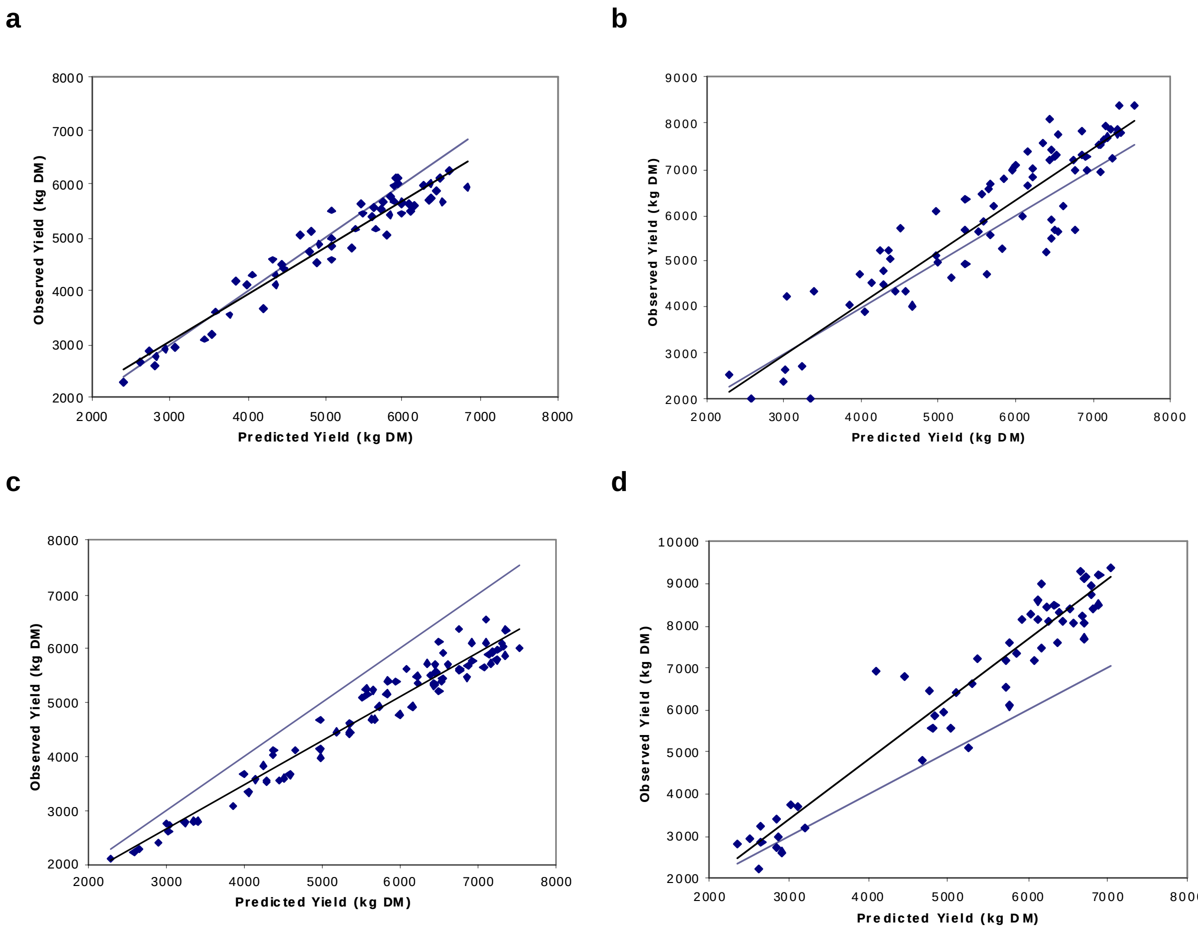


Figure 10. Modelled (predicted) and measured (observed) harvest yields for a) the MALNA 1 Boxworth trials data set 2003, b) the MALNA 1 Boxworth trials data set 2004, c) the Boxworth trials data set 2007, d) the Boxworth trials data set 2008.

Figure 10 presents the model fit for the semi-mechanistic model described above applied to two years of data (2007, 2008) at the Boxworth trials carried out as part of this current project and for the MALNA dataset in 2003 and 2004 at Boxworth for a range of N applications. Whilst the model provides a reasonable prediction in 2003 and 2004, there is considerable bias away from the x=y line in the other years. The model made significant under predictions of yield at Boxworth in 2007 (Figure 10c) and over predictions of yield in 2008 (Figure 10d). It was possible that further development of the model to better represent the grain filling period would correct the bias in these years, but as illustrated by the results for 2003 and 2004, it was not expected to improve upon the precision of the model. Model predictions were expected to agree with measurement with a precision standard deviation of only *ca*. 0.5 t/ha. The potential impact of this on predictions of grain protein is illustrated by Figure 11 which dilutes measured grain N from the co-operative dataset into measured yield adjusted for a random model prediction error of 0.5 t/ha. The figure shows that predicted grain protein concentrations differ from measured by as much as 1% as a result of the uncertainty in predicting grain yield (centred on an average 9.3 t/ha crop measured by ADAS grab samples taken prior to harvest). The magnitude of the error is comparable to that achieved by a simpler regression model that predicted grain protein directly from measurements of ear protein at MR (discussed further in following Section).

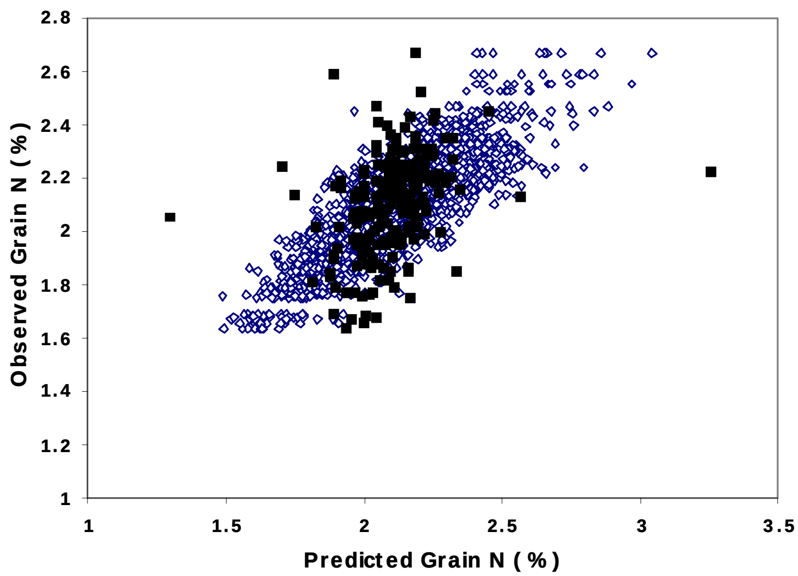


Figure 11. Illustration of the prediction error which occurs from dilution of a known grain N content into an uncertain grain yield. The open symbols plot predicted and observed grain N content assuming a random model prediction error of 0.50 t/ha; the closed symbols plot predicted and observed grain N content using a simpler regression model based only on measured ear N content at milky ripe.

Finally, one of the aims of this project was to assist the farmer or Coop in making the decision regarding application of late N. A decision-making tool which uses a physically-based model would also require a forecast of the mean or minimum temperature and solar radiation levels during the end of June and July when grain filling occurs. Forecasts several weeks ahead are not readily available or sufficiently accurate and would add to errors in the predictions. It should be noted that within the lifetime of the project. Met office forecasts conspicuously failed to predict the cool and wet summers actually experienced (e.g. 2007, 2008).

Clearly, the semi-mechanistic model has merit, providing a useful indication of final yield and being understandable in terms of crop development. However, for the reasons demonstrated above and further parsimony of approach, it was considered that developing an improved statistical approach over that considered in the first MALNA project was the way forward.

Statistical model

The second approach was to use N data from the trials sites at Boxworth and High Mowthorpe to develop a simpler statistical model of final grain protein. Additional regression factors for variety, site, year or weather were explored. The initial plan was that data only for the current project would be used in model development, calibration and validation. The Coop sample data was then used to validate the model and assess the performance of the NIR data collection process and model, as a strategy for increasing the revenue the Coop through achieving the milling wheat premium more consistently.

In order to understand the maximum potential fit the model could achieve, some exploratory analysis of the repeatability of samples and the relationship between the NIR and the reference Leco measurements of N content first had to be made. These are set out below.

Comparison of NIR and Leco data for N content

Trials data

Reference (Leco) data and NIR predictions for plant N content were collected from the trials sites at Boxworth and High Mowthorpe for a range of N treatments 0 to 300 kgN/ha. Figure 12 below presents the relationships between N at flowering and N at MR using both methods, incomplete pairs of data and outliers are removed using Cooks distances (a diagnostic which can be used to identify influential outliers in regression analysis).

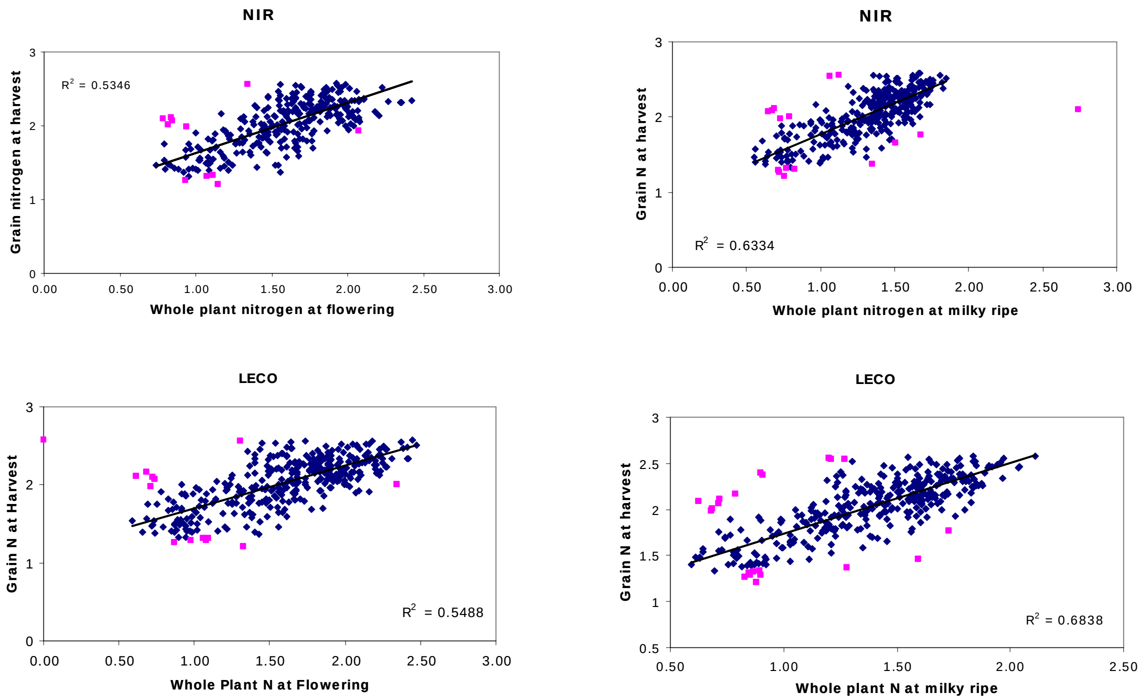


Figure 12. Relationships for the reference (Leco) data and NIR samples between flowering N estimates and Milky Ripe N estimates and final grain N at harvest (%DM) in Boxworth and High Mowthorpe trials 2007-2009. Outliers identified using Cooks distances diagnosis (square symbol).

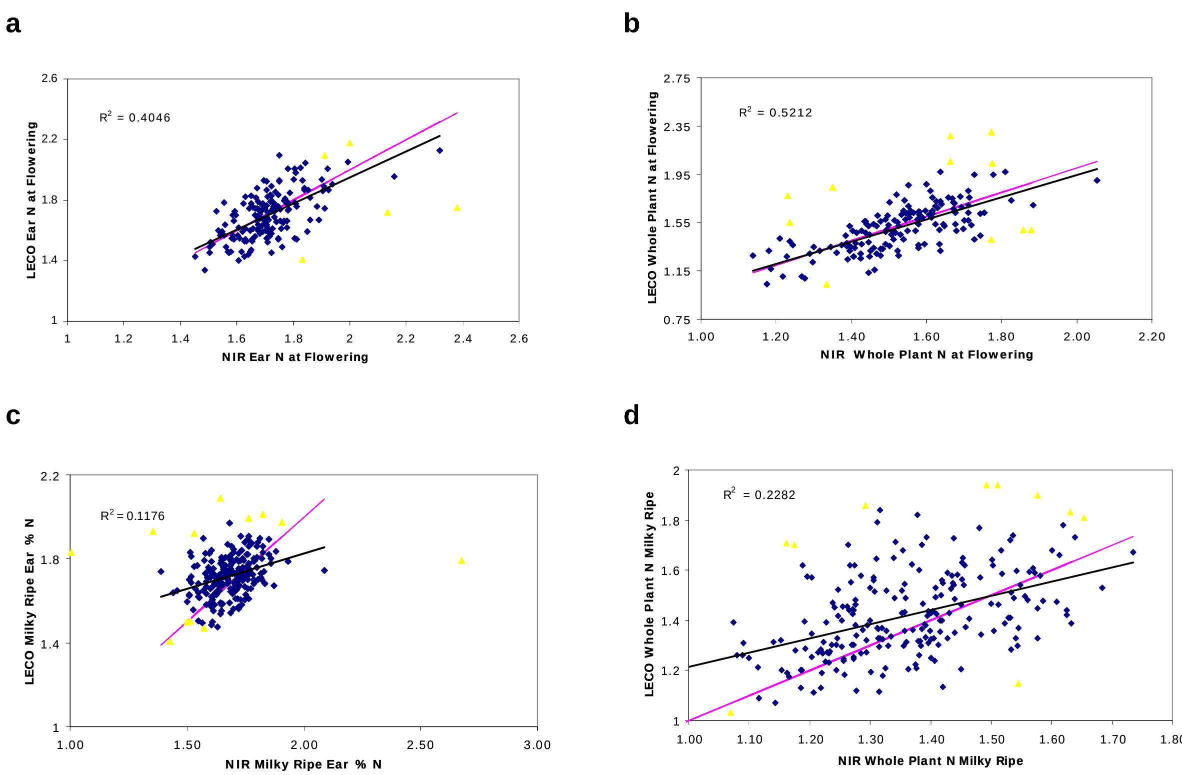


Figure 13. Relationships for the reference (Leco) data and NIR between flowering N estimates and milky ripe N estimates and final grain N at harvest (%DM) for the commercial growers data 2007-2009. Outliers identified using Cooks distances diagnosis (triangle symbol).

Coop data

Figure 13 shows the Leco and NIR relationships whole plant and ears, at flowering and MR, for data collected from growers in all three years. Note the smaller range of observed N measurements in the Coop crops as would be expected since the crops are all well fertilised at commercial levels.

For Figure 13a, n= 164, the standard deviation on the difference = 0.69 and the average difference between NIR and Leco is 0.06 $\pm$ 0.11 as protein (%). For Figure 13b, n= 148, the standard deviation on the difference = 0.76 where the average difference between NIR and Leco is 0.10 $\pm$ 0.12 as protein (%). For Figure 13c, n= 219, the standard deviation on the difference = 0.6 and the average difference between NIR and Leco is -0.19 $\pm$ 0.08 as protein (%) and for Figure 13d, n= 213, the standard deviation on the difference = 0.88 where the average difference between NIR and Leco is -0.34 $\pm$ 0.12 as protein (%).

For both the flowering datasets the bias is positive so the NIR measurements are generally higher. For the MR measurements the opposite occurs with Leco typically reporting measurements 0.26 % protein higher.

Implications of uncertainties in measured data

Clearly there is noise in all of these relationships, some of which is attributable to laboratory testing imprecision, and some to field imprecision (i.e. small number of samples of an inhomogeneous crop). To test the repeatability of the measurements of the same sample in the Leco analysis, high N and low N samples from a mixed cropped and dried crop whole plant samples from the Boxworth site which were from three 0.5 m^2 quadrats were sent to the laboratory to check for consistency of sampling (Figure 14). With repeatability standard deviations of 0.02-0.03% as N (95% confidence limits 0.04-0.06 as N) the additional 80% of the variation (~ 0.3 N or 1.71 as % protein) observed in the measurements was attributable to lack of homogeneity in the samples. Clearly, this is quite large and has implications for limits on potential model fit, it is considered that samples for ear N should have less scatter.

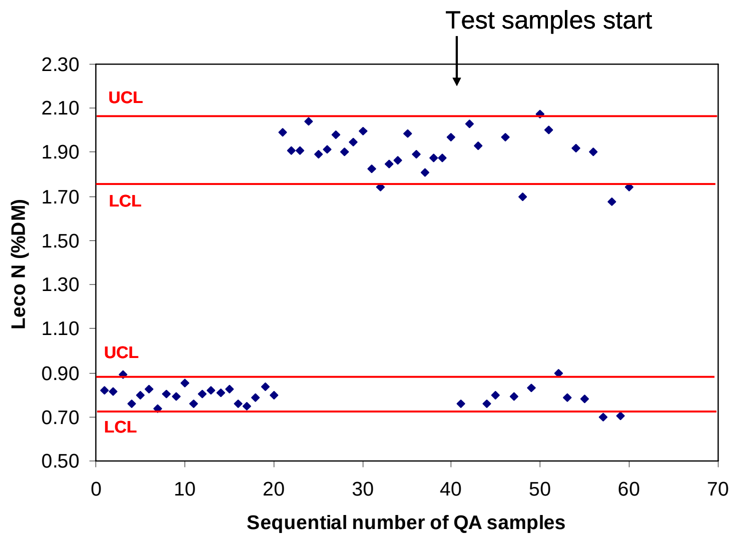


Figure 14. Reported N content of whole wheat determined by Leco (Dumas combustion) for either high or low N wheat samples. Horizontal lines; 95% confidence intervals for each data set.

Figure 15 compares the measurements of the same sample at MR using the Leco and NIR methods to help understand whether the NIR is a satisfactory replacement for Leco. As before, Cook distances have been used to remove outliers, 16 in total. The standard deviation of the difference between measurements is 0.5 (n 336) as % protein. There was a bias with the Leco on average 0.2 $\pm$ 0.054 % protein greater than the NIR samples. This is another form of error which will affect the model.

Sampling issues: Repeat measurements of the sampling area

For the Coop data 2007 to 2009, each of the commercial fields included a small area where no late FU was applied. In addition, some of the farms chose not to apply late FU to the rest of the field. Measurements of grain N content from the field sample areas that did not receive late urea N are, therefore, used to quantify the variability due to sample size and spatial variability.

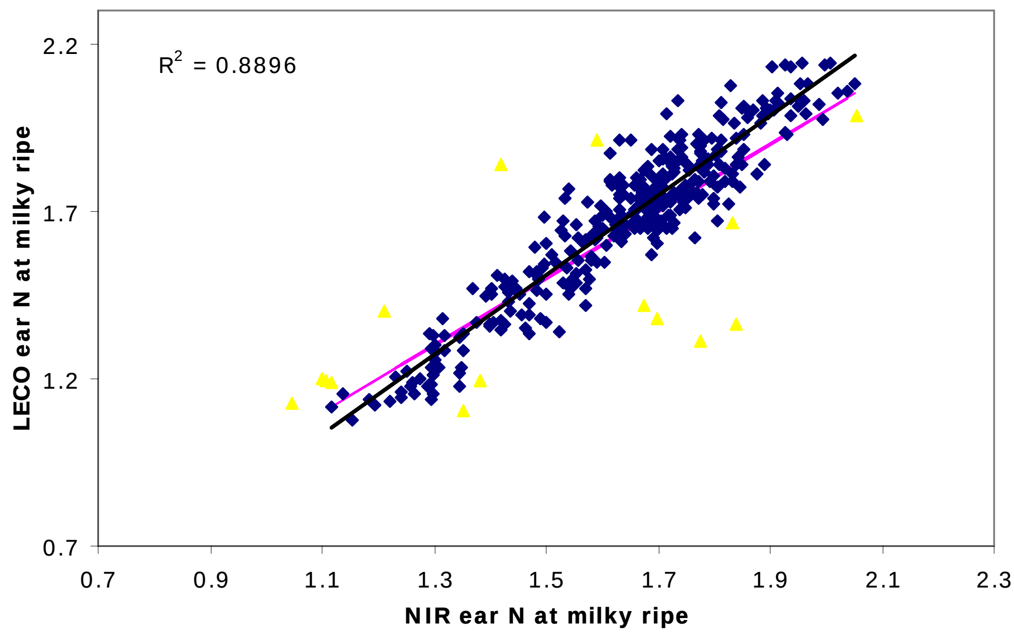


Figure 15. Relationship between NIR ear N measurements at milky ripe and Leco ear N measurements taken on the same sample.

For these fields where no FU was applied, the farm combine grain protein from the whole field and the farm combine grain protein from the sample area were used to quantify spatial variability. For this test, 7 samples were excluded as outliers using Cooks Distance test. The SD of the difference between percent nitrogen estimates as % protein was 0.44 (n 103) where the average difference between NIR and Leco is -0.03 $\pm$ 0.08 as protein (%). These data (Figure 16) are indicative of the small amount of statistical noise that will further confound any attempt to relate plant and grain N content based on samples taken at different times and from different areas of a field.

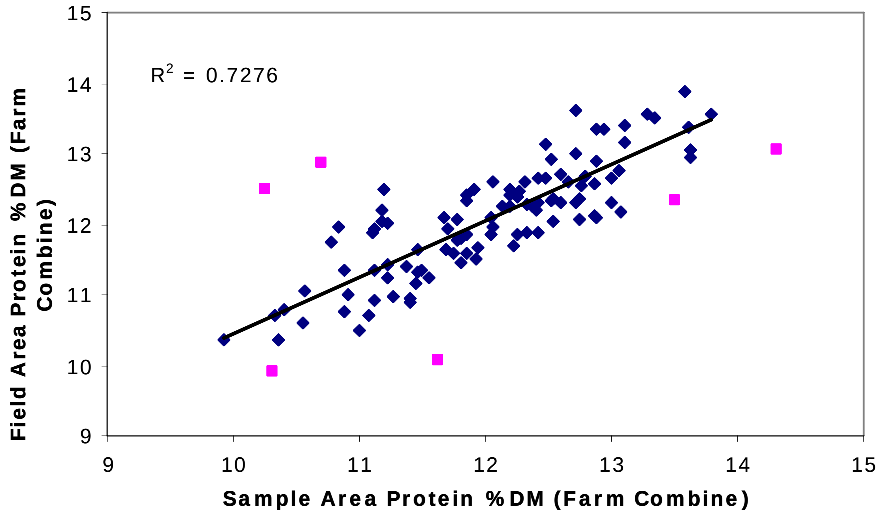


Figure 16. Grain protein content (%DM) from field sample and whole field areas that did not receive late urea nitrogen, by analysis of samples from the farm combine (grower Cooperative data, 2007 to 2009).

The similarity of the SD of the difference between percent protein estimates in Figures 15 (0.5) and Figure 16 (0.44) suggest that the noise in the scatter results largely from small scale variation (or laboratory) error, as the samples taken in the sample area and the main field were located quite closely.

Figure 17 (N = grain protein/5.7) illustrates that there is some evidence of the declining effect of the late FU with increasing grain N content i.e. this suggests that additional N was taken up only when the grain was N deficient. The figure plots the difference between grain protein contents of the whole field area (which received FU) and the field sample area that did not receive urea N, versus the grain protein content from the sample area, and supports the earlier conclusions of Dampney *et al*. (2006).

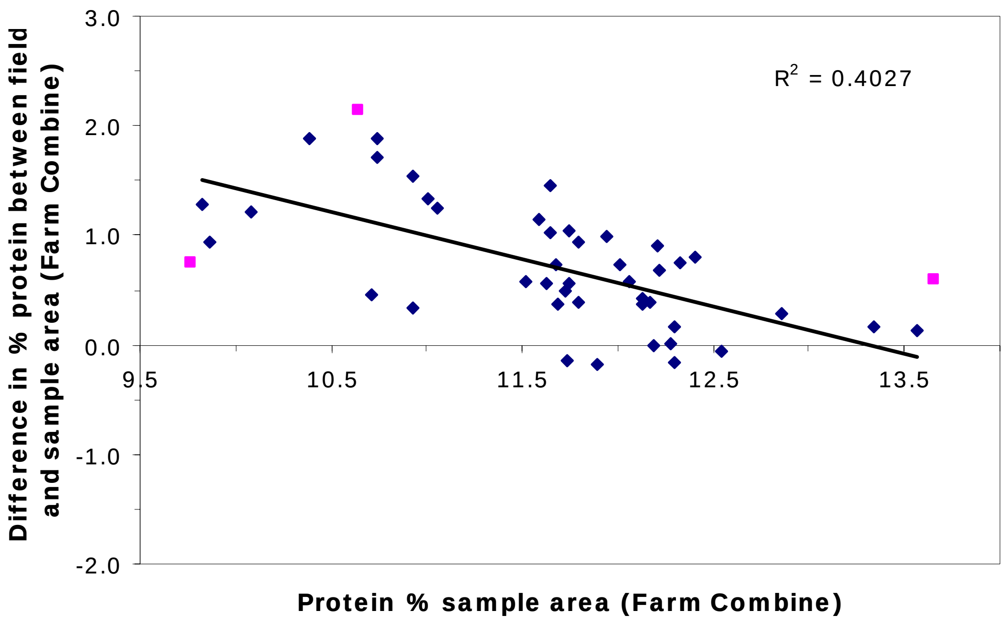


Figure 17. Difference between grain protein content on field and sample areas as a function of sample area grain protein content, for whole field areas that received late urea nitrogen, by analysis of samples from the farm combine (grower Coop data, 2007 to 2009).

Multivariate statistical analysis

To identify the best statistical model from the field trial experiments a forward stepwise multiple regression analysis was carried out. Selecting forward stepwise in Statistica ensures that the independent variables are added at each step of the regression if they improve the model significantly, otherwise they are discarded.

It was assumed that the model could include N, moisture and DM data collected at either flowering or MR but without pooling both sets of data. This was because we have assumed that any future NIR system would sample only at one growth stage and as such it was necessary to determine which produced the better forecast of protein at harvest. In the same way, data for ear N and whole plant N are treated separately as it was assumed that any future systems would sample one or the other in order to minimise costs.

This analysis was carried out for both the reference crop Leco dataset and the NIR data to check whether there was a distinct difference in model performance between the two measurement types. In all, between 189 and 239 samples were used, this varied as generally there were more missing data samples in the flowering data set than for MR.

All the measurements of ear and whole plant N at flowering and MR for the zero N application were omitted from the analysis. In addition, the Boxworth trials data for 2007 was removed; as seen in

Figure A6 of the Appendix the N application rate and yield relationship breaks down from normal behaviour as a result of poor crop establishment. This resulted in a distinct cloud of outliers from this trial. Finally, one other very distinct outlier was removed from the MR whole plant N (NIR) data of 2.74 (15.6 % protein) which was a 2009 High Mowthorpe Einstein sample (Plot 47, Block 3), this outlier can be seen clearly on Figure 13c. Cooks distance diagnosis was not used to remove any further outliers for this analysis.

Table 14 below shows the best fit models of grain protein at harvest from measurements made at flowering and MR. The standard error and p-value, respectively of each parameter are given in parenthesis. The multivariate analysis explored the influence of variety on model fit. Only the Hereward and Xi19 varieties were included in the multiple regression analysis, as these were the only two varieties available in all years. Inclusion of the Einstein and Solstice which were only planted in 2009 could otherwise represent a year specific factor. The models presented in Table 14 have either ear N or whole plant N as an independent variable along with a dummy variable that identifies Hereward as being distinct from Xi19. In two of the models, the moisture content of the ear or whole plant is included as a significant variable.

For all the models, a variety factor improved the model performance. On two occasions, the moisture content of the sample became a significant parameter in the multiple regression analysis. However, in both cases it did not add a great deal to the overall R^2.

First, it is important to note that the model fits as measured by R^2 for the NIR data are comparable to those for the Leco data, which confirms that neither set of data is substantially better than the other at predicting the grain protein across the set of trials data.

Table 14. Trials data regression modelling results (standard errors on the model parameters and p-values[†] are given in the parenthesis respectively for ear and whole plant samples at either flowering (FL) or milky ripe (MR) growth stages.

Predicting grain N at harvest using ear N data

Sample type	**Growth stage**	**Nobs***	**Intercept**	**Ear N**	**Ear % moisture**	**Hereward Factor**	R^2
NIR	MR	188		1.179 (0.0106 ***)		0.196 (0.0256 ***)	0.61
Leco	MR	189	0.2156 (0.100 *)	1.02 (0.055 ***)		0.187 (0.024 ***)	0.66
NIR	FL	184	-1.438 (0.4409 **)	1.046 (0.1166 ***)	0.02 (0.0058 ***)	0.21 (0.034 ***)	0.41
Leco	FL	189	0.318 (0.1488 ***)	0.922 (0.0789 ***)		0.187 (0.0313 ***)	0.45

Predicting grain N at harvest using whole plant N data

Sample type	**Sample time**		**Intercept**	**Whole Plant N**	**WP % moisture**	**Hereward Factor**	R^2
NIR	MR	188	0.846 (0.075 ***)	0.84 (0.051 ***)		0.14 (0.026 ***)	0.61
Leco	MR	189	2.014 (0.3246 ***)	0.847 (0.051 ***)	-0.0177 (0.0054 ***)	0.096 (0.233 ***)	0.706
NIR	FL	186	0.836 (0.093 ***)	0.69 (0.052 ***)		0.128 (0.029 ***)	0.51
Leco	FL	189	1.152 (0.0727 ***)	0.499 (0.039 ***)		0.14 (0.029 ***)	0.49

[†], Significance values: *, p<0.05; ** p<0.01; ***, p<0.001.

*, Nobs: Number of observations

The data collected at MR (GS 75) however does produce a much better regression using either ear or whole plant data than samples collected at flowering (GS 61). From a grower's perspective a model at flowering would be preferred as this would allow more time for making the decision to add a late fertiliser application and schedule late foliar N applications.

The best overall NIR model of grain protein at harvest required measurements of N at MR. For the whole plant N the R^2 = 0.61 includes the modifier for the Hereward variety, which increased the predicted grain protein by 0.91%DM on average. Figures 18 and 19 below show the predicted versus measured data using the two NIR models at MR. Their prediction errors are calculated as another independent measure of model fit.

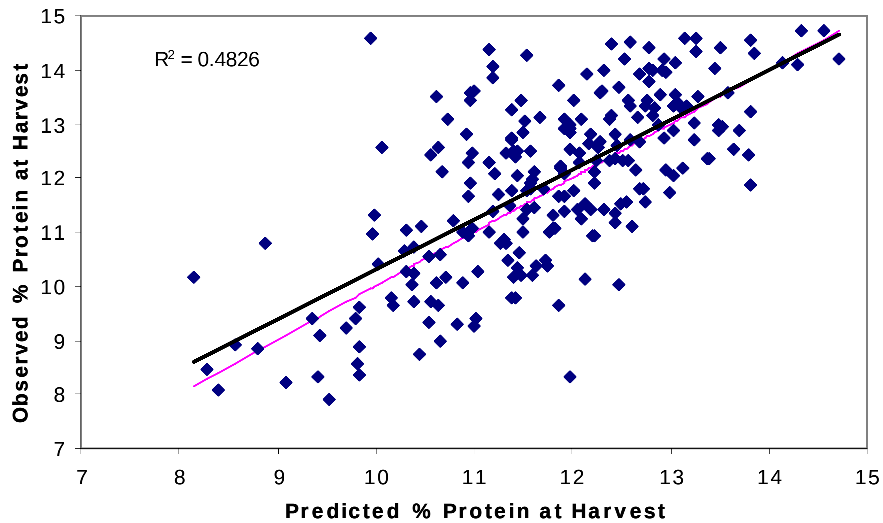


Figure 18. Predicted versus observed grain protein (%DM) at harvest using the model for NIR ear measurements given in Table 14.

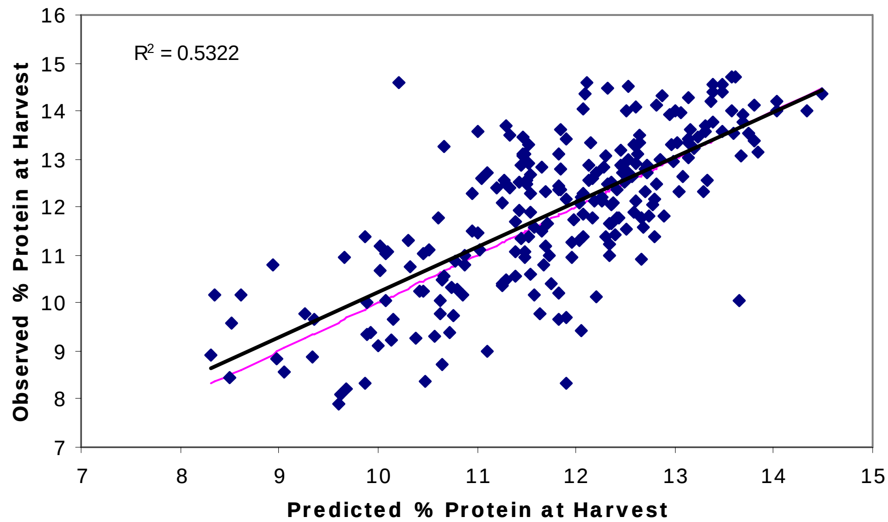


Figure 19. Predicted versus observed grain protein (%DM) at harvest using the model for NIR whole plant measurements given in Table 14.

For the model illustrated in Figure 18, n= 234, the standard deviation on the prediction error (observed – predicted) is 1.10 % protein with the average prediction error 0.12 ± 0.14 as % protein. For the model illustrated in Figure 19, for n= 235 the standard deviation on the prediction error (observed – predicted) is 1.16 % protein with the average prediction error 0.17 ± 0.15 as % protein.

For the model shown in Figure 18, with whole plant N as a predictor, the root mean squared deviation (RMSD) is 1.109 as % protein. For the model shown in Figure 19, with the ear N as a predictor the RMSD is as 1.178 % protein. All these statistics illustrate that the models are in fact similar in their performance.

Initial validation using the Coop data

The best statistical model predicts final grain protein from NIR measurements at MR as a function of whole plant N with a modifier for the Hereward variety. This model was identified from the field trials dataset and set out in Table 14.

The Coop whole plant N measurements at MR and measured by NIR (only those growers who did not apply late FU) were used to predict grain protein at harvest for the commercial growers, using the regression model identified in Table 14. However, as can been seen in Figure 20, the resultant graph of predicted Coop final grain protein versus observed final grain protein N shows poor correlation with an R^2 of only 0.12.

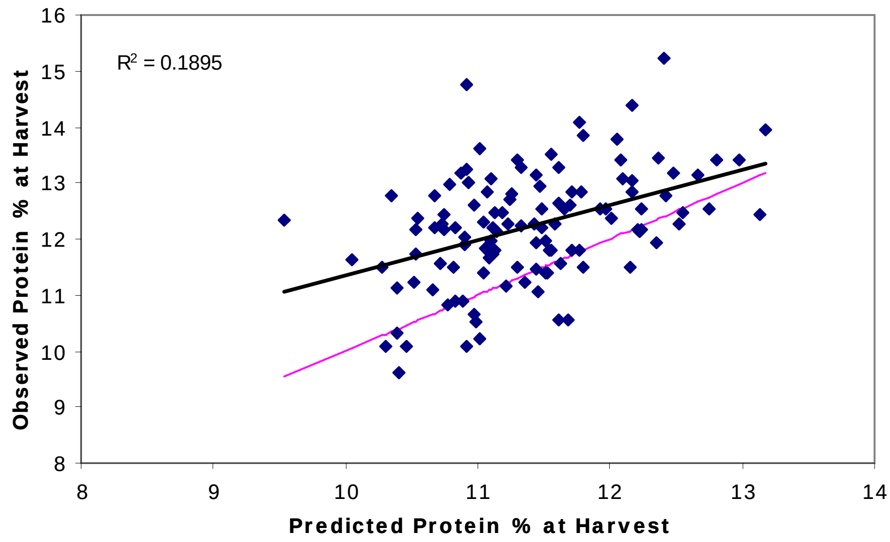


Figure 20. Predicted Coop protein at harvest versus observed Coop protein at harvest using the regression model with whole plant as a predictor developed using the trials data.

The Coop data have a much smaller span of grain proteins because all the crops are fertilised at commercial rates, as was shown in Figure 5 and this in part contributes to the poor R^2 and makes it difficult to compare R^2 values with the trials model (Figure 19). For n= 117, the standard deviation on the prediction error (observed-predicted) is 0.94 % protein with the average prediction error 0.84 $\pm$ 0.17 % protein. The prediction errors can be compared with those calculated for the trials model and clearly the error is now much larger. More importantly protein was significantly under-predicted. For the model shown in Figure 20, with whole plant N as a predictor, the RMSD is 1.585 % protein. Figure 21 illustrates how the Coop data sits within the whole data set; the model clearly is under predicting the final grain N using the model developed on the trials data.

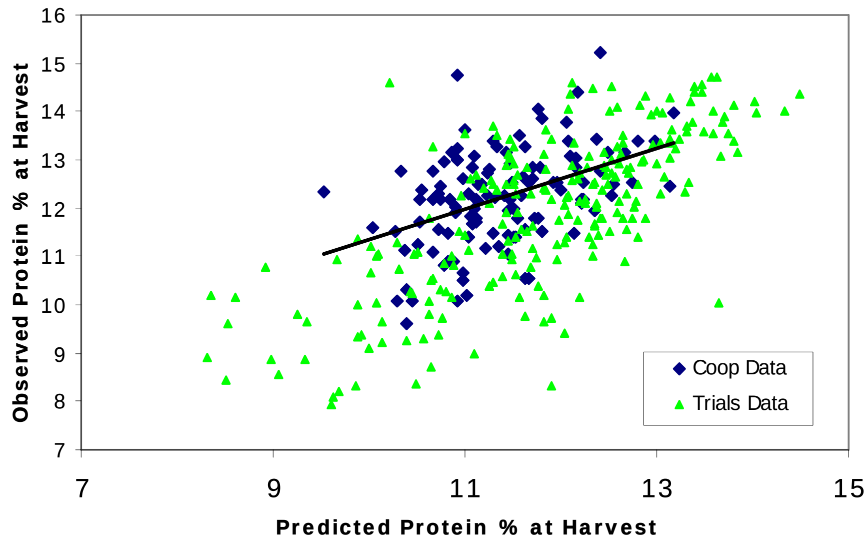


Figure 21. Observed vs predicted Coop protein at harvest using the regression model with whole plant as a predictor developed using the trials data (blue diamond) with the trials data predicted versus observed (triangle data).

The statistics calculated above reflect the observation that for the same whole plant N, Coop final grain proteins are higher than those predicted by the model calibrated at the trials sites. This may reflect the fact that the field trials sites were not truly representative of the milling wheat growers participating in the project, owing to the fact that the Coop groups were in the Eastern region, whereas one of the field trial sites was in North Yorkshire and hence climate, soil conditions and altitude would have been quite different. Moreover, the experimental crops were 1st wheats, whereas where previous cropping was known, 46% of the commercial crops were second or continuous wheats.

Clearly, the bias when applying the model developed for the trials data to the Coop data means that using the trials data to build the model does not result in a good prediction of final grain protein for the growers' crops. It was, therefore, considered necessary to pool the trials data with some of the Coop data, to see if this produced a better model (although this was not ideal as there remained only limited data for subsequent validation).

Modelling using the trials and Coop data as one dataset

The statistics have shown that for the trials data the whole plant N at MR stage was only marginally a better predictor of final grain protein than the ear N. However the sampling accuracy is known to be better for the ear N than whole plant and ideally, any predictive system would prefer ear samples as these are easy to collect and handle. Therefore in the following sections the multivariate analysis was carried out using NIR ear N data only.

All trials data for Hereward and Xi19 which were used to identify the models in Table 14 were included, plus data for Hereward, Xi19 and also Solstice from the Coop dataset (from the growers who did not apply late FU). This resulted in a data set of 260 paired samples. Solstice is the variety grown in all years by the majority of Coop growers and is given a dummy variable code to enable the model to add an extra parameter to correct for the bias observed in Figure 22. The best model between ear N and grain N at MR was identified and is presented in Table 15.

Table 15. Trials data and Coop data regression results (standard errors on the model parameters and p-values[†] are given in the parenthesis respectively.

Nobs	Ear N	Hereward Factor	Coop Factor	R^2
260	1.170 (0.677 ***)	0.199 (0.0238 ***)	0.123 (0.025 ***)	0.57

[†], ***, p<0.001.

Nobs, no of observations

The model identified in Table 15 is illustrated in Figure 22. For n= 260, the standard deviation on the prediction error (observed – predicted) is 0.97 % protein with the average prediction error 0.08 $\pm$ 0.12% protein; this is an improvement on the model developed using the trials data only.

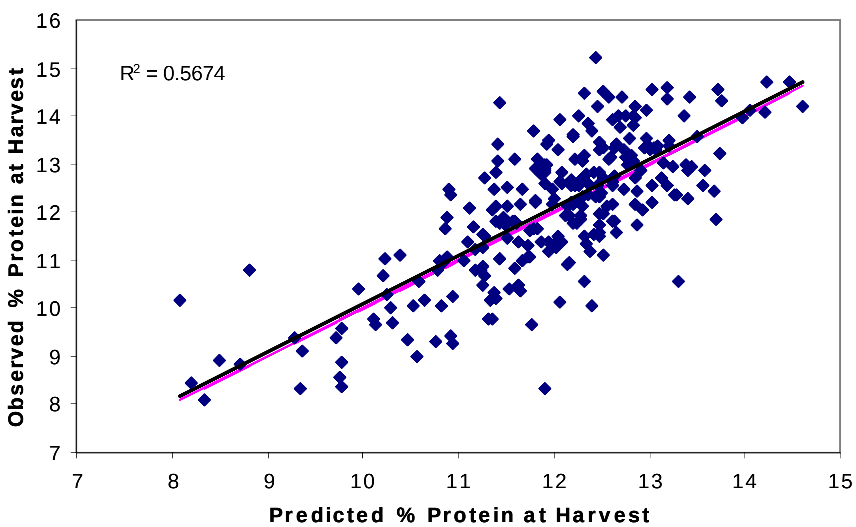


Figure 22. Predicted protein at harvest (Coop and trials data n=260) versus observed (Coop and trials data n=260) protein at harvest using the regression model (Table 15) with NIR ear data as a predictor.

For validation, the model is applied to the whole data set (n=346) which now includes all the other Coop varieties, plus the Einstein and Solstice varieties from the trials data in 2009 (Figure 23) for the growers samples who did not apply late FU. The standard deviation on the prediction error (observed – predicted) is 1.08 % protein with the average prediction error 0.25 ± 0.11 % protein. For the Coop data, this new model reduces the bias that is seen in Figure 20.

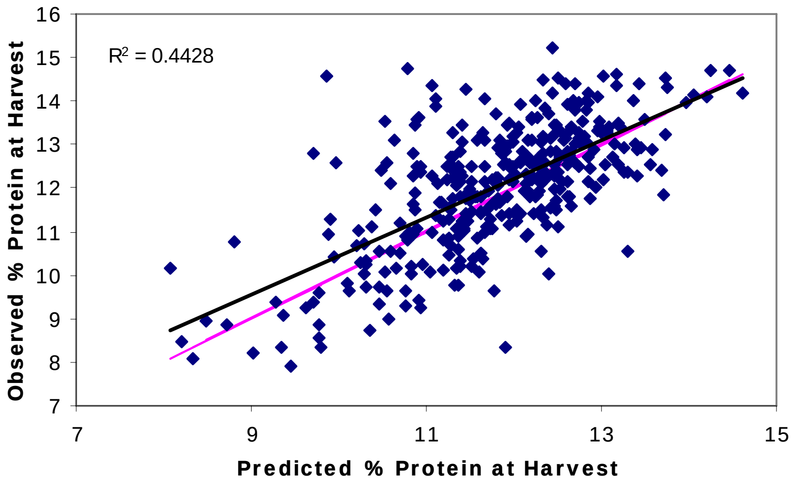


Figure 23. Predicted protein at harvest (Coop and Trials data) versus observed protein at harvest using the regression model (Table 15) with ears as a predictor (n obs 346).

In the sections above, a number of statistical models were examined, based on various options using ear or whole plant immature N as predictors with a number of modifiers. The final model is based on a combination of ADAS trial data and three varieties from within the Coop data. While a true, fully independent validation of the model could not be carried out (this could only be achieved by testing in subsequent seasons) this model was then taken forward in the following section to see how well it would have performed in various scenarios, and compared to the actual decisions the Coop growers made.

3.3.6. Financial assessment of protein prediction model

The next step was to see whether using the model to make a decision regarding application of late foliar N and the associated costs and benefits compare well, relative to what the grower group actually did in 2007-2009.

In years 2007-2009, there were 234 grower samples of crops in which whole plant or ear N at MR, harvest protein and harvest grain yield were measured, and late N use recorded. Additional growers who did not have all of these measures were not included in this analysis. Of the 205 complete crop records, 84 added late foliar N, with an average application of 37 kg/ha (range 20-100 kg/ha), to the varieties, Battalion, Cordiale, Einstein, Hereward, Malacca, RAGT, Soissons, Solstice and Xi19. There was no evidence for any single variety being more likely than others to receive a late urea application. On average, the farmers who applied late foliar N saw a protein increase of 0.74%.

Of the 205 samples, 64 exceeded the protein threshold of 12.5% at harvest (the minimum to trigger a premium). However, only 17 of the 64 had added late foliar N. It is not known what the decision making process was for those 47 fields which did not have a late urea N application, but did exceed the premium threshold. We cannot say whether this group of growers was able to identify that a crop was doing sufficiently well not to require late N, or whether the decision was based on past performance indicating that it was unnecessary.

Figures 24 and 25 illustrate the measured N in the grain at harvest for the *'sample'* field area, for the two groups of farmers; those who chose to apply foliar urea to their *'main'* field, and those who did not. Figure 25 is the *'sample'* area protein for both groups so in this instance this area never received FU and illustrates that the group of growers who chose not to apply late N in their *'main'* field have higher grain proteins in the grain than growers who go on to add to late N to their main field. In other words, the group of growers who do not apply late N generally have higher proteins than those who go on to apply late foliar N in these sample areas as noted earlier (see Table 13).

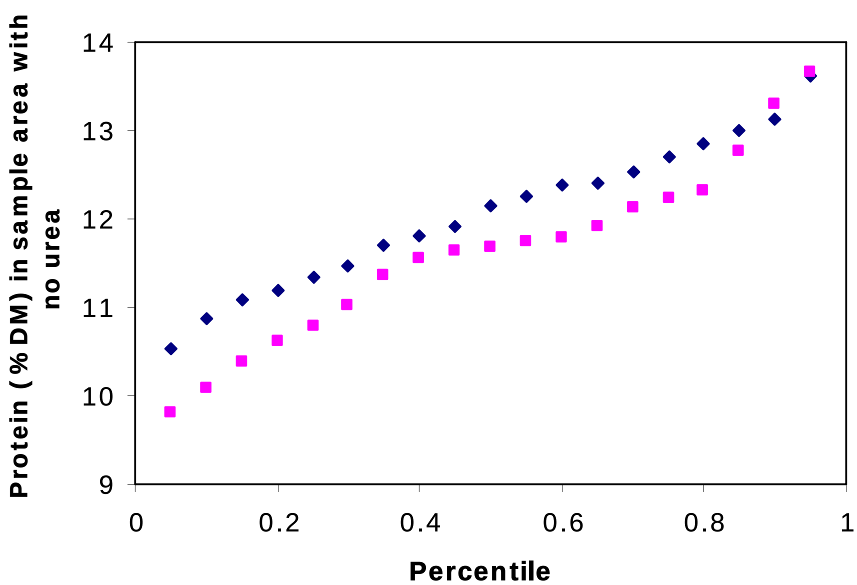


Figure 24. Percentile distribution of % protein in the untreated sample area for the group who do not apply late urea in the main field area (diamond symbol) and the group who go on to apply late foliar urea in the main field (square symbol).

However, as shown in Figure 25, the group who chose not to apply late FU in their main field were in general applying more N (kg/ha) throughout the growing season; between the 50-100th percentiles this averages +27 kg/ha.

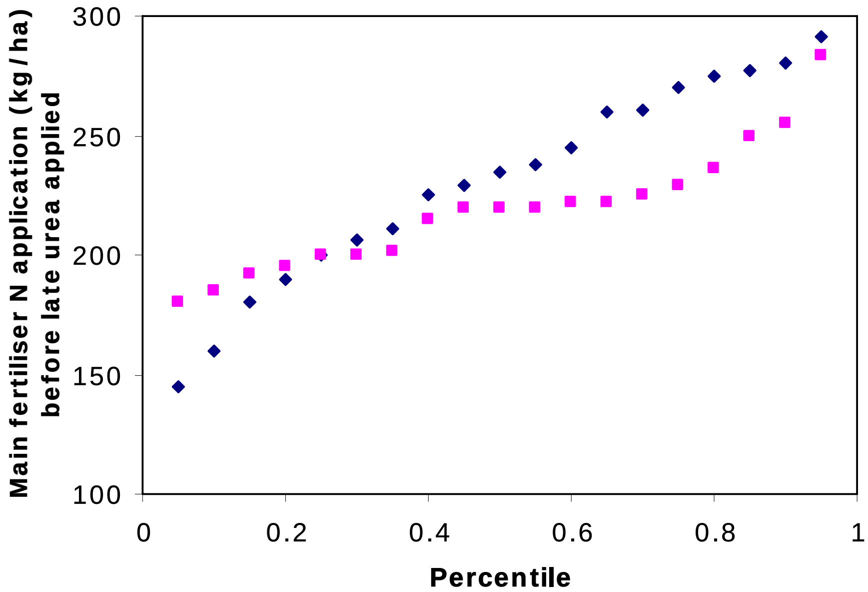


Figure 25. Percentile distribution of fertiliser N applied before flowering for the group who do not apply late foliar N to the main field (diamond symbol), and the group who do apply late foliar N to the main field (square symbol).

Assuming an average protein increase of 0.7% for an application of 40 kg N/ha as FU (when grain protein without additional N is < 12%) and 0.4% for 40kg N/ha (when grain protein is >12%), an additional 60 of the 205 growers could have reached the threshold, had they chosen to apply. In contrast, three of those who did exceed the premium threshold of 13%, could have done so without applying late FU. This means that of the 84 fields that received FU, the late N application only contributed to reaching threshold (of at least 12.5% protein) in 14 instances. The zone for growers getting close to the targets for premiums is relatively small and this would be vulnerable to any uncertainties in a model which predicted final grain protein from N at MR. However, the model does have the potential to more easily identify the growers for which applying the late N, with its associate costs is not beneficial, and hence where savings can be made.

Figure 26 illustrates how the group of growers who do add late FU see the benefit in the crop on the main field with a general increase in protein of 0.69%, compared to their untreated sample area. Whilst this group on average now has proteins which exceed the ‘no FU’ group, for most this increase still leaves their final protein well short of the target.

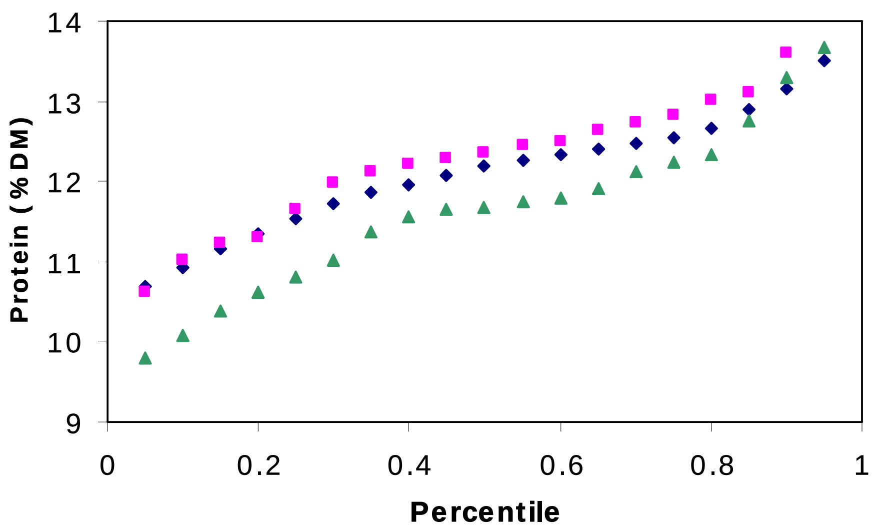


Figure 26. Percentile distribution of grain protein in the sample area for the group who do not apply late foliar N in the main field area (diamond symbol), the proteins for the main field for the group who go on to apply late foliar N (square symbol), and the sample area proteins for growers who applied late N to the main field (triangle symbol).

Using the model to make a decision

In order to assess how the individual grower's actual decisions on the quantity of late N to apply to their crops compared with using a model based decision, the different strategies were assessed by working out the average cost/benefit for the group as a whole. In addition, two alternative strategies, which were to always apply foliar N, or never apply late N, were added for comparison.

For each strategy, it was assumed that the benefit is the premium for achieving 13%, with a reduction in this premium for proteins down to 12.5%. All default costs and benefits are quantified as set out in Section 3.2.10.

The four strategies (B-D) for comparison with the actual growers' decisions (A) were:

A: Calculated the cost-benefit using the recorded data from the Coop group. The actual quantity of late N (as urea) applied by the Coop grower to each crop was used. The calculated costs and benefits were based on the reported yield at 100% DM (estimated from ADAS grab samples taken prior to harvest) and reported final grain protein.

B: Calculated the cost-benefit of a decision recommended by a 'perfect' model which can predict the recorded grain N at harvest, whether it received late FU or not, and therefore represents the best any model can hope to achieve. The costs were calculated assuming a fixed model testing cost for all growers and standard urea and spreading costs for those that were recommended to apply. Savings were made for those samples where the recommendation was to not apply, because the FU would not raise the protein close enough to the threshold. These savings were calculated using the quantity of urea recorded by the grower. Finally, samples which could have exceeded the threshold without a urea application also result in savings. For samples where no urea was added by the grower, a decision was made as to whether an application of late foliar N would enable the sample to reach the grain protein threshold to trigger the premium (assuming a variable response to 40 kgN/ha applied; +0.7% protein if final grain protein <12%, and +0.4% if >12% protein, as discussed earlier). Benefits were calculated for those who reached the threshold, by multiplying the premium by the measured grain yield at harvest (100% DM estimated from ADAS grab samples taken prior to harvest).

C: Assumed all farmers applied 40 kg N/ha late foliar N, with a variable protein response to 40kgN/ha (relative to a 12% protein reference point as in Strategy B). The grain protein of growers who applied FU was first modified to give an estimate of the final protein had they not applied the reported quantities of urea in their late application, before the impact of the standard 40kg N/ha is applied. Fertiliser and spreading costs apply to this strategy. Benefits are calculated for those who reach the threshold by multiplying the premium by the measured grain yield at harvest.

D: This strategy is the simplest and assumed no farmers apply late foliar N. There was zero fertiliser, spreading or sampling costs associated with this strategy. Benefits were calculated for those who reached the threshold by multiplying the premium by the measured grain yield at harvest. For this analysis, growers who had applied late N had their reported protein at harvest adjusted to the protein likely had FU not been added by scaling the 0.7% protein penalty if the final grain N is below 12% and a 0.4% protein penalty if their reported final grain N is above 12% by the quantities of urea they have reported to apply.

E: Calculated the cost-benefit of a decision recommended by the best-fit model identified in Table 15/Figure 23. The model first predicted the grain protein at harvest without a late foliar N application. If below the 13% threshold, the strategy recommended applying 40 kg N/ha late foliar N (with a variable protein response relative to a 12% protein reference point, as in Strategy B). If the modelled prediction would have exceeded 13% without a FU application, or if the modelled prediction plus FU would not trigger a premium, then the model recommended no application of FU. To assess the cost-benefit, the final grain protein reported by the grower was first adjusted as if none had applied FU, and a protein increase was added if the model recommended late N application. Otherwise, the reported value (less the adjustment if none had applied any FU) was used. As before, the costs were calculated assuming a fixed model testing cost for all growers and standard FU and spreading costs for those where application was recommended. Benefits were calculated for those who reached the threshold by multiplying the premium by the measured grain yield at harvest.

For example: under strategy A, for a grower with a measured grain protein of 12.5% at harvest and who had applied 40 kg N/ha as urea, the cost of the fertiliser application = 40 kg * £ 0.6 per kg urea N, plus £7/ha spreading costs; £ 31 in total. The premium received for achieving 12.5% protein was £10/tonne (£15-£5 or £1 reduction for each 0.1% protein missed). Gross benefit was £10 * 8.5 t/ha = £85; the net benefit was £54/ha). This was repeated for each growers' sample and the average benefit for the grower group calculated under each strategy, assuming each sample is associated with a field of 1 ha.

A summary of comparison of the 5 strategies with premia calculated on the sliding scale from 12.5-13% protein are presented in Table 16.

Table 16. Comparison of costs and benefits (£/ha) averaged across all 234 fields in the Coop group. Premium of £15/t at 13% grain protein decreasing by £1/t per 0.1% protein to 12.5%, a N fertiliser cost of £0.6/kg, spread cost of £7/ha and test cost of £3.60/ha.

		(£/ha)		
Strategy	**Total Cost of Urea N**	**Total Cost of NIR System**	**Total value of premia**	**Net Benefit**
A Grower model	-£11.83	£0.00	£36.40	£24.58
B 'Perfect' model	-£6.77	-£3.60	£53.33	£42.95
C All apply late N	-£31.00	£0.00	£54.84	£23.84
D No-one applies late N	£0.00	£0.00	£31.32	£31.32
E Best-fit model	-£17.24	-£3.60	£47.41	£26.57

Strategy B maximised returns in one of three ways: Firstly the samples where late N was applied but would already have exceeded the 13% protein target, would be advised not apply fertiliser and this saving calculated; secondly the samples where late N had not currently been applied, but which could have reached the threshold had an application been made were also identified, and the costs of fertiliser and the benefits of reaching the premium calculated; thirdly samples were identified where in strategy A, late N was applied but the threshold was not reached (given that a 40 kgN/ha as FU could only provide a maximum of 0.7% increase in protein) and were, therefore, incurring unnecessary fertiliser and spreading costs for no benefit, and these were advised not to apply. The additional costs were associated with testing the crop of every grower to gain knowledge of the N content of the ears at MR. For a **perfect** model this strategy performed well with fertiliser savings and additional opportunity gains for the premium. However, since the perfect model cannot be achieved, the outcome of this strategy will not be discussed in further, though is still included in some of the tables for reference.

Strategy D was the simplest and recommended that no fertiliser be added to any crop. In the data set, some crops did not reach their premium even with late N applied. As a consequence under this strategy, there were large savings for the 67 growers who failed to benefit from a premium, and who would be able to save on late N costs. The harvests of 2007 and 2008 were low protein years compared to the 10 year average (see section 3.3.1), therefore, it is not surprising that this strategy performed well due to the fertiliser saved.

Across all 3 years, the best-fit model strategy ranked as 3rd, behind the perfect model (1st), and never applying (2nd) and the growers own rule strategy (4th) and always apply (5th). The best-fit model carried the costs incurred by applying tests across the whole group, but only just out-performs the decision to apply fertiliser on all fields (strategy C) by £3/ha, averaged per Coop field.

These results are of course subject to variation in the all the parameters, fertiliser costs, premiums and so forth. For a high premium on milling wheat of £25/t, the NIR modelling strategy E out-performed the decision making of the farmers (strategy A) by nearly £10/ha averaged per Coop field, though this may not be a fair comparison as the Coop may have made different decisions had they known the value of the premium would be high. The value of the premium also altered the ranking with the strategy to all apply N producing large benefits, and the impact of the costs of applying fertiliser on all fields (strategy C) being diluted by the increased value of the premium (Table 17). It was only when the premium moves closer to £20/ha when the best-fit model strategy net-benefit exceeded the net benefit of 'don't apply'.

Table 17. Comparison of costs and benefits (£/ha) averaged across all 234 fields in the Coop group. Premium of £25/t at 13% grain protein decreasing by £1/t per 0.1% protein to 12.5%, a N fertiliser cost of £0.6/kg, spread cost of £7/ha and test cost of £3.60/ha.

	(£/ha)			
Strategy	**Total Cost of Urea N**	**Total Cost of NIR System**	**Total value of Premia**	**Net Benefit**
A Grower model	-£11.83	£0.00	£64.22	£52.40
B 'Perfect' model	-£6.77	-£3.60	£96.50	£86.13
C All apply late N	-£31.00	£0.00	£97.23	£66.23
D No-one applies late N	£0.00	£0.00	£54.85	£54.85
E Best-fit model	-£17.24	-£3.60	£82.02	£61.18

Table 18. Comparison of costs and benefits (£/ha) averaged across all 234 fields in the Coop group. Premium of £15/t at 13% grain protein, decreasing by £1/t per 0.1% protein to 12.5%, a N fertiliser cost of £0.8/kg, spread cost of £8/ha and test cost of £3.60/ha.

	(£/ha)			
Strategy	Total Cost of Urea N	Total Cost of NIR System	Total value of Premia	Net Benefit
A Grower model	-£15.22	£0.00	£36.40	£21.18
B 'Perfect' model	-£8.73	-£3.60	£53.33	£41.00
C All apply late N	-£40.00	£0.00	£54.84	£14.84
D No-one applies late N	£0.00	£0.00	£31.32	£31.32
E Best-fit model	-£22.24	-£3.60	£47.41	£21.57

Table 18 below illustrates that increasing the costs of fertiliser and spreading made strategy C very unappealing when the premium remained at £15/t, and in fact at these costs the strategy D of no-one applying late N becomes the most profitable.

Table 19 below explores the effect of increasing the late foliar N application from 40 to 100 kg N/ha for the ‘no-one apply’, ‘all-apply’ and best-fit model strategies. HGCA Project Report No. 400, reported that the potential protein increase associated with a 100 kgN/ha application is +1.5%. This analysis assumes a 1.5% protein increase where final grain protein is less than 12% protein, whereas for proteins greater than 12%, the 1.5% increase is scaled back by the ratio 0.4/0.7 (to replicate the decreasing uptake of N discussed above). Here, using the model to help target the urea applications to only those who are predicted to benefit has proved a benefit over the ‘all apply’ strategy. However as can be seen in Table 20, for a 100 kg N/ha late foliar N application, coupled with an increase in urea costs, there now becomes no real benefit of paying for NIR analysis, compared to the strategy of not applying late N. Figure 18 compared with Figure 15 demonstrates the relative insensitivity of net benefits to foliar urea rate.

Table 19. Comparison of costs and benefits (£/ha) averaged across all 234 fields in the Coop group. Premium of £15/t at 13% decreasing by £1/t for each 0.1% protein to 12.5%, a N fertiliser cost of £0.6/kg, spread cost of £7/ha and test cost of £3.60/ha. Urea application rate of 100 kgN/ha.

	(£/ha)			
Strategy	Total Cost of Urea N	Total Cost of NIR System	Total value of Premia	Net Benefit
C All apply late N	-£67.00	£0.00	£85.08	£18.08
D No-one applies late N	£0.00	£0.00	£31.84	£31.84
E Best-fit model	-£57.85	-£3.60	£85.84	£24.39

Table 20. Comparison of costs and benefits (£/ha) averaged across all 234 fields in the Coop group. Premium of £15/t at 13% grain protein decreasing by £1/t per 0.1% protein to 12.5%, a fertiliser cost of £0.8/kg; spread cost of £8/ha and test cost of £3.60/ha. Urea application rate of 100 kgN/ha.

	(£/ha)			
Strategy	**Total Cost of Urea N**	**Total Cost of NIR System**	**Total value Premia**	**Net Benefit**
C All apply late N	-£88.00	£0.00	£85.08	-£2.92
D No-one applies late N	£0.00	£0.00	£31.84	£31.84
E Best-fit model	-£75.98	-£3.60	£85.84	£6.26

Tables 16 to 20 all illustrate just how sensitive the various strategies are to fertiliser levels, costs and potential premiums, and highlight the impact that rising fertiliser prices will have on the availability of wheat at 13% protein, if premia do not rise in parallel.

Cost benefit for individuals

The discussion so far has looked at the potential benefits averaged across the field samples in the Coop group. However there were 33 growers who provided these field measurements over 3 years, and there will be those who individually would have a gained a large net benefit, and others who often didn't make the premium (and therefore make a loss). To complement a model estimate of final grain protein at harvest based on NIR measurements, a simple cost-benefit calculation with a range of premia and fertiliser rates, could also be worked through to assess the potential benefits of growing milling wheat in the field. Figure 27 shows the percentile distribution of average annual net benefit by growers using their current strategy A.

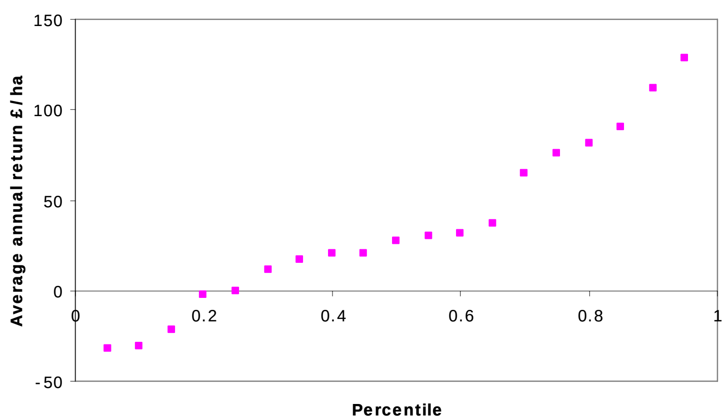


Figure 27. Percentile distribution of the net benefit (value of premia-costs) for the individual growers (2007-2009): Strategy A (growers current reported data) square symbol.

The reported benefits averaged across the grower group using this simplistic cost-benefit comparison were estimated on a per hectare basis, and the overall impact was positive. However in reality these values would be significantly reduced because to achieve the full premium, the additional HFN and Spwt quality targets must also be met. Data from the HGCA Wheat Quality Calculator illustrates that the likelihood of achieving all three quality standards is low at ~30% (10 to 50% over 2003 to 2008) for nabim Group 1 varieties. This impact has not been factored into the cost benefit analysis here. Failure to meet HFN and Spwt premia could affect alternative strategies differently because the impact of quality criteria would affect the benefits, but not the fixed costs.

3.4. Discussion

Previous studies on milling wheat have often taken quite different approaches to forecasting final grain protein. Some (e.g. Smith and Gooding, 1996) used purely empirical models based on met data and correlations with survey data for grain protein, but did not consider the actual performance of individual crops. Such models can be applied at regional or national level, and are usually of more strategic than tactical value. At the other extreme, forecasting systems based on leaf measurements with the SPAD meter (e.g. Lopez-Bellido *et al*., 2004; Nakano *et al*., 2010) using data from individual N response experiments, have demonstrated satisfying relationships between leaf greenness and final grain protein. However, such models are not widely used in commercial practice, although they have been trialled to a limited extent in the UK. In the study of Lopez-Bellido *et al.* (2004), the critical SPAD reading to achieve 13% protein was 50 for Hereward, whereas 56 is now reported for Solstice (Jamie Mackay, personal communication). In contrast, Poblaciones *et al*. (2009) in southern Spain have found a critical SPAD reading of only 41 was needed to achieve 13% protein under Mediterranean conditions, therefore both site and variety specific factors are needed to develop a universal system. The reason why the latter models fail, encompass a range of factors including: errors in sampling and measurement; greater variation in commercial crops due to site, variety and season (compared to the experimental crops on which the models were built); the fact that commercial crops fertilized close to the economic optimum, may represent only a small element of the variation in N content seen in samples from N response trials.

This project aimed to address some of the limitations of previous studies by studying both commercial farm crops of modern UK wheat varieties, as well as tightly managed N response experiments. It has also taken into account the uncertainties in measurement methods and models, to develop a pragmatic and realistic assessment of how financially valuable a protein forecasting system could be, based on measurements of N in the immature crop, and to what extent such measurements can be used to improve decision making.

Finally, although it was not a specific objective of the project, the results underlined the challenge of achieving high grain proteins in modern, high yielding breadmaking wheats, where environmental legislation increasingly limits the amount of fertiliser N which can be applied across a farm, and rising prices of N question the profitability of continuing to strive for 13% protein in many cropping situations.

3.4.1. Consideration of seasons and weather effects

This project was carried out against a background of three relatively low protein years. This limited, to some extent, the ability to fully test any protein forecasting system developed. For 5 of the 6 site-season combinations for the ADAS field trial sites (N response experiments), only 43-88% of the long term average rainfall was experienced during the period 1st March to 31st May. At the sixth site (BW 2007), most of the rainfall in that period arrived in the last week of May; April also being very dry.

In the early stages of the project it was thought that a spring rainfall modifier (i.e. low rainfall = high protein) might be applied to any model, but experience during the project demonstrated that this was not useful in practice. This observation highlights the fact that the literature is somewhat confused on this matter: Smith and Gooding (1996) showed that early spring rainfall tended to reduce grain protein, whereas late spring/early summer rainfall tended to increase grain protein by encouraging post-anthesis N uptake. However a contradiction was also noted in that late rainfall may slow the rate of senescence and hence extend grain-filling, thereby boosting yield and reducing grain protein.

Low temperatures after flowering are assumed to increase grain yield by extending the duration of grain filling, while reducing the risk of respiratory losses of accumulated DM (particularly with low night temperatures), and hence result in diluted grain protein levels. Data from the present project tend to support this hypothesis, with both low July day temperatures and high yields recorded (particularly in 2008). However, it was difficult to incorporate a forecast of July temperatures into a prediction system. While we did not explicitly test the accuracy the available long-range weather forecasts, it should be noted that the Met Office withdrew their seasonal forecasts due to criticism of their accuracy during the course of the project.

Given the uncertainties in terms of the underlying crop physiology, and the difficulties of relying on accurate weather forecasts, this project progressed on the basis of the hypothesis that actual measurements of N in the plant, taken as near to harvest as possible (e.g. MR stage), will give the best chance of assessing the true N status of the crop.

3.4.2. The form of nitrogen responses

With the exception of BW 2007, all field trials demonstrated grain yield-N responses with a classic 'Linear + exponential' function. However, the grain protein-N responses were much more variable across sites and seasons, with 8 quadratic functions and 15 linear functions, making it difficult to find a common relationship which could be used to develop a model.

Similarly, no common function could be fitted for the relationship between final grain protein and immature ear N. In part, this explains why plotting such data from a number of different sites and seasons tends to give a wide spread of points, leading to a distinctive 'box shaped' distribution, as seen in the first MALNA project (e.g. Figure 9 in HGCA Report No. 401).

Growth analysis was used to characterise the partitioning of N in the crop, in order to take these into account, if appropriate, in any predictive model. However there was little difference in NHI between varieties, and no consistent effect of applied N on NHI, other than an initial increase from a crop at zero-N to the first applied N rate. In the highest yielding year of 2008, the highest NHI was recorded, suggesting that the highest yielding crops are more effective at pulling N out of straw and chaff. This might at first be counter-intuitive (given the general negative relationship between grain yield and protein), but serves to illustrate the complexity of the system and the difficulty of including a fixed NHI into any model. Similar variability in NHI was seen in farm crops, both within and between years (see Table 10)

In 2007, the HI was low in a number of crops, and this was associated with lodging in the wet summer of that year. Growth analysis of individual farm crops was also used to make estimates of grain yield, which could be used later in the financial assessments. It was also noted that the distribution of yields was larger in 2007 with a greater proportion of lower yielding crops, whereas in a high yielding year such as 2008, all growers tend to do well. One of the challenges of this type of work is that, with the exception of those growers who have real-time yield monitors on their combines, a significant number do not keep accurate field records of grain yield. This means that there is no strong body of historic data that can be used to tailor models to particular farm situations.

3.4.3. Comparison between field trials and commercial crops

Commercial farm samples had a smaller range of N in immature crop material, and also a narrower range of grain proteins than field trials (e.g. Figures 4, 6 and 7). While this was suspected, it has not been clearly demonstrated before, because farm crops were not sampled in the previous project (HGCA Report No. 401). More difficult to reconcile is the fact that the field experiments tended to give lower grain proteins in absolute terms, meaning that the sites used for field experiments may not be truly representative of the fields of the main group of Coop growers. This is the case, even though the N response trials were carried out with host farmers and situated within commercial crops. One difference might be that the ADAS field experiments were all 1st wheats, whereas in the commercial crops (where known), 116 fields were 1^{st} wheats and 99 were 2^{nd} wheats, the latter tending to give higher grain proteins.

3.4.4. NIR calibrations

A key element of the project was to make the underlying NIR calibrations (predictions of N and MC in immature material) developed in the first MALNA project (HGCA Report No. 401) more robust, such that an NIR machine based in a Coop lab could be used to measure N in the plant, and give an instantaneous reading. The previous project built calibrations on 219 immature plant samples in total (each of ears and whole plant, at MR stage only). These were collected over four years and only represented samples from field experiments.

In contrast, the current project collected many more samples (1,210 each of ears and whole plant) representing samples both from flowering (566) and MR stage (604) which were added to the original calibrations. Moreover, of the total, 450 were representative of commercial farm crops. This means that by the end of the project, the calibrations were based both on a wide range of N contents (by including under and over-fertilized crops from the field experiments), as well as a wider set of samples typical of the wider range of soil, N levels and growing conditions seen in commercial practice.

3.4.5. Development of a forecasting system

The first objective in developing a forecasting system was to produce a simple mechanistic model of grain yield that could be used to test the accuracy that could be achieved by this modelling approach, in comparison to an empirical regression function for directly predicting grain protein. The mechanistic model would be used with measurements of actual crop N uptake from the available Coop and trials data sets to determine the uncertainty range on protein concentrations that derive from diluting known grain N content into a predicted grain yield. This would test the case of a perfect grain protein model but an imperfect prediction of yield. The reality would be an imperfect prediction of both grain nitrogen and yield.

A number of physically based models of wheat grain yield exist, but have been reported to have large prediction errors except where calibrated to site conditions. For example, the AFRC-WHEAT (Weir *et al*., 1984), CERES-Wheat (Ritchie and Otter, 1985) and SIRIUS models (Jamieson *et al*., 1998a) when applied to well managed UK trials data had prediction errors as measured by the Root Mean Square Error in the range 2.2 to 3.0 t/ha. These models explicitly simulate all stages of crop growth and the impact of environmental stress. For this project, we developed a simpler semi-mechanistic model of grain yield which does not explicitly represent water stress but was informed by measured total crop N and biomass at either flowering or MR. The model was iterative. On the first iteration, the model used default parameters to estimate biomass gain as a function of intercepted radiation and compared this to the measured biomass. The ratio of predicted and measured biomass were used to calculate a rate modifier for biomass gain, reflecting potential site specific conditions and stressors (such as water and nutrient stress), that was then used on a second iteration of the model to make a final prediction of grain yield. In this way the model used the field measurements to improve predictions and implicitly represent any environmental stress. However, while a semi-mechanistic model was successfully developed, the errors introduced when moving from yield to a grain protein estimate meant it was decided that ultimately, it would be simpler and more robust to use a statistical model.

A number of statistical models were then considered using either (i) whole plant or ears, (ii) measurements at flowering or MR, and (iii) the Leco (Dumas) reference or NIR methods for N content.

Firstly, the range of N contents in whole plant material was greater than in ears alone, for any given site and across a range of applied N rates. Hence, whole plant data generally gave better performance in grain protein prediction. However this advantage was marginal, given the extra cost of taking many kg of fresh whole plant material required for analysis, compared to the relative ease and ability to cover larger areas of ground by sampling ears alone. The final model was therefore based on measurements of ear N.

Secondly, the decision was taken to use an assessment at the MR stage, which gave much stronger relationships than those at flowering. For both Leco and NIR, the relationship between MR and final grain protein at the BW and HM trial sites was stronger than between flowering and harvest. In their work predicting grain protein concentration from SPAD meter measurements, Bail *et al*. (2005) also found that the predictive quality of their model was 10% higher at the MR stage than at flowering. Ideally, the grower would prefer measurements at flowering in order to have more time to plan the late foliar application; however the statistical analysis has shown that measurements at MR have a clear advantage.

Corroborating the relationship seen in the first MALNA project (where an ear N content of 1.9% at MR stage related to a final grain protein of 13%), the larger data set collected in the present project has provided more discrimination: The 1.9% average value being made up of a 1.8% threshold value for Hereward and a higher 2.03% for a modern variety like Xi19. For the farm crops, the N threshold for Solstice appeared to be 1.87% in ears at MR (Figure 6). For this reason, a variety (‘Hereward’) factor was introduced into the statistical model.

Thirdly, it was found that the model fits (as measured by R^2) for data from the NIR method were comparable to those from the Leco method. This confirmed that neither method was substantially better than the other at predicting grain protein, across the set of trials data, although NIR had the benefit of speed of analysis, and no requirement to dry samples. The best fit statistical model from the NIR data, was then developed using a proportion of the data from both the field trials and Coop data.

Both the NIR and Leco measurements, have sampling errors associated with them, as shown in the laboratory results. Ideally, several samples are required at each sampling point in order to increase accuracy of the N measurement, though this would add to the cost of the service. One of the learnings of this project is that the uncertainty of Leco measurements may be ± 0.3% protein DM basis (± 2*Rsd of *ca*. 0.15%, based on a repeatability sd of 0.23%; HGCA, 2004), meaning that single determination of grain protein using the Dumas reference method cannot actually detect differences as small as 0.1% protein (upon which deductions are made at mill intake, albeit by an NIR method).

In summary, the model predicted the % protein of the Coop group quite well and was an improvement in model performance over the first MALNA project: HGCA Project No. 401 reported an R^2 of 0.52 for a predictive model of final grain protein (experimental samples only and data based on the Kjeldahl reference method). In the present project, the R^2 of 0.57 is actually better than it might at first appear, because it works on farm as well as experimental crops, and also works using NIR predictions, rather than the Leco reference method, although it is accepted that the system requires further field testing with a completely independent data set before it can be considered fully validated in at least one other cropping season.

3.4.6. Financial assessment

Having developed a forecasting system, an assessment was made of whether it is worth applying late foliar N or not. An overall summary of the financial performance of different scenarios is shown in Table 21.

Table 21. Summary of ranking of different scenarios where 1 = best and 4 = worst, from Tables 16 to 20 (excluding 'perfect' model, strategy B).

Scenario considered:	Baseline	Large premium	High N cost	Higher levels of late N	Higher levels of late N and N cost
Table:	4.15	4.16	4.17	4.18	4.19
A Grower decision	3	4	(3)		
C All apply late N	4	1	4	3	3
D No-one applies late N	1	3	1	1	1
E Best-fit model	2	2	(2)*	2	2

* Values in parentheses were numerically very close and could be considered to be ranked equally.

It is clear that the best strategy changes with the price of N, and the premium for milling wheat, although overall the use of the NIR and statistical model performs reasonably well, giving benefits in the range £6 – 61/ha. Further work is required to get accurate operational costs of a commercial NIR system to confirm these figures. Ideally, the system should be tested using data from a higher protein year.

With respect to the magnitude of the response to late FU in relation to the underlying grain protein content (without late N) as used in the financial analyses (+0.7% protein if <12% or +0.4% if above 12% grain protein) it should be noted that there is still some debate on this matter amongst researchers. This was the relationship seen by Dampney and Salmon (1990), and was also observed in farm crops in the present study (see Figure 17). However, an analysis of the data from Dampney *et al*. (2006), indicated that there was no discernable effect of the underlying grain protein level on the response to late N. Further modelling and research work may be needed to study this effect in more detail, i.e. to better understand the relationships between the grain protein response to late foliar N and grain yield and to consider this in farm as well as experimental crops.

One of the main advantages of the forecasting system, in theory, is to eliminate unnecessary applications where the grower is unlikely to achieve the threshold. It is in these circumstances that real savings for the Coop can be made, by realising that the FU will not provide enough of a boost to get a premium. The model, however, makes recommendations whereby many growers should apply N, but it is not always correct; this is where the difficulty of measuring protein accurately affects the predictive power of the model, represented by the uncertainty inherent in the 'cloud' of data. Reductions in the premiums paid are made on the basis of 0.1% protein reductions from the threshold. The size of these penalty increments are smaller than the differences in protein which the analysis methods can detect with any certainty. Overall, the best strategy was that no-one applies late N unless the expected premium was over £20/t. It may be expected that this would also be the best strategy in a high protein year, given that still only a minority of crops would benefit from extra protein.

3.4.7. Implementation of the system

It should be noted that given the broadly similar performance of NIR predictions and Leco measurements, both are options for implementation of such a system: Individual growers could send samples by post to a commercial analytical lab. In this case, the main disadvantage would be the extra time to deliver the samples and receive the results (2-3 days at best), whereas the NIR result is instantaneous giving an advantage in terms of the time for decision-making, and the cost of the lab analysis is dependent on how many measurements per sample are requested (in the present study single determinations were carried out, replicate measurements of the same sample in the lab, might improve precision). For a Coop who already possess a Leco N analyzer, then one option is to carry out N analysis directly using the lab reference method, the main additional costs would relate to investments in a forced air-flow crop drying oven, a lab mill suitable for grinding the dried sample prior to analysis, and greater staff time in the Coop lab. The overall costs of in-house Leco N measurements may therefore be similar to the purchase and operation of the NIR instrument, although the drying oven and mill may have other uses which would partly offset the capital costs, but by the same token, the NIR could also find other uses, for instance in manure analysis.

3.4.8. Caveats

This exercise was designed to explore the relative scale of cost and benefits between decisions made collectively across the whole group. Some individual farmers would of course benefit much more than the average suggested and would only have costs if they never achieve the premium as can be seen in Figure 27. The impact of a series of high protein years in succession has also not been explored. Of course this sort of exercise could be set-up with many different assumptions and additional cost and benefit factors, including environmental costs, so the results above should only be interpreted as indicative within the scope of this project.

Achieving the milling wheat premium is also dependent on meeting Hagberg Falling Number (HFN) and Specific Weight (Spwt) standards of 250 s and 76 kg/hl respectively. Data from the HGCA Wheat Quality Calculator also illustrates that the likelihood of achieving all three quality standards is low ~ 30% (10 to 50% over 2003 to 2008) for nabim Group 1 varieties. HGCA (2010) report that only 26% of UK wheat met quality premium requirements in 2009, with an even lower figure of 8% in 2008. This impact has not been factored into the cost benefit analysis here. Failure to meet HFN and Spwt premia could affect alternative strategies differently because the impact of quality criteria would affect the benefits, but not the fixed costs. However, discussions with growers during the project suggested that this is very grower specific i.e. some growers never have a problem meeting Spwt. Therefore, it is better for readers of the report to assess the impact of the non-protein quality factors in the light of their own experience.

Finally, the costs of running the system are indicative; there may be additional costs associated with updating the NIR calibrations each year, including an annual requirement for reference N analysis on a set of representative samples. However, this is a commercial decision, and would need to be developed further with the instrument manufacturer.

3.4.9. Potential environmental benefits of a forecasting system

An important reason for government sponsorship of this project was to assess where savings in late N use were possible. The results clearly show that there were a number of growers who were applying N when their baseline proteins were so low, they would never achieve 13% protein. In such instances it would better financially for the grower to not apply late N, and this in turn would also benefit the environment.

Based on the data used in the cost benefit analyses, 84 (41%) of the 205 growers samples applied later foliar N. This is broadly in line with the proportion applying late N to breadmaking wheats for the national crop as was the average amount of late N (37 kg/ha) where applied. Of these, if armed with a forecasting system and using the standard scenario (premium £15/t with deductions to 12.5% protein; N cost £0.6/kg), it was seen that 91 growers would not have been recommended to apply late N (there were 114 recommendations to fertilise). There are more growers recommended to add late foliar urea (114), than originally applied fertiliser in the farmers group (84). The model has false recommendations where the fertiliser recommended did not correspond to an observed final protein above the threshold (36 instances) compared with the growers strategy which had 70 instances where fertiliser had no benefit in terms of triggering the premium threshold. The overall result therefore, was that the model saw a greater net profit and reduced the fertiliser applied that had no benefit.

Whilst overall the NIR best-fit model has resulted in an increase in overall late N application recommendations across the Coop, the efficiency of N use is much greater with the aid of the model, with approximately 42% of the applications made with the aid of the model being responsible for achieving premia, compared with 16% under the existing farmer strategy. The 'no-one apply late N' would of course lead to great savings in N use, although this would have had greater implications for the industry as there would be less wheat available of acceptable quality to meet market requirements.

Environmental costs could be included in a more detailed cost benefit analysis and might change the overall assessment of the strategies. These costs could include additional society costs associated with the production of N fertiliser, and the air quality and climate change impacts of the ammonia and nitrous oxide emissions. Spencer *et al*. (2008) produced a report on the cost of gaseous emissions due to agricultural pollution and their impacts on society for Defra (Project SFSO601). The society costs of emitted carbon dioxide are £25/t CO_2e and for ammonia are £1,840/t NH_3. The greenhouse gas emissions associated with the manufacture, packaging and transport of ammonium nitrate fertiliser are estimated to be 7.1 kg CO_2e/kg N (Kindred *et al*., 2008). Assuming that 2% of the applied N is lost as ammonia (0.025 kg NH_3/kg N; Chambers and Dampney, 2009), the combined direct and indirect nitrous oxide emissions are 5.8 kg CO_2e/kg N (IPCC, 2006). The total society cost of the ammonia and greenhouse gas emissions is £0.37/kg N applied or £14.70/ha. The society cost of a urea fertiliser application is potentially much higher at £0.83/kg N applied or £33.25/hectare. Although having a lower production emission (estimated to be 4 kg CO_2e/kg N) a greater percentage of the applied N is lost as ammonia (25%; Chambers and Dampney, 2009). Avoiding later foliar N applications when there was a low probability of achieving the breadmaking quality threshold would therefore potentially have a significant society benefit. Note that these cost estimates do not account for the impact of leached nitrogen fertiliser on water quality, which would lead to further environmental benefits.

Overall, the best strategy is consistently that no-one applies late-N unless the premiums are high. However, the main sector which would appear to lose financially might be the milling industry, due to a reduced supply of 13% protein wheat. This conclusion, in turn, raises important questions about whether the 13% protein breadmaking quality target is really justified, since it encourages over-use of N, leading to a pollution risk, and in the three years of study here, led to growers wasting money in a number of instances. Moreover, it should be noted that given the uncertainties in measurement of protein, a grower may actually aim for 13.5% protein, to avoid the risk of financial deductions on testing at mill intake (note earlier comments on uncertainty in analytical measurements), further encouraging over-use of N. The need for new breadmaking technologies and/or breeding strategies to reduce the requirement for 13% protein grain is highlighted by this research.

3.5. Conclusions and Recommendations

This project highlighted some reasons why previous forecasting systems have failed in commercial practice and has shown the increasing difficulty of achieving 13% protein in modern high yielding varieties. Specific conclusions are as follows:

1. Robust, updated NIR calibrations are now available for N and moisture in immature plant material, including whole crop and ears collected at flowering as well as at MR,
2. The best grain protein forecasts were not improved by spring rainfall data, by forecasts of weather during grain filling, or by yield forecasts,
3. The best model used ear measurements taken at MR stage, plus a variety factor to distinguish variety yield potential, and a ‘farm’ factor,
4. The Dumas reference and NIR methods of measuring ear N performed similarly; NIR was simpler and faster to use on fresh plant material,
5. Plant N and grain protein varied less in commercial crops than in N response trials whilst sampling errors were greater; hence farm N measures were uncertain,
6. Data collection from farms showed that many growers could keep better records of yield and grain protein, which would improve N management over time,
7. The best protein prediction method showed no benefit for individual crops, but significant benefits could accrue if predictions were applied across a group of fields, or over a number of seasons,
8. Farms showed consistent differences in protein achievement; these may be inherent and unavoidable, or they may indicate persistent on-farm inaccuracies in N management. In either case, ear N analysis appears to offer a useful additional diagnostic tool, to augment measurements of soil N and grain N in supporting good N management,
9. N response trials in three low protein seasons showed that modern high yielding varieties required >290 kg/ha applied N in 13 out of 14 instances to achieve 13% final grain protein, much more than was applied by growers (233 kg/ha). Further experience of ear N analysis is desirable in high protein years,
10. Full exploitation of group actions to forecast grain protein might require results to be kept confidential, so that prices were not affected; the full value of protein forecasts will only become clear after a system is deployed commercially,
11. Given the difficulties of achieving 13% protein in high yielding wheat varieties. while staying within environmental limits for N applications, in many cases, the best approach was not to apply late N,
12. Financial benefits both for growers and for the public can be seen to accrue from implementing a decision support system based on forecasting final grain protein, to target late N use; this might require the milling industry to offer larger premiums to ensure continuing availability of breadmaking wheat with 13% grain protein.

The following recommendations for further study are made:

1. Ear N analysis should be tested (in research and commercially) over a wider range of seasons, to include a ‘high protein’ year,
2. Work is required to develop accurate in field-sensing systems for late crop N status, which could be tractor or satellite mounted and could average results over large areas,
3. Work is needed to relate variability in crop N status across a field with yield and grain protein for those same fields at harvest. This should be possible using modern on-combine yield monitoring, in-line protein determination by NIR, and satellite positioning,
4. Given the uncertainties in grain protein measurements, particularly when based on Dumas, commercial deductions for differences in grain protein of 0.1% may need to be reconsidered by the industry,
5. The industry should reconsider whether the 13% protein target could be reduced or avoided, since it encourages wasteful N fertiliser use, which in many cases is of no benefit to growers, and which deters breeders from increasing yield potential.

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3.7. Acknowledgements

Many thanks go to Philip Darke and Caroline Rogers of Camgrain, and Phil Green of Fengrain for coordinating lab testing of samples collected by their members and to Richard Keeping of Heygates and Simon Hook of HGCA for their support through the course of the project.

Acknowledgement is extended to the participating growers, without whom the project would not have been possible:

Tony Alterton	David Fountain	Charles Partridge
John Argent	James Frost	Robert Rush
Steve Baldock	Rupert Gosling	Robert Stevenson
David Beak	David Green	Julian Swift
Richard Beeton	Les Harrison	Andrew Tetlow
Jim Bray	Michael Hills	James Tubby
Richard Broad	Edward Hitchcock	Ian Tulloch
Paul Cherry	John Jefferies	Graham Wedd
Andrew Crossley	John King	Ian Welch
Stuart Curtis	Matthew Knight	David White
Carl Driver	Bill Lister	John Witherow
Lewis Duke	Don Morris	James Wyld

Finally the contributions of Roy Cross, Millie Bowden and Hannah Collis of ADAS for collecting and processing field samples, and Chris Dyer for statistical analysis, is gratefully acknowledged.

ANNEX 1. GROWERS FIELD SAMPLING PROTOCOL YEAR 1 (2007)

Sampling to be carried out at both flowering and MR stage

Aim: At each sampling stage, the aim was to take five samples each of 50 cm of row. The five samples were bulked together, placed in a plastic bag, sealed and delivered to laboratory for scanning and protein prediction. Equipment supplied: plastic bags, measuring stick (50 cm length), labels (pre-printed), secateurs. Procedure was as follows:

1. Representative area in centre of field, between tramlines was selected (first sample at least 10 metres from the headland and 6 metres away from a tramline),
2. Before taking the plant sample, date of sampling written on the pre-printed label and label placed in the bag and average row width recorded,
3. Measuring stick placed on ground alongside one row. All plants cut off at ground level along one side of the stick (50 cm) and placed in plastic bag, taking care to avoid biasing the sample by selecting only the biggest plants or thickest area of crop,
4. Plant samples folded to fit in the bag, but not chopped at this stage (this was carried out in the laboratory),
5. Sampler moved 15 paces along the row and then took 2 paces to the left and chose another representative area. Sampling repeated as before and added to the first sample,
6. Sampler moved 15 paces along the row 2 paces to left and chose another representative area. Sampling repeated as before and added to the first two samples,
7. Move into the central area between the tramlines, and return in the opposite direction, taking two more samples (at intervals of 15 paces and 2 to the left). Add these two samples to the bulk so that you have collected 5 samples in total,
8. Bulk all five samples together and place in the plastic bag and seal to prevent moisture loss,
9. Place in a cool place out of direct sunlight (place bagged sample inside a potato sack if the sample is to be left in the light),
10. Deliver to lab within 24 hrs of sampling, and leave samples in reception in designated area.

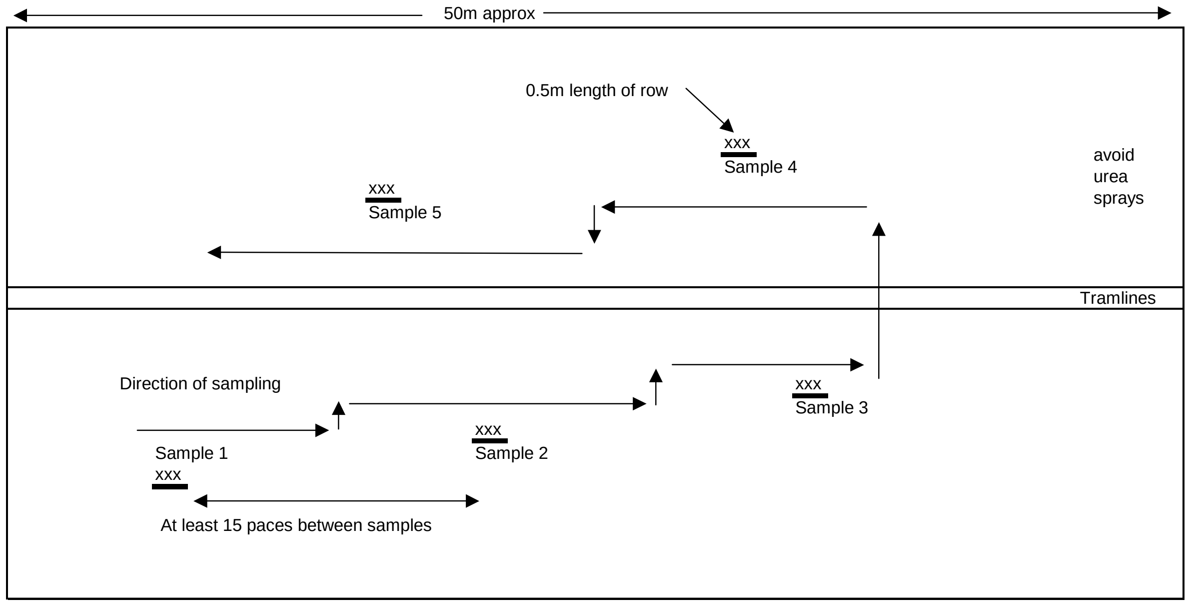


Figure A1. Diagrammatic representation of field sampling pattern 2007

ANNEX 2. GROWERS FIELD SAMPLING PROTOCOL YEARS 2 AND 3 (2008/09)

Sampling to be carried out at both flowering and MR stage.

Aim: At each sampling stage, the aim was to take four samples using the metal quadrat supplied. The four samples were bulked together, placed in a plastic bag, sealed and delivered to laboratory for scanning and protein prediction.

Equipment required to take out to field – plastic bags, metal quadrat (31.6 x 31.6 cm), labels (pre-printed), secateurs. Procedure as follows:

1. Representative area in centre of field between tramlines identified. First sample selected to be at least 10 metres from the headland and 6 metres away from a tramline,
2. Before taking the plant sample, date of sampling written on the pre-printed label and label placed in the bag,
3. Quadrat (0.1 m^2) placed on ground across the rows and diagonal to the direction of drilling. All the plants cut off at ground level inside the quadrat and place in plastic bag, taking care to not bias the sample by selecting only the biggest plants or thickest area of crop,
4. Plant samples folded to fit in the bag, but not chopped at this stage (this will be done at the laboratory),
5. Sampler moved 15 paces along the row and then 2 paces to the left and another representative area chosen. Sampling repeated as before and added to the first sample,
6. Sampler moved into the central area between the next set of tramlines, and returned in the opposite direction, taking two more samples (at intervals of 15 paces and 2 to the left). These two samples added to the bulk so that 4 samples in total were collected,
7. All four samples (total 0.4 m^2) bulked together and placed in the plastic bag and sealed to prevent moisture loss,
8. Bag placed in a cool place out of direct sunlight (bagged sample placed inside a potato sack if the sample is to be left in the light),
9. Sample delivered to the lab within 24 hours of sampling, and left in reception in designated area.

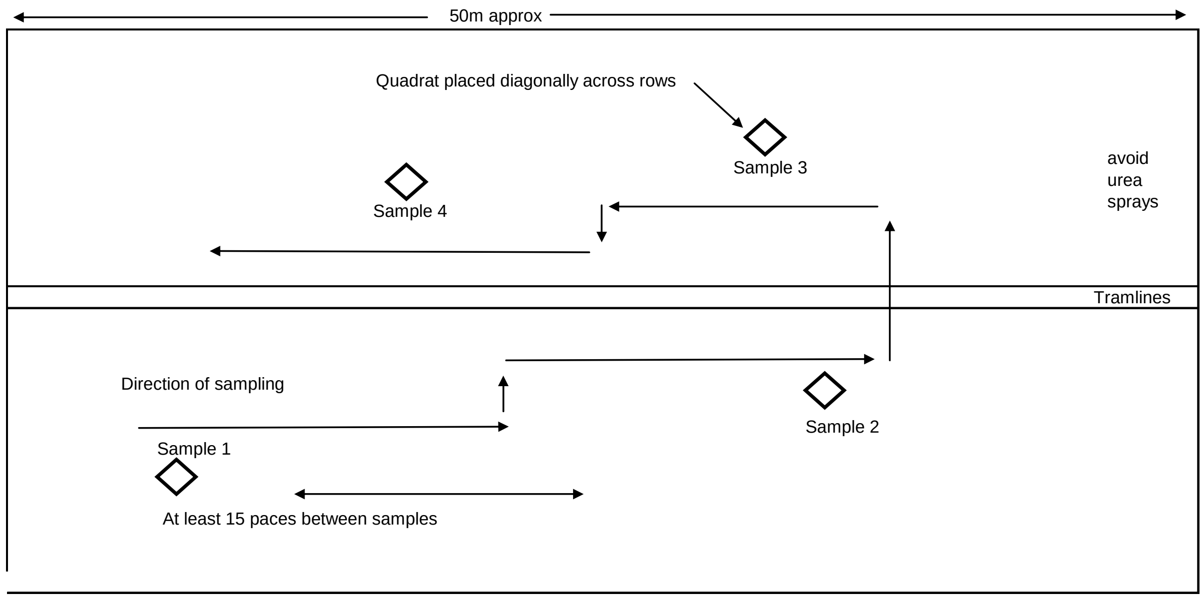


Figure A2. Diagramatic representation of field sampling pattern 2008/09

ANNEX 3. METEOROLOGICAL DATA BOXWORTH AND HIGH MOWTHORPE

Table A1. Average daily temperatures, and total rainfall by month through the three growing seasons 2007-2009 at Boxworth, Cambridgeshire and High Mowthorpe, Yorkshire compared to 40 year long term averages (LTA; 1970-2009)

a) Boxworth		**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**
Air temperature (^oC)												
2006/07	Max	17.3	11.9	9.2	10.0	9.4	12.1	18.2	17.8	21.5	21.7	20.1
	Min	9.6	4.7	3.4	3.9	2.3	2.4	5.4	7.7	10.8	11.7	10.8
2007/08	Max	14.3	10.1	7.6	9.4	9.3	9.6	12.0	17.5	18.4	21.3	20.6
	Min	7.0	3.7	2.5	3.9	0.8	2.2	4.0	8.5	10.2	12.3	13.1
2008/09	Max	13.5	9.4	6.1	5.1	6.2	11.3	14.6	17.1	19.7	20.9	20.9
	Min	6.1	4.6	1.4	0.4	1.4	3.5	5.8	7.9	10.2	12.2	14.4
LTA	Max	14.6	9.8	7.3	6.9	7.4	10.1	12.8	16.6	19.8	22.4	22.4
	Min	7.1	3.8	1.8	1.3	1.0	2.4	3.7	6.6	9.5	11.6	11.8
Rainfall (mm)												
		Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
2006/07		55.1	69.3	49.2	97.0	52.4	33.6	1.4	117.0	69.0	63.3	50.0
2007/08		63.8	26.6	30.8	53.8	13.2	30.7	35.4	56.2	32.2	53.0	49.4
2008/09		55.2	66.6	19.8	32.8	42.6	26.4	16.6	21.0	50.2	82.6	70.6
LTA		45.9	33.0	39.0	44.6	46.6	51.8	43.6	50.7	50.1	53.3	53.6

b) High Mowthorpe		**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**
Air temperature (^oC)												
2006/07	Max	14.7	9.8	7.3	8.3	7.5	8.9	14.5	14.1	17.0	18.1	19.6
	Min	9.1	4.3	2.8	2.6	2.4	2.3	5.9	6.8	9.7	10.6	10.6
2007/08	Max	12.8	8.7	5.7	7.1	7.2	7.5	9.6	14.8	16.2	17.3	18.5
	Min	6.8	3.3	1.2	2.5	0.8	1.1	2.4	6.4	7.6	9.7	11.4
2008/09	Max	11.7	7.9	4.8	4.0	5.0	9.4	12.3	14.6	16.6	19.0	20.6
	Min	5.9	3.2	0.7	0.3	0.6	2.2	4.2	6.6	8.7	10.6	11.7
LTA	Max	16.5	12.3	6.0	5.3	5.6	7.9	10.3	13.8	16.7	19.2	19.5
	Min	9.2	6.5	1.4	0.5	0.6	1.7	3.2	5.8	8.4	10.6	10.8
Rainfall (mm)												
		Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
2006/07		63.8	63.0	69.7	63.9	80.6	37.1	4.5	66.7	232.0	90.7	37.5
2007/08		25.4	88.0	61.2	163.8	22.0	70.4	50.2	23.0	49.6	56.6	157.8
2008/09		39.6	56.0	68.8	65.8	45.4	27.6	35.8	50.2	39.0	93.2	22.8
LTA		58.8	67.0	72.6	69.9	50.6	56.5	55.4	51.5	64.1	58.0	63.5

ANNEX 4. COEFFICIENTS FOR FITTED N RESPONSE CURVES AND PREDICTED VALUES FROM CURVE FITTING (SEE FIGURES A3 TO A8)

HM2007 [see Figure A3]	**Variety x sowing date**			
Yield				
Parameters for curves	Hereward-E	Hereward-L	Xi19-E	Xi19-L
A	12.76	5.64	9.19	6.49
B	-8.21	-1.59	-4.66	-1.78
C	-0.012028	-0.002815	-0.00142	-0.00121
R	0.993952	0.99	0.99	0.989559
%Variation accounted for	97	61.1	89.5	62.2
Opt N rate kg/ha (6:1 ratio)	**168**	**60**	**183**	**91**
SE of optimum N rate	10	15	31	>opt
Grain yield (t/ha) at optimum N	7.78	4.60	8.18	5.69
Conc. Of N in plant material at optimum N rate for yield (no premia)				
Flower Ear (N%)	1.86	1.95	1.94	1.9
Flower WP (N%)	1.8	1.89	1.8	1.83
Milky Ripe Ear (N%)	1.75	1.85	1.95	1.9
Milky Ripe WP (N%)	1.59	1.53	1.62	1.55
Grain (N%)	2.15	2.2	2.09	2.08
Grain protein	12.26	12.54	11.91	11.86
N rate (kg/ha) at 13% protein	**240**	**150**	**>290**	**220**
Predicted conc. of N in plant material when final grain protein was 13%				
Flowering Ear (N%)	1.86	2.03	2.00	2.07
Flower WP (N%)	1.85	2.14	1.93	2.21
Milky Ripe Ear (N%)	1.81	1.93	2.05	2.09
Milky Ripe WP (N%)	1.71	1.69	1.86	1.86
Other parameters				
Flowering Ear %N	Hereward-E	Hereward-L	Xi19-E	Xi19-L
A	1.8605	2.0936	2.0232	2.218
B	-0.34401	-0.39484	-0.49555	-0.55615
R	0.96936	0.98306	0.99015	0.99376
Flowering WP %N	Hereward-E	Hereward-L	Xi19-E	Xi19-L
A	1.8797	2.437	2.0189	2.5717
B	-0.86835	-1.1192	-1.0555	-1.2709
R	0.98587	0.98816	0.99154	0.99404
Milky Ripe Ear %N	Hereward-E	Hereward-L	Xi19-E	Xi19-L
A	1.9185	2.0571	2.1214	2.2583
B	-0.56065	-0.37652	-0.7763	-0.61803
R	0.99299	0.99015	0.99179	0.99385
Milky ripe WP %N	Hereward-E	Hereward-L	Xi19-E	Xi19-L
A	1.9367	2.0958	2.4201	2.1985
B	-0.98741	-0.85218	-1.4775	-1.0647
R	0.99381	0.9932	0.99666	0.99459
Grain %N	Hereward-E	Hereward-L	Xi19-E	Xi19-L
A	1.8568	2.0922	1.7789	1.9255
B	0.001769	0.001742	0.001717	0.001682

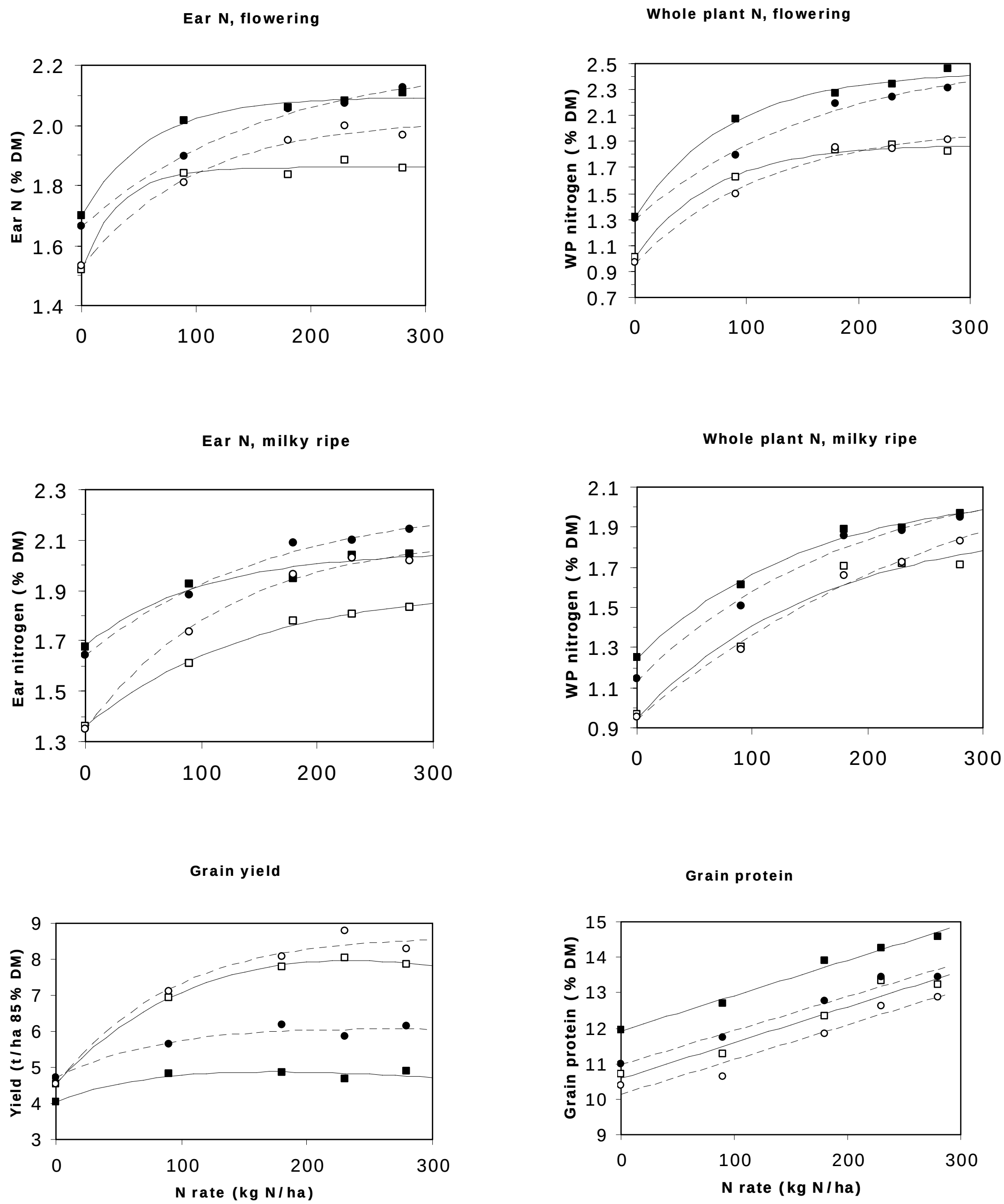


Figure A3. Nitrogen in immature crop, grain yield and grain protein for crops at High Mowthorpe in 2007 for varieties Hereward (■,□) and Xi19 (●,○). Early sown crops, open symbols/dashed lines; Late sown crops, closed symbols/solid lines. For parameters of curves see preceding table.

HM2008 [see Figure A4]	**Variety x sowing date**			
Yield				
Parameters for curves	Hereward-E	Hereward-L	Xi19-E	Xi19-L
A	9.90	305.74	19.28	6.49
B	-5.46	-301.86	-15.12	-3.11
C	-0.006063	-0.163691	-0.02938	-0.00126
R	0.989245	0.999369	0.994848	0.9789
%Variation accounted for	93.7	89.8	98.1	84.6
Opt N rate (6:1 ratio)	**147**	**183**	**153**	**104**
SE of optimum N rate	18	>opt	5	33
Grain yield (t/ha) at optimum N	7.90	6.85	7.93	6.02
Conc. Of N in plant material at optimum N rate for yield (no premia)				
Flower Ear (N%)	2.00	1.87	1.94	1.94
Flower WP (N%)	1.79	1.94	1.88	1.8
Milky Ripe Ear (N%)	1.83	1.84	1.92	1.85
Milky Ripe WP (N%)	1.63	1.69	1.59	1.46
Grain (N%)	2.20	2.34	1.95	2.01
Grain protein	12.54	13.338	11.115	11.457
N rate (kg/ha) at 13% protein	**180**	**150**	**>290**	**220**
Conc of N in plant material when final grain protein was 13%				
Flowering Ear (N%)	2.05	1.85	1.98	2.06
Flower WP (N%)	1.85	1.87	2.03	2.1
Milky Ripe Ear (N%)	1.86	1.81	2.02	1.96
Milky Ripe WP (N%)	1.68	1.62	1.8	1.66

Other parameters				
Flowering Ear %N	Hereward-E	Hereward-L	Xi19-E	Xi19-L
A	2.2805	33.407	1.985	2.109
B	-0.86816	-31.908	-0.55096	-0.55419
C	-0.00148	-0.021467		
R	0.99189	0.99921	0.98318	0.98858
Flowering WP %N	Hereward-E	Hereward-L	Xi19-E	Xi19-L
A	1.9798	2.103	2.0621	2.3331
B	-1.0014	-0.95591	-1.061	-1.1665
R	0.98886	0.99052	0.98842	0.99251
Milky Ripe Ear %N	Hereward-E	Hereward-L	Xi19-E	Xi19-L
A	1.9076	1.8914	2.0474	2.0124
B	-0.49742	-0.37594	-0.6395	-0.47799
R	0.98725	0.98958	0.98972	0.98938
Milky ripe WP %N	Hereward-E	Hereward-L	Xi19-E	Xi19-L
A	1.8238	2.0611	1.9432	2.0864
B	-0.8386	-0.88719	-0.94613	-0.91665
R	0.99021	0.9953	0.99351	0.99642
Grain %N	Hereward-E	Hereward-L	Xi19-E	Xi19-L
A	2.8132	2.6211	1.585	1.7608
B	-1.1458	-0.80742	0.002378	0.002399
R	0.99581	0.99426		

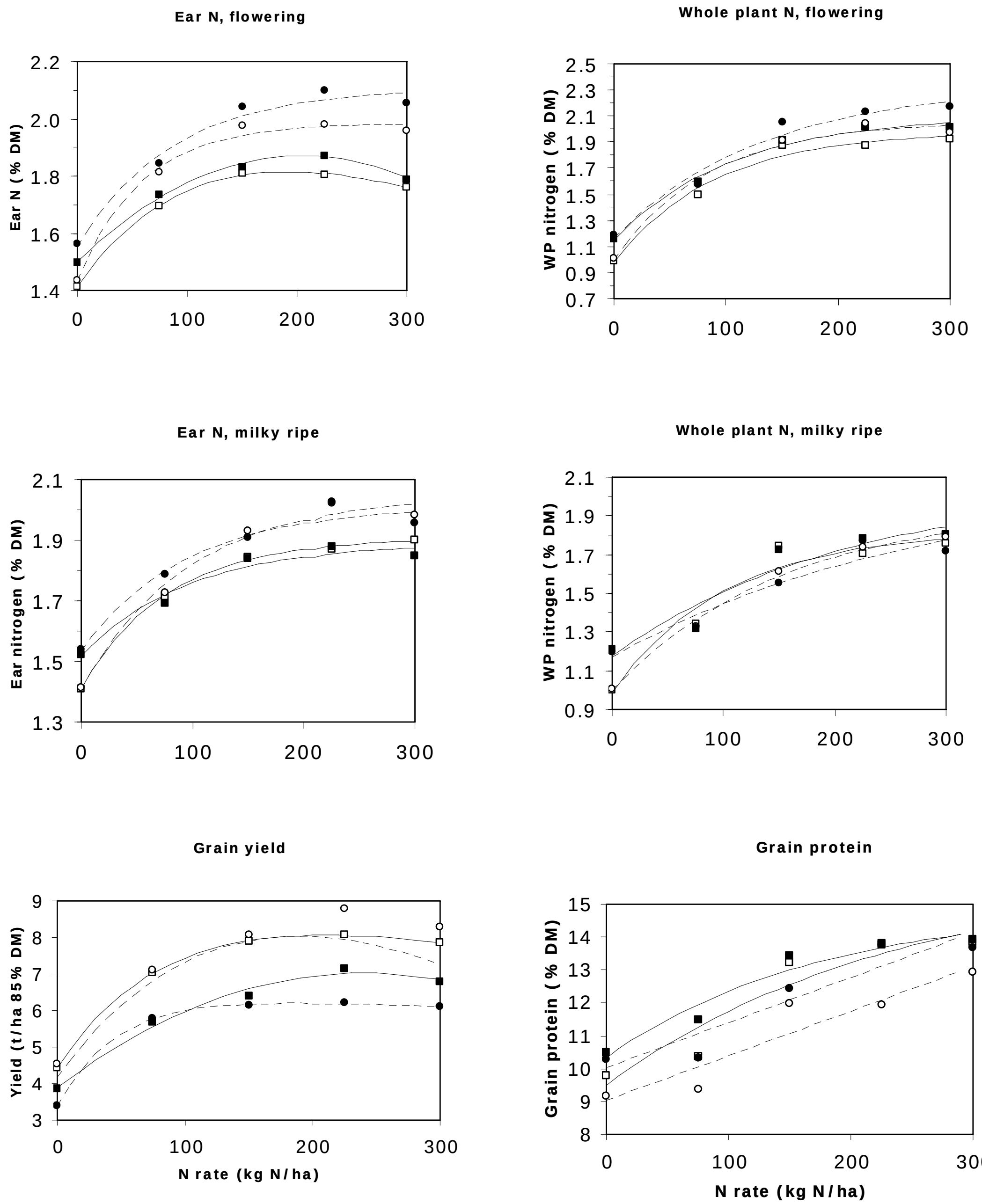


Figure A4. Nitrogen in immature crop, grain yield and grain protein for crops at High Mowthorpe in 2008 for varieties Hereward (■,□) and Xi19 (●,○).Early sown crops, open symbols/dashed lines; Late sown crops, closed symbols/solid lines. For parameters of curves see preceding table.

HM2009 [see Figure A5]	Variety			
Yield				
Parameters for curves	Einstein	Hereward	Solstice	Xi19
A	10.82	36.94	32.56	8.71
B	-5.78	-31.74	-27.50	-3.12
C	0.003066	-0.034296	-0.026403	0.010196
R	0.987929	0.99773	0.997582	0.99
%Variation accounted for	93.1	93.8	92.4	90.7
Opt N rate (6:1 ratio)	**261**	**256**	**297**	**>380**
SE of optimum N rate	100	38	175	0
Grain yield (t/ha) at optimum N	11.38	5.61	11.32	11.57
Conc. Of N in plant material at optimum N rate for yield (no premia)				
Flower Ear (N%)	no fit	2	1.83	2.03
Flower WP (N%)	1.72	1.73	1.84	2.11
Milky Ripe Ear (N%)	1.63	1.71	1.7	1.81
Milky Ripe WP (N%)	1.38	1.46	1.48	1.62
Grain (N%)	1.84	2.11	2.06	2.14
Grain protein	10.488	12.027	11.742	12.198
N rate (kg/ha) at 13% protein	**>380**	**360**	**>380**	**>380**
Predicted conc. of N in plant material when final grain protein was 13%				
Flowering Ear (N%)	Protein	2	1.91	Protein
Flower WP (N%)	never	1.99	2.06	Never
Milky Ripe Ear (N%)	reaches	1.83	1.84	reaches
Milky Ripe WP (N%)	13%	1.63	1.66	13%

Other parameters				
Flowering Ear %N	Einstein	Hereward	Solstice	Xi19
A	No fit	2.0039	1.5579	1.6006
B	possible	-0.31441	0.000924	0.001135
R		0.9801		
Flowering WP %N	Einstein	Hereward	Solstice	Xi19
A	2.3644	1.0783	1.065	1.1679
B	-1.3687	0.002532	0.002615	0.002467
R	0.9971			
Milky Ripe Ear %N	Einstein	Hereward	Solstice	Xi19
A	2.1547	2.1781	1.1913	1.2051
B	-0.98492	-0.97431	0.001708	0.001588
R	0.9976	0.99713		
Milky ripe WP %N	Einstein	Hereward	Solstice	Xi19
A	0.8317	2.3531	0.8656	0.8861
B	0.002086	-1.4885	0.00208	0.00194
R		0.99799		
Grain %N	Einstein	Hereward	Solstice	Xi19
A	1.3324	2.8447	1.3043	1.3327
B	0.001954	-1.4028	0.002535	0.002115
R		0.99746		

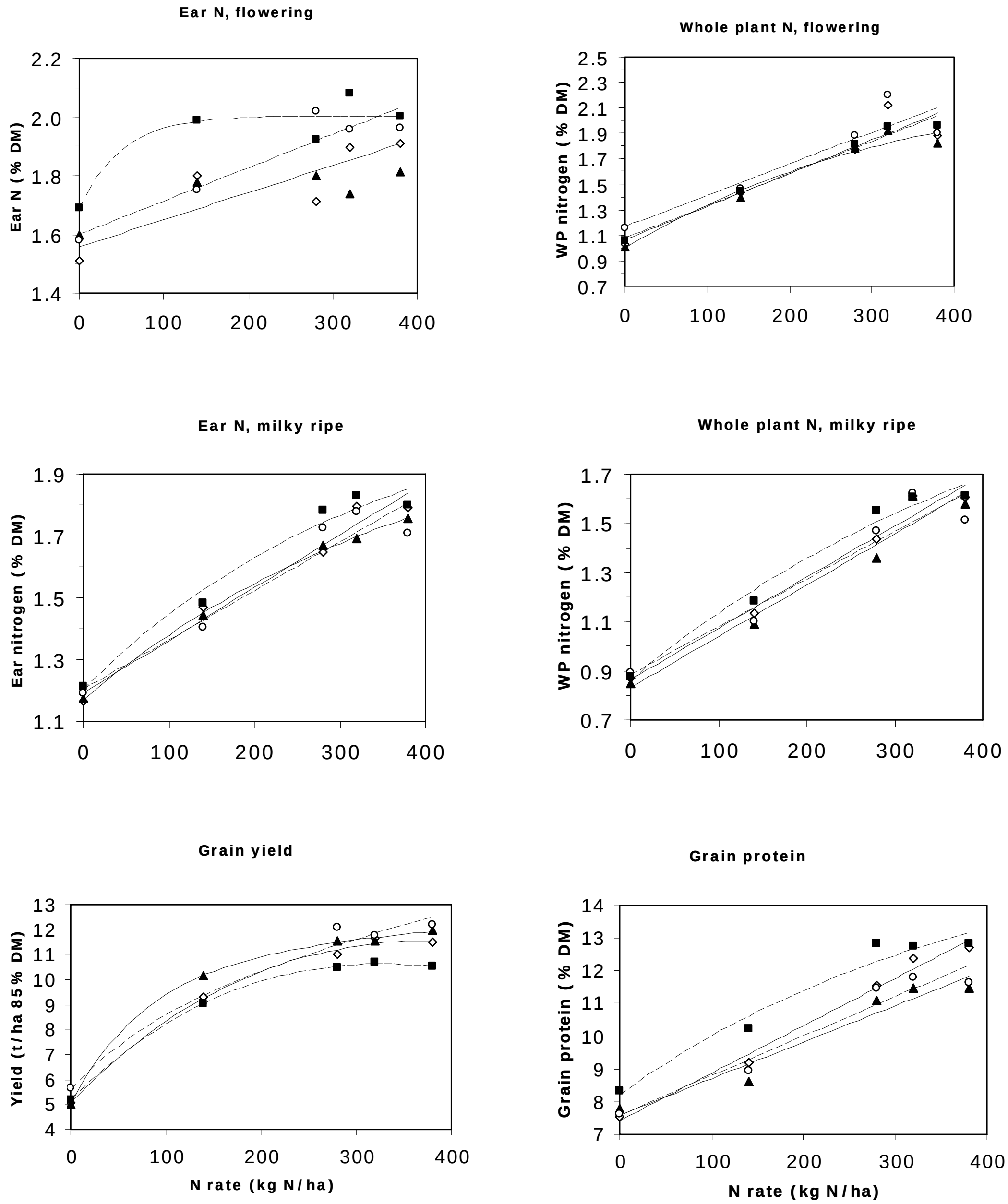


Figure A5. Nitrogen in immature crop, grain yield and grain protein for crops at High Mowthorpe in 2009 for varieties Hereward (■ ---), Xi19 (○---). Solstice (◇—) and Einstein (▲—). Note: Curve could not be fitted for Einstein, ear N% at flowering. For parameters of curves see preceding table

BW2007 [see Figure A6]	**Variety x sowing date**			
Yield				
Parameters for curves	Hereward-E	Hereward-L	Xi19-E	Xi19-L
A	86.41	5.65	12.01	7.19
B	-80.39	-0.92	-5.47	-2.46
C	-0.065402	-0.001174	-0.01851	-0.00448
R	0.998972	0.99	0.99	0.99
%Variation accounted for	70.1	0	59.3	13.7
Opt N rate (6:1 ratio)	**143**	**no sensible fit**	**81**	**85**
SE of optimum N rate	>opt	*	10	28
Grain yield (t/ha) at optimum N	7.67	0.00	8.09	5.77
Conc. of N in plant material at optimum N rate for yield (no premia)				
Flower Ear (N%)	1.62	0	1.56	1.94
Flower WP (N%)	1.29	0	1.13	1.72
Milky Ripe Ear (N%)	no fit	0	no fit	1.77
Milky Ripe WP (N%)	1.38	0	1.32	1.47
Grain (N%)	2.01	0	1.93	2.06
Grain protein	11.457	0	11.001	11.742
N rate (kg/ha) at 13% protein	**310**	**280**	**>320**	**>320**
Predicted conc. of N in plant material when final grain protein was 13%				
Flowering Ear (N%)	1.71	1.96	Protein	Protein
Flower WP (N%)	1.77	2.18	Never	Never
Milky Ripe Ear (N%)	no fit	1.78	reaches	reaches
Milky Ripe WP (N%)	no fit	1.63	13%	13%
Other parameters				
Flowering Ear %N	Hereward-E	Hereward-L	Xi19-E	Xi19-L
A	1.738	1.9567	2.1918	1.8655
B	-0.38129	-0.29667	-0.782	0.000829
R	0.99206	0.96585	0.99735	
Flowering WP %N	Hereward-E	Hereward-L	Xi19-E	Xi19-L
A	0.8825	2.2335	1.9178	2.1081
B	0.002867	-0.89521	-1.1314	-0.83087
R		0.98991	0.99557	0.99094
Milky Ripe Ear %N	Hereward-E	Hereward-L	Xi19-E	Xi19-L
A	no fit	1.789	no fit	1.9188
B	possible	-0.30899	Possible	-0.40103
R		0.98517		0.98735
Milky ripe WP %N	Hereward-E	Hereward-L	Xi19-E	Xi19-L
A	1.4117	1.6311	1.3626	1.3685
B	-0.34645	-0.45458	-0.41588	0.001222
R	0.98334	0.97319	0.97088	
Grain %N	Hereward-E	Hereward-L	Xi19-E	Xi19-L
A	1.781	2.086	1.819	2.3437
B	0.001597	0.000695	0.001337	-0.45883
R				0.99423

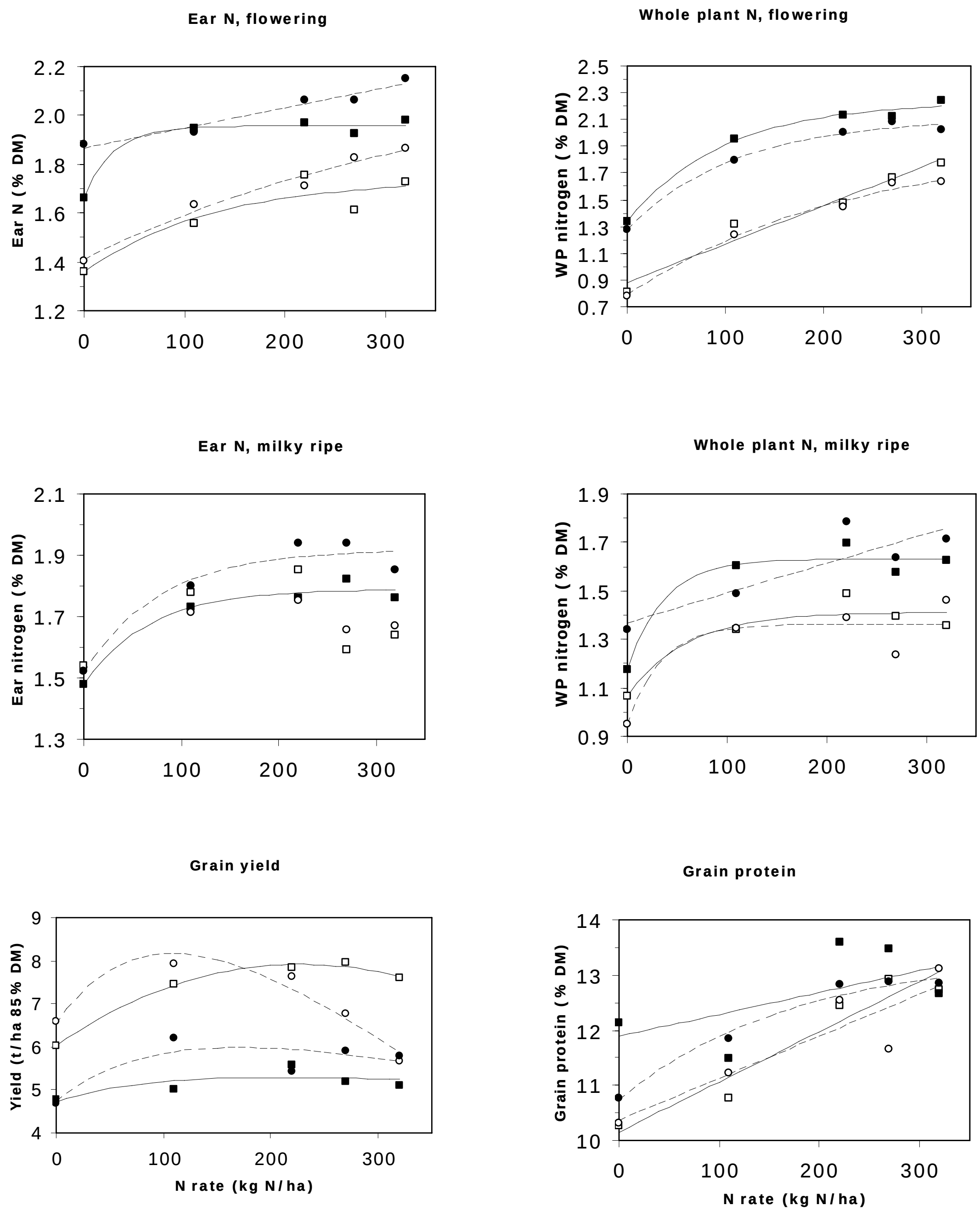


Figure A6. Nitrogen in immature crop, grain yield and grain protein for crops at Boxworth in 2007 for varieties Hereward (■,□) and Xi19 (●,○). Early sown crops, open symbols/dashed lines; Late sown crops, closed symbols/solid lines. Note: curves could not be fitted for Hereward and Xi19 late sown, ear N% at milky ripe stage. For parameters of curves see preceding table.

BW2008 [see Figure A7]	**Variety x sowing date**			
Yield				
Parameters for curves	Hereward-E	Hereward-L	Xi19-E	Xi19-L
A	12.34	8.63	58.50	10.78
B	-8.91	-4.82	-54.95	-7.32
C	-0.00569	0.005612	-0.06341	-0.00051
R	0.992319	0.99	0.997854	0.986865
%Variation accounted for	93.2	94.5	95.3	96.5
Opt N rate (6:1 ratio)	**230**	**> max**	**247**	**204**
SE of optimum N rate	48	*	>opt	27
Grain yield (t/ha) at optimum N	9.52	9.76	10.52	10.18
Conc. Of N in plant material at optimum N rate for yield (no premia)				
Flower Ear (N%)	1.67	1.81	1.73	1.69
Flower WP (N%)	1.67	1.92	1.69	1.5
Milky Ripe Ear (N%)	1.62	1.7	1.67	1.5
Milky Ripe WP (N%)	1.27	1.51	1.33	1.18
Grain (N%)	1.96	1.95	1.93	no fit
Grain protein	11.17	11.12	11.00	no fit
N rate (kg/ha) at 13% protein	**>300**	**300**	**>300**	**>300**
Predicted conc. of N in plant material when final grain protein was 13%				
Flowering Ear (N%)				
Flower WP (N%)	% N in grain never reached 2.28 (13% protein) for any variety			
Milky Ripe Ear (N%)				
Milky Ripe WP (N%)				

Other parameters				
Flowering Ear %N	Hereward-E	Hereward-L	Xi19-E	Xi19-L
A	1.2149	2.0187	1.2927	1.8517
B	0.001974	-0.81598	0.001764	-0.68227
R		0.99671		0.99287
Flowering WP %N	Hereward-E	Hereward-L	Xi19-E	Xi19-L
A	0.625	0.7054	0.6761	0.6873
B	0.004536	0.004039	0.00411	0.003964
Milky Ripe Ear %N	Hereward-E	Hereward-L	Xi19-E	Xi19-L
A	2.5863	1.1067	1.1517	1.8928
B	-1.4569	0.001987	0.002084	-0.77609
R	0.99821			0.99665
Milky ripe WP %N	Hereward-E	Hereward-L	Xi19-E	Xi19-L
A	0.6226	0.6303	0.5851	0.6252
B	0.00281	0.002937	0.00302	0.002737
Grain %N	Hereward-E	Hereward-L	Xi19-E	Xi19-L
A	1.5623	1.584	1.757	no fit
B	0.001709	0.001236	0.000713	Possible

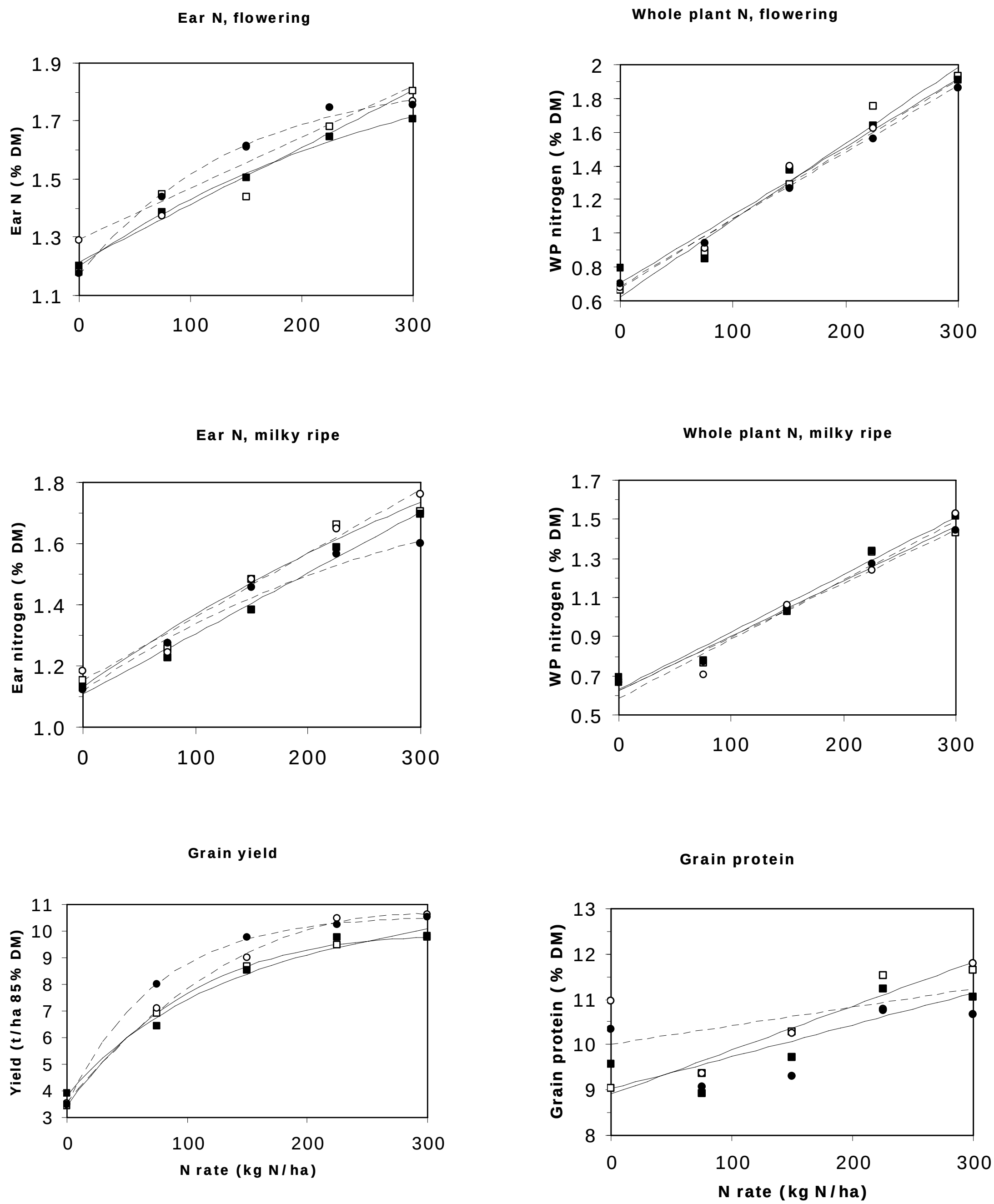


Figure A7. Nitrogen in immature crop, grain yield and grain protein for crops at Boxworth in 2008 for varieties Hereward (■,□) and Xi19 (●,○). Early sown crops, open symbols/dashed lines; Late sown crops, closed symbols/solid lines. For parameters of curves see preceding table.

BW2009 [see Figure A8]	Variety			
Yield				
Parameters for curves	Einstein	Hereward	Solstice	Xi19
A	10.43	10.28	9.24	13.31
B	-4.52	-4.30	-2.82	-7.82
C	0.000556	-0.002871	0.000377	-0.009144
R	0.99	0.990266	0.987851	0.991293
%Variation accounted for	88.7	80.5	86	88.8
Opt N rate (6:1 ratio)	**211**	**159**	**148**	**172**
SE of optimum N rate	46	49	54	30
Grain yield (t/ha) at opt. N	10.00	8.91	8.83	10.00
Conc. Of N in plant material at optimum N rate for yield (no premia)				
Flower Ear (N%)	1.56	1.73	1.58	1.77
Flower WP (N%)	1.49	1.51	1.48	1.56
Milky Ripe Ear (N%)	1.6	1.65	1.64	1.76
Milky Ripe WP (N%)	1.3	1.34	1.25	1.42
Grain (N%)	2.15	2.18	2.19	2.1
Grain protein	12.255	12.426	12.483	11.97
N rate (kg/ha) at 13% protein	**>320**	**200**	**190**	**>320**
Predicted conc. of N in plant material when final grain protein was 13%				
Flowering Ear (N%)	Protein	1.75	1.61	Protein
Flower WP (N%)	Never	1.57	1.52	never
Milky Ripe Ear (N%)	reaches	1.68	1.66	reaches
Milky Ripe WP (N%)	13%	1.4	1.3	13%

Other parameters				
Flowering Ear %N	Einstein	Hereward	Solstice	Xi19
A	1.6789	1.7962	1.7601	1.8475
B	-0.41392	-0.37192	-0.4423	-0.44467
R	0.994	0.98947	0.99406	0.98961
Flowering WP %N	Einstein	Hereward	Solstice	Xi19
A	2.264	1.7769	1.5793	1.8552
B	-1.354	-0.79451	-0.72586	-0.94112
R	0.99734	0.99316	0.98683	0.99337
Milky Ripe Ear %N	Einstein	Hereward	Solstice	Xi19
A	1.6771	1.7619	1.6967	1.7778
B	-0.45638	-0.42221	-0.45233	-0.44546
R	0.99133	0.9914	0.98654	0.98266
Milky ripe WP %N	Einstein	Hereward	Solstice	Xi19
A	1.4332	1.7211	1.5285	1.5135
B	-0.65377	-0.83513	-0.65574	-0.63686
R	0.9925	0.99503	0.99429	0.98916
Grain %N	Einstein	Hereward	Solstice	Xi19
A	2.2805	3.0329	2.4936	2.3186
B	-0.89901	-1.4865	-1.1196	-0.8974
R	0.99073	0.99653	0.99116	0.9917

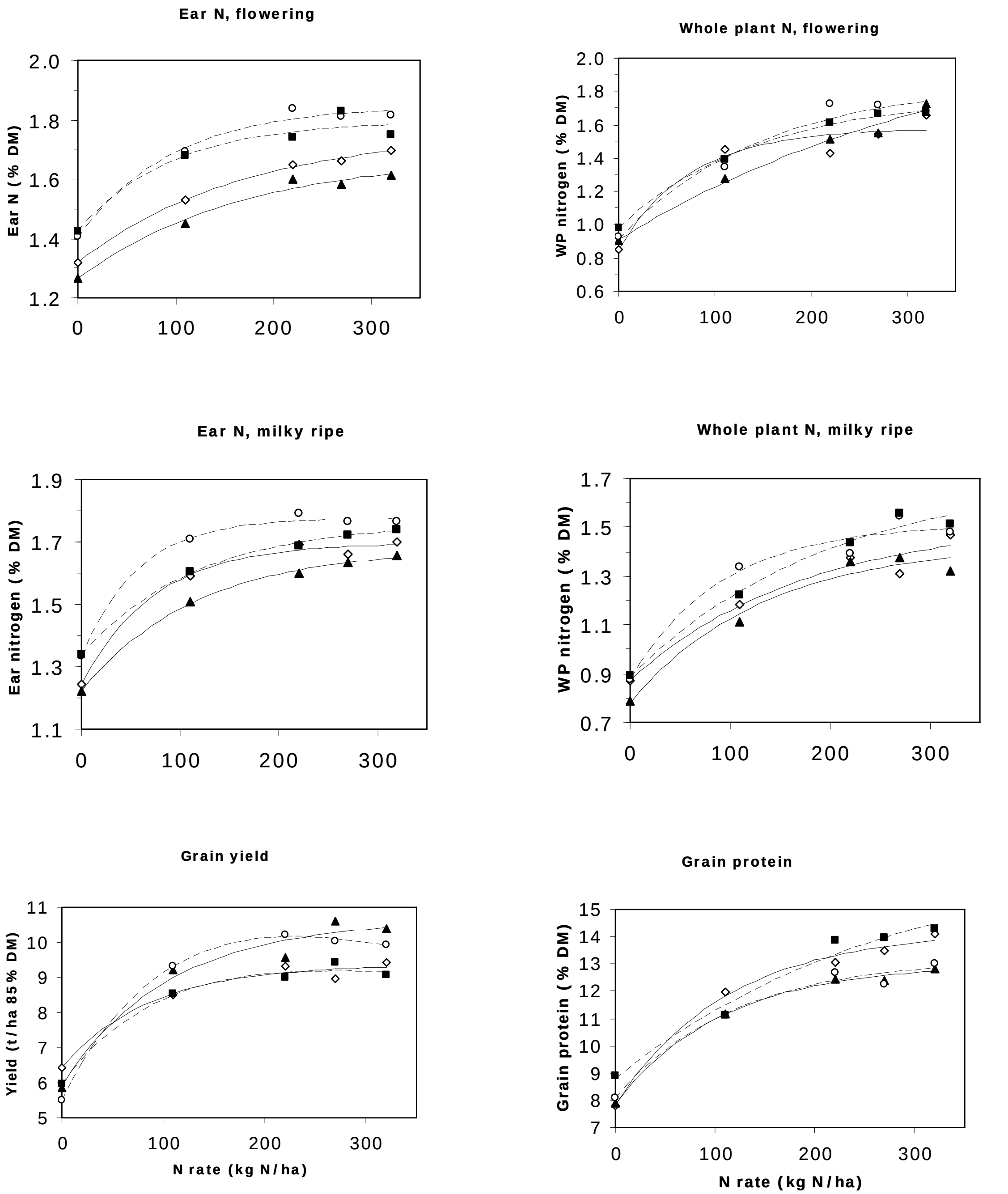


Figure A8. Nitrogen in immature crop, grain yield and grain protein for crops at Boxworth in 2009 for varieties Hereward (■ ---), Xi19 (○---). Solstice (◇—) and Einstein (▲—). For parameters of curves see preceding table.

ANNEX 5. NITROGEN CONTENT IN IMMATURE MATERIAL PREDICTED AT THE ECONOMIC OPTIMUM N RATE, OR AT THE N RATE WHICH WOULD HAVE GIVEN 13% FINAL GRAIN PROTEIN USING EQUATIONS OF CURVES IN ANNEX 3, AND MAXIMUM AND MINIMUM MEASURED IN FIELD EXPERIMENTS.

HM2007	**Hereward-E**	**Hereward-L**	**Xi19-E**	**Xi19-L**
Flower Ear (N%) at opt N	1.86	1.95	1.94	1.90
Flower Ear (N%) at 13% GP	1.86	2.03	2.00	2.07
Max value measured†	1.89	2.11	2.00	2.12
Min value measured†	1.52	1.70	1.53	1.66
Range (max-min)	0.37	0.41	0.47	0.46
Flower WP (N%) at opt N	1.80	1.89	1.80	1.83
Flower WP (N%) at 13% GP	1.85	2.14	1.93	2.21
Max value measured	1.88	2.46	1.91	2.31
Min value measured	1.01	1.31	0.97	1.31
Range (max-min)	0.86	1.15	0.94	1.01
MR Ear (N%) at opt N	1.75	1.85	1.95	1.90
MR Ear (N%) at 13% GP	1.81	1.93	2.05	2.09
Max value measured	1.83	2.03	2.03	2.14
Min value measured	1.36	1.35	1.35	1.64
Range (max-min)	0.47	0.68	0.68	0.50
MR WP (N%) at opt N	1.59	1.53	1.62	1.55
MR WP (N%) at 13% GP	1.71	1.69	1.86	1.86
Max value measured	1.72	1.97	1.83	1.95
Min value measured	0.97	1.25	0.95	1.14
Range (max-min)	0.75	0.72	0.88	0.81

†, maximum and minimum value derived from treatment means of data from ANOVA

E, Early sowing; L, Late sowing

HM2008				
	Hereward-E	**Hereward-L**	**Xi19-E**	**Xi19-L**
Flower Ear (N%) at opt N	2.00	1.87	1.94	1.94
Flower Ear (N%) at 13% GP	2.05	1.85	1.98	2.06
Max value measured†	1.81	1.87	1.98	2.10
Min value measured†	1.41	1.50	1.44	1.56
Range (max-min)	0.40	0.37	0.54	0.54
Flower WP (N%) at opt N	1.79	1.94	1.88	1.80
Flower WP (N%) at 13% GP	1.85	1.87	2.03	2.10
Max value measured	1.93	2.02	2.04	2.17
Min value measured	0.99	1.16	1.01	1.19
Range (max-min)	0.94	0.86	1.03	0.98
MR Ear (N%) at opt N	1.83	1.84	1.92	1.85
MR Ear (N%) at 13% GP	1.86	1.81	2.02	1.96
Max value measured	1.90	1.88	2.02	2.02
Min value measured	1.41	1.52	1.41	1.54
Range (max-min)	0.49	0.36	0.61	0.49
MR WP (N%) at opt N	1.63	1.69	1.59	1.46
MR WP (N%) at 13% GP	1.68	1.62	1.8	1.66
Max value measured	1.76	1.80	1.79	1.77
Min value measured	1.00	1.21	1.01	1.20
Range (max-min)	0.76	0.59	0.79	0.57

†, maximum and minimum value derived from treatment means of data from ANOVA

E, Early sowing; L, Late sowing

HM2009	Einstein	Hereward	Solstice	Xi19
Flower Ear (N%) at opt N	*	2.00	1.83	2.03
Flower Ear (N%) at 13% GP		2.00	1.91	
Max value measured†	1.82	2.08	1.91	2.02
Min value measured†	1.60	1.69	1.51	1.58
Range (max-min)	0.22	0.39	0.40	0.44
Flower WP (N%) at opt N	1.72	1.73	1.84	2.11
Flower WP (N%) at 13% GP		1.99	2.06	
Max value measured	1.93	1.97	2.12	2.20
Min value measured	1.01	1.06	1.03	1.16
Range (max-min)	0.92	0.91	1.09	1.05
MR Ear (N%) at opt N	1.63	1.71	1.7	1.81
MR Ear (N%) at 13% GP	*	1.83	1.84	*
Max value measured	1.75	1.83	1.80	1.78
Min value measured	1.17	1.21	1.16	1.19
Range (max-min)	0.58	0.61	0.63	0.59
MR WP (N%) at opt N	1.38	1.46	1.48	1.62
MR WP (N%) at 13% GP	*	1.63	1.66	*
Max value measured	1.613	1.614	1.613	1.624
Min value measured	0.849	0.878	0.849	0.891
Range (max-min)	0.76	0.74	0.76	0.73

* not possible to predict either because of inability to fit curve or because 13% protein was not reached in the trial.

†, maximum and minimum value derived from treatment means of data from ANOVA

BW2007	Hereward-E	Hereward-L	Xi19-E	Xi19-L
Flower Ear (N%) at opt N	1.62	*	1.56	1.94
Flower Ear (N%) at 13% GP	1.71	1.96		
Max value measured†	1.75	1.98	1.86	2.15
Min value measured†	1.36	1.66	1.66	1.88
Range (max-min)	0.39	0.32	0.20	0.27
Flower WP (N%) at opt N	1.29	*	1.13	1.72
Flower WP (N%) at 13% GP		2.18		
Max value measured	1.77	2.24	1.63	2.08
Min value measured	0.81	1.34	0.78	1.28
Range (max-min)	0.96	0.90	0.85	0.80
MR Ear (N%) at opt N	*	*	*	1.77
MR Ear (N%) at 13% GP	*	1.78	*	*
Max value measured	1.85	1.82	1.75	1.94
Min value measured	1.54	1.48	1.52	1.52
Range (max-min)	0.31	0.34	0.23	0.42
MR WP (N%) at opt N	1.38	0.00	1.32	1.47
MR WP (N%) at 13% GP	*	1.63	0.13	0.13
Max value measured	1.49	1.70	1.46	1.79
Min value measured	1.07	1.18	0.95	1.34
Range (max-min)	0.42	0.52	0.52	0.45

* not possible to predict either because of inability to fit curve or because 13% protein was not reached in the trial.

†, maximum and minimum value derived from treatment means of data from ANOVA

E, Early sowing; L, Late sowing

BW2008				
	Hereward-E	**Hereward-L**	**Xi19-E**	**Xi19-L**
Flower Ear (N%) at opt N	1.67	1.81	1.73	1.69
Flower Ear (N%) at 13% GP	*	*	*	*
Max value measured†	1.81	1.71	1.77	1.76
Min value measured†	1.18	1.20	1.29	1.17
Range (max-min)	0.62	0.51	0.48	0.58
Flower WP (N%) at opt N	1.67	1.92	1.69	1.50
Flower WP (N%) at 13% GP	*	*	*	*
Max value measured	1.93	1.91	1.86	1.86
Min value measured	0.67	0.79	0.67	0.70
Range (max-min)	1.27	1.12	1.18	1.16
MR Ear (N%) at opt N	1.62	1.7	1.67	1.5
MR Ear (N%) at 13% GP	*	*	*	*
Max value measured	1.71	1.70	1.76	1.60
Min value measured	1.15	1.13	1.18	1.12
Range (max-min)	0.55	0.57	0.58	0.48
MR WP (N%) at opt N	1.27	1.51	1.33	1.18
MR WP (N%) at 13% GP	*	*	*	*
Max value measured	1.43	1.51	1.53	1.44
Min value measured	0.66	0.69	0.66	0.66
Range (max-min)	0.77	0.82	0.87	0.78

* not possible to predict because 13% protein was not reached in the trial.

†, maximum and minimum value derived from treatment means of data from ANOVA

E, Early sowing; L, Late sowing

BW2009	Einstein	Hereward	Solstice	Xi19
Flower Ear (N%) at opt N	1.56	1.73	1.58	1.77
Flower Ear (N%) at 13% GP	*	1.75	1.61	*
Max value measured†	1.61	1.83	1.70	1.84
Min value measured†	1.27	1.42	1.32	1.40
Range (max-min)	0.35	0.40	0.38	0.43
Flower WP (N%) at opt N	1.49	1.51	1.48	1.56
Flower WP (N%) at 13% GP	*	1.57	1.52	*
Max value measured	1.725	1.674	1.725	1.726
Min value measured	0.849	0.984	0.903	0.925
Range (max-min)	0.88	0.69	0.82	0.80
MR Ear (N%) at opt N	1.6	1.65	1.64	1.76
MR Ear (N%) at 13% GP	*	1.68	1.66	*
Max value measured	1.6547	1.74	1.699	1.7923
Min value measured	1.22	1.339	1.2447	1.3327
Range (max-min)	0.43	0.40	0.45	0.46
MR WP (N%) at opt N	1.3	1.34	1.25	1.42
MR WP (N%) at 13% GP	*	1.4	1.3	*
Max value measured	1.376	1.558	1.468	1.545
Min value measured	0.786	0.89	0.871	0.875
Range (max-min)	0.59	0.67	0.60	0.67

* not possible to predict either because of inability to fit curve or because 13% protein was not reached in the trial.

†, maximum and minimum value derived from treatment means of data from ANOVA

ANNEX 6. TOTAL DRY MATTER (DM) AND NITROGEN (N) UPTAKE AND DM AND N PARTITIONING IN FIELD TRIALS DETERMINED BY PRE-HARVEST GROWTH ANALYSIS AT BOXWORTH AND HIGH MOWTHORPE 2007-2009.

Note: no growth analysis data available for HM 2007.

HM2008

Total DM (t/ha)

Sowing date	Variety	Nitrogen (kg/ha)	0		75		150		225	300
Early	Hereward		5.9		12.2		11.0		11.4	12.3
	Xi19		6.0		11.7		12.8		11.1	10.6
Late	Hereward		6.7		11.0		12.8		12.1	13.4
	Xi19		5.4		11.7		13.1		11.5	12.9
		N rate mean	*6.0*		*11.6*		*12.4*		*11.5*	*12.3*
Least significant differences:		Sowing date	2.18	Variety			0.73	Nitrogen		1.16
Significance of effects			ns				ns			***

Total N uptake (kg/ha)

Sowing date	Variety	Nitrogen (kg/ha)	0		75		150		225	300
Early	Hereward		97		150		205		231	223
	Xi19		79		128		186		180	185
Late	Hereward		85		133		187		208	206
	Xi19		70		130		166		181	180
		N rate mean	*83*		*135*		*186*		*200*	*199*
Least significant differences:		Sowing date	37.7	Variety			6.7	Nitrogen		10.6
Significance of effects			ns				***			***

DM harvest index (%)

Sowing date	Variety	Nitrogen (kg/ha)	0		75		150		225	300
Early	Hereward		40.9		49.0		53.3		52.3	53.7
	Xi19		50.3		54.8		57.6		55.3	54.7
Late	Hereward		47.0		50.3		50.1		50.1	51.3
	Xi19		50.4		50.0		52.1		52.1	53.1
		N rate mean	*47.1*		*51.0*		*53.2*		*52.4*	*53.2*
Least significant differences:		Sowing date	10.92	Variety			1.21	Nitrogen		1.92
Significance of effects			ns				***			***

N harvest index (%)

Sowing date	Variety	Nitrogen (kg/ha)	0		75		150		225	300
Early	Hereward		66.8		72.7		76.3		71.7	72.8
	Xi19		72.0		74.9		75.6		78.9	75.7
Late	Hereward		70.9		73.2		68.6		71.3	68.6
	Xi19		74.2		68.8		69.2		70.6	68.9
		N rate mean	*71.0*		*72.4*		*72.4*		*73.1*	*71.5*
Least significant differences:		Sowing date	10.46	Variety			1.89	Nitrogen		2.99
Significance of effects			ns				ns			ns

HM2009

Total DM (t/ha)

Variety	Nitrogen (kg/ha)	0	140	280	320	380
Einstein		8.5	14.9	17.7	18.5	19.5
Hereward		7.5	17.3	19.2	16.3	20.3
Solstice		7.4	14.7	19.8	18.7	19.5
Xi19		7.8	16.3	21.5	20.4	19.7
	N rate mean	*7.8*	*15.8*	*19.5*	*18.5*	*19.8*
Least significant differences:			Variety	1.27	Nitrogen	1.42
Significance of effects				ns		***

Total N uptake (kg/ha)

Variety	Nitrogen (kg/ha)	0	140	280	320	380
Einstein		77	159	238	254	258
Hereward		83	181	261	258	273
Solstice		73	165	244	288	302
Xi19		83	158	278	271	270
	N rate mean	*79*	*165*	*255*	*268*	*276*
Least significant differences:			Variety	10.7	Nitrogen	12.0
Significance of effects				*		***

DM harvest index (%)

Variety	Nitrogen (kg/ha)	0	140	280	320	380
Einstein		54.0	60.2	60.5	60.5	59.8
Hereward		51.1	53.0	53.7	58.2	55.8
Solstice		55.4	57.6	59.6	53.5	56.3
Xi19		54.3	56.3	58.8	58.4	60.9
	N rate mean	*53.7*	*56.8*	*58.1*	*57.7*	*58.2*
Least significant differences:			Variety	1.84	Nitrogen	2.06
Significance of effects				***		***

N harvest index (%)

Variety	Nitrogen (kg/ha)	0	140	280	320	380
Einstein		75.4	82.6	80.6	78.0	79.2
Hereward		78.5	76.2	77.0	78.9	73.8
Solstice		77.9	77.7	77.9	74.8	72.1
Xi19		78.4	76.4	75.2	76.7	78.7
	N rate mean	*77.5*	*78.2*	*77.7*	*77.1*	*76.0*
Least significant differences:			Variety	2.19	Nitrogen	2.45
Significance of effects				*		ns

BW2007

Total DM (t/ha)

Sowing date	Variety	Nitrogen (kg/ha)	0	110	220	270	320
Early	Hereward		14.3	13.6	17.0	15.3	17.0
	Xi19		11.1	16.3	12.2	14.3	14.9
Late	Hereward		12.4	12.9	14.6	14.5	14.4
	Xi19		10.5	13.3	13.2	15.9	11.8
		N rate mean	*12.1*	*14.0*	*14.2*	*15.0*	*14.5*
Least significant differences:		Sowing date	2.87	Variety	1.57	Nitrogen	2.48
Significance of effects			ns		ns		ns

Total N uptake (kg/ha)

Sowing date	Variety	Nitrogen (kg/ha)	0	110	220	270	320
Early	Hereward		149	196	248	250	248
	Xi19		145	203	254	230	212
Late	Hereward		132	166	216	190	197
	Xi19		121	175	183	205	172
		N rate mean	*136*	*185*	*225*	*219*	*207*
Least significant differences:		Sowing date	16.4	Variety	12.2	Nitrogen	19.3
Significance of effects			*		ns		***

DM harvest index (%)

Sowing date	Variety	Nitrogen (kg/ha)	0	110	220	270	320
Early	Hereward		41.0	57.3	43.8	43.2	42.3
	Xi19		40.5	47.5	52.9	35.2	39.8
Late	Hereward		47.4	45.1	44.1	42.8	55.0
	Xi19		59.1	49.2	47.4	48.0	56.8
		N rate mean	*47.0*	*49.8*	*47.1*	*42.3*	*48.5*
Least significant differences:		Sowing date	5.22	Variety	5.30	Nitrogen	8.38
Significance of effects			p=0.05		ns		ns

N harvest index (%)

Sowing date	Variety	Nitrogen (kg/ha)	0	110	220	270	320
Early	Hereward		62.0	57.8	58.7	61.2	58.4
	Xi19		69.7	65.2	60.2	50.7	52.1
Late	Hereward		64.4	51.8	52.1	56.5	50.1
	Xi19		64.1	62.3	56.8	54.8	52.6
		N rate mean	*65.1*	*59.2*	*56.9*	*55.8*	*53.3*
Least significant differences:		Sowing date	8.55	Variety	2.76	Nitrogen	4.36
Significance of effects			ns		ns		***

BW2008

Total DM (t/ha)

Sowing date	Variety	Nitrogen (kg/ha)	0	75	150	225	300
Early	Hereward		7.6	14.2	16.0	17.4	19.8
	Xi19		6.0	14.6	15.4	18.2	17.5
Late	Hereward		7.3	13.2	14.2	19.2	17.6
	Xi19		7.9	15.1	18.0	16.7	19.1
		N rate mean	*7.2*	*14.3*	*15.9*	*17.9*	*18.5*
Least significant differences:		Sowing date	5.03	Variety	1.03	Nitrogen	1.63
Significance of effects			ns		ns		***

Total N Uptake (kg/ha)

Sowing date	Variety	Nitrogen (kg/ha)	0	75	150	225	300
Early	Hereward		59	120	162	214	236
	Xi19		66	119	163	211	234
Late	Hereward		66	105	146	205	213
	Xi19		65	130	165	193	222
		N rate mean	*64*	*118*	*159*	*206*	*226*
Least significant differences:		Sowing date	18.1	Variety	9.6	Nitrogen	15.2
Significance of effects			ns		ns		***

DM harvest index (%)

Sowing date	Variety	Nitrogen (kg/ha)	0	75	150	225	300
Early	Hereward		43.0	44.0	48.3	47.9	49.6
	Xi19		45.5	48.8	52.2	52.7	48.1
Late	Hereward		46.9	49.6	51.3	50.2	52.0
	Xi19		49.1	45.1	53.0	55.5	52.2
		N rate mean	*46.1*	*46.8*	*51.2*	*51.6*	*50.5*
Least significant differences:		Sowing date	4.70	Variety	1.65	Nitrogen	2.61
Significance of effects			ns		*		***

N harvest index (%)

Sowing date	Variety	Nitrogen (kg/ha)	0	75	150	225	300
Early	Hereward		79.5	80.4	82.3	77.4	71.6
	Xi19		87.3	83.1	84.7	79.9	80.0
Late	Hereward		85.1	81.7	84.8	79.3	75.5
	Xi19		81.8	83.1	82.4	84.9	75.2
		N rate mean	*83.4*	*82.1*	*83.5*	*80.4*	*75.6*
Least significant differences:		Sowing date	2.23	Variety	1.14	Nitrogen	1.80
Significance of effects			ns		*		***

BW2009

Total DM (t/ha)

Variety	Nitrogen (kg/ha)	0	110	220	270	320
Einstein		11.6	14.8	15.6	17.0	18.1
Hereward		11.5	14.8	17.2	16.6	16.6
Solstice		10.0	15.2	14.7	12.3	16.9
Xi19		10.6	15.5	18.4	15.6	14.7
	N rate mean	*10.9*	*15.1*	*16.4*	*15.4*	*16.6*
Least significant differences:			Variety	1.87	Nitrogen	1.68
Significance of effects				ns		***

Total N uptake (kg/ha)

Variety	Nitrogen (kg/ha)	0	110	220	270	320
Einstein		97	191	218	243	248
Hereward		107	175	237	247	248
Solstice		98	193	221	220	258
Xi19		93	196	252	229	236
	N rate mean	*99*	*189*	*232*	*235*	*247*
Least significant differences:			Variety	10.2	Nitrogen	11.5
Significance of effects				ns		***

DM harvest index (%)

Variety	Nitrogen (kg/ha)	0	110	220	270	320
Einstein		46.9	51.4	53.1	53.6	53.3
Hereward		48.2	52.0	49.7	49.6	50.7
Solstice		48.9	49.4	56.1	48.2	49.0
Xi19		48.6	50.8	51.4	51.6	52.3
	N rate mean	*48.1*	*50.9*	*52.6*	*50.7*	*51.3*
Least significant differences:			Variety	2.05	Nitrogen	2.30
Significance of effects				ns		***

N harvest index (%)

Variety	Nitrogen (kg/ha)	0	110	220	270	320
Einstein		71.2	80.1	81.4	80.7	80.4
Hereward		74.6	80.7	78.5	79.4	78.1
Solstice		76.3	77.9	82.5	82.1	76.9
Xi19		71.5	78.9	76.5	79.7	81.9
	N rate mean	*73.4*	*79.4*	*79.7*	*80.5*	*79.3*
Least significant differences:			Variety	2.37	Nitrogen	2.65
Significance of effects				ns		***

ANNEX 7. CROP SOIL, VARIETY AND HUSBANDRY DETAILS FOR GROWERS SAMPLES

Farm Field ID	Soil type	Sowing date	Variety	Total N Applied (kg/ha)†	Animal manures last year	Animal manures in previous 5 years	Ploughed out long leys	Urea; Late foliar N (kg/ha)	Previous crop	Fert. N to prev crop (kg/ha)
2007										
1.1	Medium	10/10/06	Solstice	279	None	None	None	0	Wheat	180
1.2	Medium	19/9/06	Malacca	280	None	None	None	0	Wheat	180
2.1	Medium	30/10/06	Cordiale	225	None	Some/lots	None	25	Spring oats	176
2.2	Medium	18/10/06	Cordiale	260	None	None	None	0	Wheat	240
3.1	Deep Clay	15/9/06	Solstice	240	None	Some (sewage)	None	0	Oilseed rape	230
3.2	Deep Clay	4/10/06	Solstice	240	None	None	None	0	Oilseed rape	230
3.3	Deep Clay	5/10/06	Xi19	293	None	None	None	0	OSR	170
4.1	Deep Clay	26/9/06	Xi19	291	None	None	None	0	Wheat Cont.	269
4.2	Deep Clay	26/9/06	Xi19	289	None	None	None	0	W.Beans	None
4.3	Deep Clay	26/9/06	Xi19	291	None	None	None	0	Wheat	214
5.1	Deep Clay	8/10/06	Xi19	283	None	None	None	20	Wheat	290
5.2	Deep Clay	28/9/06	Cordiale	280	None	None	None	20	Wheat	211
6.1	Deep Clay	20/9/06	Solstice	240	None	None	None	0	Wheat	215
6.2	Deep Clay	22/9/06	Einstein	277	None	None	None	0	Wheat	232
6.3	Deep Clay	15/10/06	Cordiale	248	None	None	None	0	Wheat	200
6.4	Deep Clay	22/9/06	Einstein	235	None	None	None	0	Wheat	200
7.1	Shallow/Medium	9/10/06	Solstice	235	None	None	None	0	Wheat	225
7.2	Shallow/Medium	9/10/06	Soissons	248	None	None	None	0	Wheat	200
7.3	Medium	8/10/06	Solstice	209	None	None	None	0	OSR	245
8.1	Shallow/Medium	E. Oct 06	Xi19	281	None	None	None	0	Wheat	211
8.2	Shallow/Medium	E. Oct 06	Xi19	0	None	None	None	0	*	0
8.3	Medium	16/11/06	Xi19	0	None	None	None	0	*	0
9.1	Deep Clay	3/10/06	Solstice	0	None	None	None	0	*	0
9.2	Deep Clay	3/10/06	Solstice	0	None	None	None	0	*	0

†, Fertiliser N applied prior to late foliar N; *, data not available

Farm Field ID	Soil type	Sowing date	Variety	Total N Applied (kg/ha)†	Animal manures last year	Animal manures in previous 5 years	Ploughed out long leys	Urea; Late foliar N (kg/ha)	Previous crop	Fert. N to prev crop (kg/ha)
10.1	Medium	22/9/06	Xi19	284	None	None	None	0	Wheat	152
10.2	Medium	15/9/06	Solstice	284	None	None	None	0	Wheat	152
11.1	Medium	5/10/06	RAGT	284	None	None	None	0	Wheat	152
11.2	Medium	18/9/06	Alchemy	280	None	None	None	0	Wheat	176
11.3	Medium	27/9/06	RAGT	200	None	None	None	40	Spr. beans	0
11.4	Medium	17/9/06	Welford	200	None	None	None	0	OSR	170
12.1	Deep Clay	15/10/06	Solstice	200	None	None	None	0	OSR	170
12.2	Deep Clay	15/10/06	Solstice	240	None	None	None	40	Wheat	280
13.1	Deep Clay	16/10/06	Einstein	192	None	None	None	36	Peas	None
13.2	Deep Clay	16/10/06	Einstein	193	None	None	None	36	Wheat	201
13.3	Deep Clay	12/10/06	Solstice	193	None	None	None	36	Wheat	202
13.4	Deep Clay	28/9/06	Solstice	193	None	None	None	36	Wheat	202
14.1	Deep Clay	4/10/06	Xi19	238	None	None	None	40	Spr. Barley	113
14.2	Deep Clay	4/10/06	Xi19	230	None	None	None	40	Wheat	215
15.1	Deep Clay	26/9/06	Solstice	230	None	None	None	0	Wint. Beans	None
15.2	Deep Clay/chalky	27/9/06	Solstice	275	None	None	None	0	OSR	200
15.3	Deep Clay	26/9/06	Solstice	275	None	None	None	0	OSR	200
15.4	Deep Clay	26/9/06	Solstice	275	None	None	None	0	OSR	200
16.1	Medium	16/10/06	Solstice	275	None	None	None	0	OSR	200
16.2	Medium	17/10/06	Cordiale	272	None	None	None	0	Wheat	196
17.1	Medium	24/9/06	Solstice	272	None	None	None	0	Wheat	197
17.2	Medium	24/9/06	Solstice	270	None	None	None	0	Spr. barley	129
17.3	Medium	24/9/06	Solstice	270	None	None	None	0	Spr. Barley	129
17.4	Medium	16/10/06	Solstice	185	None	Some (Sewage)	None	40	OSR	226

†, Fertiliser N applied prior to late foliar N

*, data not available

Farm Field ID	Soil type	Sowing date	Variety	Total N Applied (kg/ha)†	Animal manures last year	Animal manures in previous 5 years	Ploughed out long leys	Urea; Late foliar N (kg/ha)	Previous crop	Fert. N to prev crop (kg/ha)
18.1	Medium	2/11/06	Hereward	192	Lots	Some (Sewage)	None	40	Wheat	193
18.2	Medium	27/10/06	Hereward	196	None	Some (Sewage)	None	40	OSR	226
19.1	Medium	17/9/07	Solstice	233	None	Some (Sewage)	None	40	Wheat	209
19.2	Medium	21/9/06	Solstice	215	None	None	None	40	OSR	218
19.3	Medium	25/9/07	Einstein	258	None	None	None	40	Sugar Beet	96
20.1	Deep Clay	10/10/06	Solstice	278	None	None	None	40	Wheat	255
20.2	Deep Clay	27/9/06	Solstice	334	None	None	None	40	Sugar Beet	*
20.3	Deep Clay	20/9/06	Solstice	334	None	None	None	40	Sugar Beet	185
21.1	Medium	24/11/06	Solstice	220	None	None	10years+	20	OSR	220
21.2	Peaty over clay	11/9/06	Solstice	220	None	None	10years+	20	OSR	220
21.3	Organic	6/11/06	Solstice	220	None	None	10years+	20	OSR	220
21.4	Organic	8/11/06	Solstice	220	None	None	10years+	20	OSR	220
22.1	*	20/9/06	Hereward	135	None	None	None	0	OSR	100
22.2	Medium	21/9/06	Hereward	150	None	None	None	0	Comb. Peas	None
22.3	*	22/9/06	Hereward	160	None	Some	None	0	Sugar Beet	None
22.4	*	20/9/06	Hereward	160	None	Some	None	0	Comb. Peas	None
23.1	Organic	4/10/06	Malacca	180	None	None	None	40	Peas	None
23.2	Organic	9/10/06	Hereward	180	None	None	None	40	Potatoes	150
23.3	Organic	12/10/06	Malacca	180	None	None	None	0	Peas	None
23.4	Organic	3/10/06	Solstice	180	None	None	None	0	Mustard	100
24.1	Peaty/Silty	8/11/06	Soissons	236	None	None	None	20	Wheat 3rd	200
24.2	Medium	6/11/06	Malacca	212	None	None	None	20	Wheat 1st	200
24.3	Organic	7/11/06	Soissons	212	None	None	None	0	Wheat 4th	200

†, Fertiliser N applied prior to late foliar N

*, data not available

Farm Field ID	Soil type	Sowing date	Variety	Total N Applied (kg/ha)†	Animal manures last year	Animal manures in previous 5 years	Ploughed out long leys	Urea; Late foliar N (kg/ha)	Previous crop	Fert. N to prev crop (kg/ha)
25.1	Deep clay	1/11/06	Solstice	222	None	None	None	40	Borage	Nil
25.2	Deep clay	26/10/06	Einstein	222	None	Some	None	40	Borage	Nil
25.3	Deep Clay	2/11/06	Einstein	222	None	None	None	40	OSR	200
25.4	Deep clay	4/11/06	Einstein	222	None	Some	None	40	Borage	Nil
28.1	Deep Clay	27/9/06	Solstice	215	None	Sewage sludge	None	40	Spr. Beans	Nil
28.2	Deep Clay	22/9/06	Solstice	190	None	None	None	0	Wheat 3rd	200
28.3	Deep Clay	23/9/06	Solstice	235	None	None	None	0	Barley	140
2008										
1.5	Deep Clay	6/10/07	Solstice	279	None	None	None	0	Wheat	180
1.6	Deep Clay	6/10/07	Solstice	280	None	None	None	0	Wheat	180
2.5	Medium	30/9/07	Cordiale	225	None	Some/lots	None	25	Spring oats	176
3.5	Deep Clay	2/10/07	Solstice	260	None	None	None	0	Wheat	240
3.6	Deep Clay	23/9/07	Solstice	240	None	Some s. sludge	None	0	Oilseed rape	230
3.7	Deep Clay	19/9/07	Solstice	240	None	None	None	0	Oilseed rape	230
4.5	Deep Clay	26/9/07	Xi19	293	None	None	None	0	OSR	170
4.6	Deep Clay	7/10/07	Xi19	291	None	None	None	0	Wheat Cont.	269
4.7	Deep Clay	28/9/07	Solstice	289	None	None	None	0	W.Beans	None
4.8	Deep Clay	7/10/07	Xi19	291	None	None	None	0	Wheat	214
5.5	Deep Clay	12/10/07	Xi19	283	None	None	None	20	Wheat	290
5.6	Deep Clay	13/10/07	Xi19	280	None	None	None	20	Wheat	211
5.7	Deep Clay	6/10/07	Einstein	240	None	None	None	0	Wheat	215
5.8	Deep Clay	1/11/07	Einstein	277	None	None	None	0	Wheat	232
6.5	Medium	28/9/08	Cordiale	248	None	None	None	0	Wheat	200
6.6	Medium	4/10/07	Battalion	235	None	None	None	0	Wheat	200
6.7	Medium	10/10/07	Solstice	235	None	None	None	0	Wheat	225
6.8	Deep Clay	3/10/07	Einstein	248	None	None	None	0	Wheat	200

†, Fertiliser N applied prior to late foliar N

*, data not available

Farm Field ID	Soil type	Sowing date	Variety	Total N Applied (kg/ha)†	Animal manures last year	Animal manures in previous 5 years	Ploughed out long leys	Urea; Late foliar N (kg/ha)	Previous crop	Fert. N to prev crop (kg/ha)
7.5	Medium	5/10/07	Soissons	209	None	None	None	0	OSR	245
7.6	Medium	8/10/07	Solstice	281	None	None	None	0	Wheat	211
8.5	*	*	Xi19	*	*	*	*	*	*	*
8.6	*	*	Xi19	*	*	*	*	*	*	*
8.7	*	*	Xi19	*	*	*	*	*	*	*
8.8	*	*	Xi19	*	*	*	*	*	*	*
9.5	Deep Clay	5/10/07	Solstice	284	None	None	None	0	Wheat	152
9.6	Deep Clay	5/10/07	Solstice	284	None	None	None	0	Wheat	152
9.7	Deep Clay	6/10/07	Solstice	284	None	None	None	0	Wheat	152
9.8	Deep Clay	4/10/07	Solstice	280	None	None	None	0	Wheat	176
10.5	Deep Clay	15/9/07	Solstice	200	None	None	None	40	Spr. Beans	0
10.6	Deep Clay	23/9/07	Einstein	200	None	None	None	0	OSR	170
10.7	Deep Clay	21/9/07	Einstein	200	None	None	None	0	OSR	170
10.8	Deep Clay	30/9/07	Xi19	240	None	None	None	40	Wheat	280
11.5	Medium	5/10/07	Solstice	192	None	None	None	36	Peas	None
11.6	Medium	5/10/07	Solstice	193	None	None	None	36	Wheat	201
11.7	Medium	5/10/07	Solstice	193	None	None	None	36	Wheat	202
11.8	Medium	5/10/07	Solstice	193	None	None	None	36	Wheat	202
12.5	Deep Clay	5/10/07	Solstice	238	None	None	None	40	Spr. Barley	113
12.6	Deep Clay	4/10/07	Solstice	230	None	None	None	40	Wheat	215
13.6	Deep Clay	1/10/07	Einstein	230	None	None	None	0	Wint. Beans	None
13.8	Deep Clay	1/10/07	Solstice	275	None	None	None	0	OSR	200
13.9	Deep Clay	1/10/07	Solstice	275	None	None	None	0	OSR	200
13.10	Deep Clay	1/10/07	Solstice	275	None	None	None	0	OSR	200
13.11	Deep Clay	1/10/07	Solstice	275	None	None	None	0	OSR	200

†, Fertiliser N applied prior to late foliar N

*, data not available

Farm Field ID	Soil type	Sowing date	Variety	Total N Applied (kg/ha)†	Animal manures last year	Animal manures in previous 5 years	Ploughed out long leys	Urea; Late foliar N (kg/ha)	Previous crop	Fert. N to prev crop (kg/ha)
14.5	Deep Clay	8/10/07	Solstice	272	None	None	None	0	Wheat	195.92
14.6	Deep Clay	8/10/07	Solstice	272	None	None	None	0	Wheat	196.75
14.7	Deep Clay	11/10/07	Solstice	270	None	None	None	0	Spr. barley	128.71
14.8	Deep Clay	11/10/07	Solstice	270	None	None	None	0	Spr. Barley	128.71
16.5	Medium/Deep clay	6/10/07	Cordiale	185	None	Some (Sewage)	None	40	OSR	226
16.6	Medium/Deep clay	7/10/07	Cordiale	192	Lots 32.51 kg/ha N	Some (Sewage)	None	40	Wheat	193
16.7	Medium/Deep clay	30/9/07	Solstice	196	None	Some (Sewage)	None	40	OSR	226
16.8	Medium/Deep clay	14/10/07	Solstice	233	None	Some (Sewage)	None	40	Wheat	209
17.5	FSL over chalk	*	Solstice	215	None	None	None	40	OSR	218
17.6	L. sand over chalk	15/10/07	Solstice	258	None	None	None	40	Sugar Beet	96
17.7	L. sand over chalk	7/10/07	Xi19	278	None	None	None	40	Wheat	255
18.5	Medium	21/10/07	Hereward	334	None	None	None	40	Sugar Beet	*
18.6	Medium	14/10/07	Hereward	334	None	None	None	40	Sugar Beet	185
19.5	Medium	20/9/07	Solstice	220	None	None	10years+	20	OSR	220
19.6	Medium	20/9/07	Solstice	220	None	None	10years+	20	OSR	220
19.7	Medium	21/9/07	Solstice	220	None	None	10years+	20	OSR	220
19.8	Medium	19/9/07	Solstice	220	None	None	10years+	20	OSR	220
23.5	Peaty soil	1/10/07	Solstice	135	None	None	None	0	OSR	100
23.6	Organic soil	12/10/07	Solstice	150	None	None	None	0	Comb. Peas	None
23.7	Medium	26/10/07	Solstice	160	None	Some	None	0	Sugar Beet	None
23.8	Organic soil	14/10/08	Solstice	160	None	Some	None	0	Comb. Peas	None
24.5	Peaty/Silt	11/10/07	Soissons	180	None	None	None	40	Peas	None
24.6	Organic soil	11/10/07	Soissons	180	None	None	None	40	Potatoes	150
24.7	Medium	14/10/08	Gladiator	180	None	None	None	0	Peas	None
24.8	Medium	14/10/08	Gladiator	180	None	None	None	0	Mustard	100

†, Fertiliser N applied prior to late foliar N

*, data not available

Farm Field ID	Soil type	Sowing date	Variety	Total N Applied (kg/ha)†	Animal manures last year	Animal manures in previous 5 years	Ploughed out long leys	Urea; Late foliar N (kg/ha)	Previous crop	Fert. N to prev crop (kg/ha)
25.5	Deep Clay	1/10/08	Solstice	236	None	None	None	20	Wheat 3rd	200
25.6	Deep Clay	5/10/07	Solstice	212	None	None	None	20	Wheat 1st	200
25.7	Deep Clay	2/10/07	Cordiale	212	None	None	None	0	Wheat 4th	200
28.5	Medium	17/9/08	Solstice	222	None	None	None	40	Borage	Nil
28.6	Medium	17/9/07	Solstice	222	None	some	None	40	Borage	Nil
28.7	Medium	20/9/07	Solstice	222	None	None	None	40	OSR	200
28.8	Medium	17/9/07	Solstice	222	None	Some	None	40	Borage	Nil
29.5	Deep Clay	2/10/07	Solstice	215	None	Dry S. sludge	None	40	Spr.Beans	Nil
29.6	Deep Clay	4/10/07	Einstein	190	None	None	None	0	Wheat 3rd	200
29.7	Deep Clay	13/10/07	Cordiale	235	None	None	None	0	Barley	140
30.5	Medium	4/10/07	Xi19	253	None	None	None	40	Wheat	185
30.6	Medium	3/10/07	Xi19	228	None	None	None	36	Wint. Beans	None
30.7	Medium/Deep clay	30/9/07	Xi19	225	None	None	None	28	OSR	232
31.5	Shallow over chalk	0/1/00	Battalion	*	*	*	*	*	*	0
32.5	Deep Clay	17/10/07	Battalion	250	None	None	None	50	Wheat	188
2009										
1.12	Deep Clay	9/10/08	Solstice	276	None	None	None	0	Wheat	196
1.13	Deep Clay	9/10/08	Solstice	257	None	None	None	0	Wheat	170
2.12	Medium	29/9/08	Cordiale	238	None	Some (Pig FYM)	None	100	Canary seed	100
3.12	Medium	17/9/08	Solstice	250	None	Some	None	0	OSR	230
3.13	Medium	3/10/08	Solstice	270	None	None	None	0	Wheat	240
3.14	Medium	1/10/08	Solstice	270	None	Some	None	0	Wheat	240
4.12	Deep Clay	1/10/08	Xi19	300	None	None	None	0	Wheat	280
4.13	Deep Clay	20/9/08	Solstice	280	None	None	None	0	W.Beans	0
4.14	Deep Clay	30/9/08	Xi19	300	None	None	None	0	Wheat	280
4.15	Deep Clay	30/9/08	Xi19	300	None	None	None	0	Wheat	280

†, Fertiliser N applied prior to late foliar N

*, data not available

Farm Field ID	Soil type	Sowing date	Variety	Total N Applied (kg/ha)†	Animal manures last year	Animal manures in previous 5 years	Ploughed out long leys	Urea; Late foliar N (kg/ha)	Previous crop	Fert. N to prev crop (kg/ha)
5.12	Deep Clay	28/9/08	Magister	260	None	None	None	0	OSR	258
5.13	Deep Clay	28/9/08	Solstice	260	None	None	None	0	OSR	258
6.12	*	0/1/00	*	*	*	*	*	*	*	*
6.13	*	0/1/00	*	*	*	*	*	*	*	*
6.14	*	0/1/00	*	*	*	*	*	*	*	*
6.15	*	0/1/00	*	*	*	*	*	*	*	*
7.12	Medium	10/10/08	Solstice	312	None	None	None	0	W. Wheat	254
7.13	Medium	16/10/08	Soissons	265	None	None	None	0	OSR	206
9.12	Deep Clay	9/10/08	Solstice	229	None	None	None	0	Wheat	160
9.13	Deep Clay	2/10/08	Solstice	238	None	None	None	0	Wheat	175
9.14	Deep Clay	3/10/08	Solstice	238	None	None	None	0	Wheat	175
10.12	Deep Clay	1/10/08	Solstice	200	None	None	None	40	Spr. Beans	0
10.13	Deep Clay	18/9/08	Cordiale	200	None	None	None	40	OSR	180
10.14	Deep Clay	7/10/08	Cordiale	220	None	None	None	40	Wheat	200
11.12	Medium	12/10/08	Solstice	216	None	None	None	35	Wheat	175
11.13	Medium	12/10/08	Solstice	231	None	None	None	31	Wheat	232
12.12	Deep Clay	20/10/08	Solstice	229	None	None	None	35.5	Wheat	225
12.13	Deep Clay	20/10/08	Solstice	225	None	None	None	35.5	Wheat	195
13.12	*	0/1/00	*	*	*	*	*	*	*	*
13.13	*	0/1/00	*	*	*	*	*	*	*	*
13.14	*	0/1/00	*	*	*	*	*	*	*	*
13.15	*	0/1/00	*	*	*	*	*	*	*	*
14.12	*	0/1/00	*	*	*	*	*	*	*	*
14.13	*	0/1/00	*	*	*	*	*	*	*	*

†, Fertiliser N applied prior to late foliar N

*, data not available

Farm Field ID	Soil type	Sowing date	Variety	Total N Applied (kg/ha)[†]	Animal manures last year	Animal manures in previous 5 years	Ploughed out long leys	Urea; Late foliar N (kg/ha)	Previous crop	Fert. N to prev crop (kg/ha)
16.12	Deep Clay	26/9/08	Cordiale	181	None	Some	None	80	OSR	158
16.13	Deep Clay	27/9/08	Cordiale	211	Some (s. sludge)	Some	None	50	Wheat	194
16.14	Deep Clay	30/9/08	Solstice	200	None	Some	None	60	OSR	199
16.15	Deep Clay	2/10/08	Solstice	235	None	None	0	40	Wheat	258
17.12	Medium	23/11/09	Magister	218	None	Some (Sewage)	No	0	Sugar beet	100
17.13	Medium	26/9/08	Solstice	175	Some (Guess Sewage)	Some (Sewage)	No	40	OSR	206
17.14	Medium	2/10/08	Solstice	185	None	None	No	40	Wheat	231
18.12	Medium	17/10/08	Hereward	451	None	None	None	40	Wheat	334
18.13	Medium	17/10/08	Hereward	451	None	None	None	40	Wheat	334
19.12	Deep Clay	26/9/09	Solstice	85	*	*	*	*	*	*
19.13	Medium	0/1/00	*	*	*	*	*	*	*	*
19.14	Deep Clay	0/1/00	*	*	*	*	*	*	*	*
20.12	Deep Clay	15/9/09	Solstice	226	None	None	None	0	Peas	0
20.13	Deep Clay	15/9/09	Solstice	246	None	None	None	0	Wheat	240
23.12	Organic	9/12/08	Xi19	145	None	Some	None	0	Sugar Beet	30
23.13	Organic	12/10/08	Solstice	160	None	Some	None	0	Comb. Peas	0
23.14	Mineral	14/10/08	Solstice	170	None	None	None	0	Comb. Peas	0
23.15	Medium	10/10/09	Hereward	155	None	None	None	0	Comb. Peas	0
24.12	Peaty/Silt	10/11/08	Soissons	181	None	None	None	40	Peas	0
24.13	Peaty/Silt	11/11/08	Soissons	181	None	None	None	40	Potatoes	230
24.14	Med/Organic Sandy	19/11/08	Gladiator	181	None	None	None	0	Mustard	100
24.15	Med/Organic Sandy	18/11/08	Gladiator	181	None	None	None	0	Mustard	100
25.12	Medium	7/12/08	Solstice	201	Some ??	None	None	30	Wheat	220
25.13	Mediam	26/10/08	Solstice	201	Some??	None	None	30	Wheat	220
25.14	Medium	25/10/08	Solstice	201	Some??	None	None	30	Wheat	220

†, Fertiliser N applied prior to late foliar N

*, data not available

Farm Field ID	Soil type	Sowing date	Variety	Total N Applied (kg/ha)†	Animal manures last year	Animal manures in previous 5 years	Ploughed out long leys	Urea; Late foliar N (kg/ha)	Previous crop	Fert. N to prev crop (kg/ha)
25.15	Medium	23/10/08	Solstice	201	Some??	None	None	30	Wheat	220
28.12	Deep Clay	1/10/09	Solstice	222	None	Some	None	40	Wheat	240
28.13	Deep Clay	29/9/09	Solstice	222	None	Some	None	40	Wheat	240
28.14	Deep Clay	24/9/09	Solstice	222	None	Some	None	40	OSR	200
28.15	Medium	24/9/09	Solstice	222	None	Some	None	40	OSR	200
29.12	*	*	*	*	*	*	*	*	*	*
29.13	*	*	*	*	*	*	*	*	*	*
29.14	*	*	*	*	*	*	*	*	*	*
30.12	Deep Clay	12/10/08	Xi19	250	None	None	None	40	Wheat	190
30.13	Medium	13/10/08	Xi19	229	None	None	None	40	Wheat	190
30.14	Medium	29/9/08	Solstice	196	None	*	None	36	OSR	215
31.12	Medium	23/9/08	Solstice	195	None	None	None	40	OSR	225
31.13	Medium	22/9/08	Solstice	200	None	None	None	40	OSR	225
31.14	Deep Clay	23/10/08	Solstice	202	None	None	None	40	Sugar beet	100
31.15	Medium	22/10/09	Solstice	206	None	None	None	40	Potatoes	*
33.12	Deep Clay	29/9/08	Solstice	196	None	None	None	40	OSR	268
33.13	Deep Clay	0/1/00	*	*	*	*	*	40	*	*
34.12	Light sandy soils	21/9/09	Solstice	179	None	None	None	40	Oats	12
34.13	Light sandy soils	19/10/09	Solstice	179	None	None	None	40	Sugar Beet	110
35.12	Deep Clay	16/10/08	Solstice	220	None	None	None	40	Wheat	200
35.13	Deep Clay	17/10/08	Solstice	224	None	None	None	40	Wheat	200
35.14	Deep Clay	15/10/08	Solstice	220	None	None	None	40	Wheat Cont.	275
36.12	*	*	*	*	*	*	*	*	*	*
36.13	*	*	*	*	*	*	*	*	*	*
36.14	*	*	*	*	*	*	*	*	*	*
36.15	*	*	*	*	*	*	*	*	*	*

†, Fertiliser N applied prior to late foliar N

*, data not available

ANNEX 8. CROP N CONCENTRATIONS (BY DUMAS COMBUSTION REFERENCE METHOD) AND GRAIN PROTEIN (NX5.7) FOR GROWERS SAMPLES

Farm Field ID	Flowering Ear N (% DM)	Flowering WP N (% DM)	M. Ripe Ear N (%DM)	M. Ripe WP N (%DM)	Grain protein sample area by ADAS (% DM)	Grain protein sample area by grower (%DM)	Grain protein whole field by grower (%DM)	Straw and Chaff N (%DM)	Total N uptake (kg/ha)	Grain N offtake (kg/ha)	NHI
2007											
1.1	1.52	1.72	1.83	1.49	13.3	12.6	12.7	0.80	333	257	77.2
1.2	1.78	1.69	1.84	1.86	13.6	13.6	12.9	0.89	314	239	76.0
2.1	*	*	1.73	1.52	12.4	13.2	13.6	0.78	300	231	76.8
2.2	*	*	1.80	1.53	12.3	13.3	13.1	0.74	320	249	77.8
3.1	*	*	1.76	1.45	13.0	12.7	13.0	0.93	300	211	70.1
3.2	*	*	1.64	1.84	11.8	*	*	0.92	332	227	68.5
3.3	*	*	1.86	1.79	12.0	13.1	*	0.74	256	193	75.5
4.1	*	*	1.77	1.65	12.3	12.9	13.3	0.87	358	248	69.4
4.2	*	*	1.88	1.62	13.9	13.3	13.5	1.01	382	270	70.5
4.3	*	*	1.73	1.53	11.4	13.1	13.4	0.80	298	214	71.6
5.1	*	*	1.80	1.58	12.5	13.1	13.1	1.06	251	173	68.9
5.2	*	*	1.86	1.70	13.2	13.0	12.3	0.98	273	201	73.5
6.1	1.41	1.73	1.74	1.94	12.5	*	11.1	0.96	309	231	74.6
6.2	*	*	1.71	1.82	12.3	*	*	0.81	256	185	72.2
6.3	1.61	1.53	1.67	1.71	11.1	10.3	9.9	0.79	317	231	73.0
6.4	1.54	1.73	1.68	1.62	11.2	11.0	10.5	0.74	240	185	77.0
7.1	1.73	1.62	1.82	1.73	12.5	12.5	12.7	0.95	301	210	69.9
7.2	1.66	1.44	1.80	1.56	12.8	12.2	12.4	1.00	218	149	68.3
7.3	1.76	2.06	1.75	1.81	12.5	13.1	12.8	1.10	312	203	65.1
8.1	*	*	1.66	1.35	11.2	11.5	12.5	0.80	336	234	69.6
8.2	*	*	1.55	1.40	10.7	10.1	11.2	0.80	282	195	69.1
8.3	1.67	1.54	1.65	1.29	10.8	11.8	11.5	0.93	311	211	67.9
9.1	*	*	1.59	1.36	12.5	11.4	10.9	1.10	317	194	61.1
9.2	1.55	1.41	1.62	1.37	12.1	10.8	12.0	0.85	255	180	70.5
10.1	0.78	1.37	1.61	1.30	11.3	10.9	11.9	0.93	289	206	71.3

Farm Field ID	Flowering Ear N (% DM)	Flowering WP N (% DM)	M. Ripe Ear N (%DM)	M. Ripe WP N (%DM)	Grain protein sample area by ADAS (% DM)	Grain protein sample area by grower (%DM)	Grain protein whole field by grower (%DM)	Straw and Chaff N (%DM)	Total N uptake (kg/ha)	Grain N offtake (kg/ha)	NHI
10.2	1.54	1.45	1.69	1.30	12.4	12.3	12.7	0.88	316	211	66.6
11.1	1.66	1.6	1.68	1.40	13.1	14.3	15.6	0.86	286	190	66.4
11.2	1.56	1.52	1.55	1.31	11.4	12.1	12.3	1.28	326	170	52.1
11.3	*	*	1.71	1.52	13.7	14.8	15.4	1.00	356	235	66.1
11.4	*	*	1.74	1.48	13.1	14.3	13.1	1.05	250	225	90.0
12.1	*	*	1.74	1.62	12.5	12.4	12.9	1.36	247	162	65.9
12.2	1.45	1.59	1.78	1.45	12.6	11.9	12.8	0.81	261	197	75.6
13.1	*	*	1.72	1.46	11.7	11.7	11.6	0.62	301	238	79.0
13.2	*	*	1.74	1.48	12.2	12.5	12.0	0.68	268	207	77.3
13.3	*	*	1.58	1.61	11.9	11.9	11.9	0.86	302	206	68.4
13.4	*	*	1.65	1.44	12.6	12.8	12.5	0.71	314	234	74.7
14.1	*	*	1.67	1.40	11.6	*	*	0.93	279	197	70.3
14.2	*	*	1.79	1.43	10.5	*	*	0.66	275	210	76.4
15.1	1.61	1.76	1.65	1.37	11.4	10.8	11.7	0.80	237	171	72.3
15.2	1.46	1.41	1.66	1.55	11.6	11.1	11.3	0.95	259	177	68.3
15.3	1.54	1.48	1.66	1.36	12.0	10.9	11.3	0.90	248	175	70.6
15.4	1.54	1.54	1.69	1.35	11.8	11.2	11.2	0.71	221	166	75.1
16.1	1.49	1.34	1.66	1.49	11.3	11.1	12.0	0.73	236	175	74.0
16.2	1.55	1.35	1.67	1.28	10.1	10.3	12.5	0.69	206	158	76.4
17.1	*	*	1.59	1.55	12.6	12.3	11.9	0.87	312	226	72.4
17.2	*	*	1.70	1.53	12.5	12.6	12.3	1.09	319	215	67.2
17.3	*	*	1.78	1.68	13.4	12.3	12.6	1.12	347	242	69.7
17.4	*	*	1.80	1.69	13.5	12.7	12.3	0.98	311	232	74.6
18.1	1.66	1.27	1.63	1.41	12.4	11.9	12.7	1.14	241	148	61.4
18.2	1.59	1.4	1.56	1.40	10.5	11.2	12.2	0.82	160	105	65.7
19.1	*	*	1.76	1.49	12.7	*	12.4	0.97	302	205	67.7
19.2	1.6	*	1.67	1.59	12.5	*	13.2	0.89	315	229	72.7
19.3	1.59	1.52	1.69	1.68	13.4	*	*	0.91	306	224	73.2
20.1	*	*	1.73	1.48	13.3	12.7	13.1	0.84	355	276	77.7

Farm Field ID	Flowering Ear N (% DM)	Flowering WP N (% DM)	M. Ripe Ear N (%DM)	M. Ripe WP N (%DM)	Grain protein sample area by ADAS (% DM)	Grain protein sample area by grower (%DM)	Grain protein whole field by grower (%DM)	Straw and Chaff N (%DM)	Total N uptake (kg/ha)	Grain N offtake (kg/ha)	NHI
20.2	*	*	1.75	1.38	12.1	*	13.5	0.85	350	255	72.9
20.3	1.89	1.78	1.69	1.62	12.3	13.3	13.3	0.81	374	265	70.9
21.1	1.58	1.81	1.70	1.66	12.5	11.9	12.4	1.03	287	190	66.1
21.2	1.62	1.87	1.73	1.94	13.8	12.7	13.6	1.35	*	*	*
21.3	1.86	2.27	1.71	1.68	13.2	12.4	12.3	1.73	396	181	45.8
21.4	1.87	1.95	1.66	1.51	12.8	11.9	12.5	1.22	347	197	56.7
22.1	*	*	1.62	1.64	13.4	13.6	13.1	1.33	375	201	53.5
22.2	*	*	1.76	1.56	15.2	15.3	15.6	1.22	305	156	51.2
22.3	*	1.68	1.65	1.60	12.5	12.9	13.3	1.25	308	170	55.2
22.4	1.69	1.97	1.68	1.74	13.4	13.3	13.6	1.55	411	191	46.5
23.1	*	*	1.76	1.62	13.0	12.7	12.6	1.11	338	223	65.9
23.2	*	*	1.80	1.90	14.0	13.8	13.6	1.59	373	189	50.7
23.3	1.74	1.76	1.79	1.65	12.8	13.0	12.7	1.12	322	219	68.1
23.4	*	*	1.70	1.72	13.1	12.9	12.9	1.29	374	229	61.4
24.1	*	*	1.86	1.58	12.6	12.2	12.3	1.22	212	127	59.8
24.2	1.77	1.48	1.83	1.57	13.9	12.7	14.7	1.08	239	163	68.4
24.3	*	*	1.83	1.50	12.7	13.1	13.2	1.11	226	147	65.0
25.1	1.74	1.95	1.79	1.78	12.8	14.3	13.9	1.10	198	136	68.6
25.2	1.78	1.54	1.66	1.70	12.9	13.9	14.3	0.89	226	169	74.6
25.3	1.82	1.69	1.87	1.77	12.8	13.7	14.2	0.89	196	150	76.6
25.4	1.8	1.67	1.73	1.57	12.7	13.6	14.1	1.10	253	177	69.9
28.1	1.77	1.32	1.53	1.26	10.8	10.5	11.3	0.75	202	143	70.7
28.2	1.68	1.29	1.55	1.25	10.7	10.5	11.0	0.77	238	165	69.3
28.3	1.83	1.28	1.56	1.21	10.2	10.3	11.4	0.80	239	165	69.2
2008											
1.5	1.57	1.76	1.82	1.30	12.2	12.3	12.3	0.39	193	166	85.8
1.6	1.62	1.61	1.76	1.27	12.3	12.4	12.2	0.44	192	164	85.3
2.5	1.46	1.35	1.58	1.25	10.0	10.6	9.8	0.38	191	156	81.5
3.5	1.53	1.58	1.59	1.20	11.8	*	*	0.44	266	223	83.8

Farm Field ID	Flowering Ear N (% DM)	Flowering WP N (% DM)	M. Ripe Ear N (%DM)	M. Ripe WP N (%DM)	Grain protein sample area by ADAS (% DM)	Grain protein sample area by grower (%DM)	Grain protein whole field by grower (%DM)	Straw and Chaff N (%DM)	Total N uptake (kg/ha)	Grain N offtake (kg/ha)	NHI
3.6	1.53	1.70	1.61	1.30	11.7	11.9	11.7	0.50	276	227	82.2
3.7	1.60	1.65	1.60	1.33	11.8	*	*	0.52	264	217	81.9
4.5	1.67	1.86	1.71	1.37	11.5	11.5	11.3	0.71	278	218	78.4
4.6	1.55	1.64	1.69	1.37	11.3	11.2	11.4	0.50	268	220	82.2
4.7	1.52	1.74	1.57	1.46	11.8	*	*	0.65	325	257	78.9
4.8	1.50	1.48	1.58	1.27	10.7	10.9	10.8	0.47	210	172	82.2
5.5	1.77	1.79	1.73	1.43	*	11.4	12.4	0.47	*	*	*
5.6	1.76	1.64	1.75	1.49	*	11.8	12.0	*	*	*	*
5.7	1.53	1.42	1.50	1.36	10.5	10.5	10.6	0.39	223	190	85.3
5.8	1.54	1.72	1.56	1.52	11.5	10.9	11.0	0.63	248	189	76.2
6.5	1.66	1.47	1.71	1.46	10.9	11.3	11.0	0.41	180	154	85.8
6.6	1.60	1.34	1.65	1.31	11.5	11.5	11.3	0.48	210	171	81.7
6.7	1.45	1.30	1.50	1.30	10.8	10.4	10.4	0.35	168	147	87.5
6.8	1.51	1.29	1.64	1.19	10.3	10.4	10.8	0.42	163	135	82.9
7.5	1.58	1.31	1.57	1.28	12.3	*	12.4	0.55	239	192	80.3
7.6	1.55	1.76	1.77	1.24	13.5	10.7	12.9	0.57	262	204	77.8
8.5	1.61	1.17	1.68	1.27	9.8	9.1	13.3	0.39	211	179	84.6
8.6	1.61	1.10	1.62	1.24	9.0	8.8	11.2	0.36	181	153	84.5
8.7	1.81	1.25	1.76	1.26	10.2	9.7	11.2	0.38	191	164	85.6
8.8	1.64	1.35	1.73	1.38	11.2	10.9	11.8	0.46	213	176	82.5
9.5	1.57	1.27	1.62	1.23	11.2	11.1	10.7	0.36	216	185	85.4
9.6	1.60	1.62	1.60	1.30	11.4	11.4	10.9	0.41	247	207	83.7
9.7	1.59	1.37	1.63	1.21	10.7	10.3	10.7	0.39	215	181	84.2
9.8	1.60	1.35	1.66	1.23	11.9	11.2	12.0	0.42	238	196	82.1
10.5	1.61	1.16	1.54	1.23	10.6	11.1	11.7	0.54	263	208	79.0
10.6	1.57	1.65	1.61	1.44	11.8	11.8	11.8	0.66	287	236	82.3
10.7	1.49	1.56	1.58	1.41	11.5	*	*	0.70	296	221	74.8
10.8	1.76	1.52	1.64	1.33	11.0	10.6	11.5	0.53	240	196	81.5
11.5	1.74	1.63	1.69	1.36	12.1	11.2	12.3	0.51	279	228	81.8

Farm Field ID	Flowering Ear N (% DM)	Flowering WP N (% DM)	M. Ripe Ear N (%DM)	M. Ripe WP N (%DM)	Grain protein sample area by ADAS (% DM)	Grain protein sample area by grower (%DM)	Grain protein whole field by grower (%DM)	Straw and Chaff N (%DM)	Total N uptake (kg/ha)	Grain N offtake (kg/ha)	NHI
11.6	1.68	1.65	1.81	1.33	12.4	11.7	11.7	0.37	186	162	86.7
11.7	1.75	1.47	1.73	1.32	11.8	11.6	12.3	0.37	220	188	85.4
11.8	1.83	1.62	1.73	1.18	12.0	11.7	12.8	0.46	260	215	82.8
12.5	1.61	1.33	1.74	1.25	11.7	11.5	12.3	0.38	217	186	85.6
12.6	1.53	1.55	1.79	1.26	12.7	*	*	0.44	202	169	83.8
13.6	1.70	1.52	1.80	1.48	12.8	12.7	12.1	0.50	176	142	80.8
13.8	1.55	1.52	1.75	1.29	11.5	11.7	11.6	0.39	245	209	85.4
13.9	1.59	1.48	1.75	1.47	12.4	11.2	12.0	0.50	257	210	81.9
13.10	1.55	1.49	1.78	1.54	12.8	12.3	11.9	0.61	296	234	79.0
13.11	1.70	1.57	1.75	1.19	12.2	12.0	12.1	0.47	261	216	82.5
14.5	1.72	1.54	1.79	1.25	11.4	11.1	10.9	0.45	266	225	84.6
14.6	1.66	1.72	1.70	1.32	11.9	11.7	11.9	0.57	270	220	81.6
14.7	1.78	1.73	1.65	1.33	11.2	11.5	11.2	0.61	281	224	79.5
14.8	1.70	1.63	1.67	1.36	11.0	11.4	11.4	0.49	258	213	82.5
16.5	1.45	1.22	1.49	1.09	9.4	9.8	10.8	0.35	209	178	85.0
16.6	1.44	1.32	1.51	1.20	9.3	9.8	10.5	0.38	219	183	83.5
16.7	1.46	1.47	1.54	1.20	9.6	9.8	11.1	0.40	188	155	82.3
16.8	1.46	1.81	1.65	1.33	11.1	10.9	11.3	0.57	239	187	78.2
17.5	1.54	1.86	1.68	1.53	12.2	12.3	13.1	0.72	327	246	75.3
17.6	1.47	1.59	1.67	1.31	12.5	12.2	12.2	0.57	297	245	82.6
17.7	1.60	1.77	1.82	1.49	12.4	12.2	12.9	0.53	250	205	81.9
18.5	1.62	1.56	1.66	1.37	11.4	11.7	11.6	0.55	248	188	75.8
18.6	1.54	1.04	1.41	0.98	10.0	9.9	12.1	0.34	170	141	82.6
19.5	1.60	1.38	1.69	1.18	11.3	11.4	*	0.47	285	235	82.5
19.6	1.70	1.38	1.73	1.38	11.8	11.7	*	0.49	278	227	81.7
19.7	1.57	1.70	1.70	1.14	11.9	11.7	*	0.47	286	238	83.4
19.8	1.53	1.45	1.70	1.41	11.8	11.9	*	0.49	266	221	83.2
23.5	1.62	1.50	1.65	1.20	11.2	11.1	11.9	0.40	235	199	84.9
23.6	1.76	2.10	1.71	1.59	11.9	11.5	11.6	0.94	312	206	66.2

Farm Field ID	Flowering Ear N (% DM)	Flowering WP N (% DM)	M. Ripe Ear N (%DM)	M. Ripe WP N (%DM)	Grain protein sample area by ADAS (% DM)	Grain protein sample area by grower (%DM)	Grain protein whole field by grower (%DM)	Straw and Chaff N (%DM)	Total N uptake (kg/ha)	Grain N offtake (kg/ha)	NHI
23.7	1.63	1.83	1.67	1.60	12.2	11.9	12.3	0.77	305	216	70.8
23.8	1.54	1.75	1.68	1.54	12.2	12.4	12.7	0.69	306	229	74.8
24.5	1.97	2.12	1.80	1.58	12.4	12.5	12.5	0.83	241	173	71.9
24.6	2.13	*	1.79	1.83	*	12.1	12.6	*	*	*	*
24.7	1.65	1.11	1.64	1.25	10.1	10.6	11.1	0.48	236	190	80.3
24.8	1.71	1.50	1.62	1.17	9.6	11.1	11.9	0.43	213	175	81.9
25.5	1.52	1.09	1.61	1.20	10.1	10.1	11.3	0.38	173	151	87.0
25.6	1.49	1.38	1.60	1.03	10.4	9.2	11.2	0.48	197	151	77.0
25.7	1.34	1.27	1.83	1.28	11.1	11.4	11.1	0.37	151	127	83.8
28.5	1.59	1.36	1.59	1.21	10.3	*	*	0.48	242	197	81.4
28.6	1.47	1.37	1.50	1.12	9.5	9.2	10.5	0.38	188	155	82.8
28.7	1.43	1.32	1.48	1.11	10.6	10.1	10.6	0.60	281	214	76.2
28.8	1.40	1.29	1.50	1.12	9.6	*	*	0.45	209	165	79.0
29.5	1.63	1.49	1.60	1.28	11.4	11.7	11.3	0.66	277	207	74.9
29.6	1.43	1.28	1.47	1.07	10.1	9.9	10.4	0.43	192	154	80.4
29.7	1.64	1.58	1.74	1.40	12.3	11.6	10.1	0.72	280	209	74.5
30.5	1.79	1.69	1.73	1.30	11.5	10.8	11.2	0.51	233	190	81.7
30.6	1.65	1.59	1.63	1.36	10.8	11.7	10.7	0.52	259	212	82.0
30.7	1.67	1.63	1.70	1.32	10.6	10.4	11.0	0.51	260	209	80.3
31.5	1.64	1.78	1.83	1.39	12.2	*	*	0.53	197	162	82.0
32.5	1.57	1.35	1.63	1.21	11.1	9.5	9.6	0.56	206	158	76.4
2009											
1.12	1.73	1.57	1.91	1.42	*	13.5	12.3	*	*	*	*
1.13	1.86	1.76	1.84	1.47	12.9	13.1	12.2	0.70	352	251	71.2
2.12	2.01	1.69	1.74	1.70	12.2	13.3	12.3	0.64	308	223	72.3
3.12	2.01	1.71	1.80	1.37	12.1	12.1	12.6	0.69	344	242	70.2
3.13	1.98	1.57	1.89	1.54	*	12.5	12.9	*	*	*	*
3.14	1.82	1.50	1.97	1.52	13.0	*	*	0.60	253	190	75.1
4.12	1.95	1.75	1.88	1.32	*	11.8	11.8	*	*	*	*

Farm Field ID	Flowering Ear N (% DM)	Flowering WP N (% DM)	M. Ripe Ear N (%DM)	M. Ripe WP N (%DM)	Grain protein sample area by ADAS (% DM)	Grain protein sample area by grower (%DM)	Grain protein whole field by grower (%DM)	Straw and Chaff N (%DM)	Total N uptake (kg/ha)	Grain N offtake (kg/ha)	NHI
4.13	1.78	1.42	1.78	1.40	12.2	*	*	0.57	275	201	73.2
4.14	1.94	1.74	2.01	1.73	*	12.9	12.1	*	*	*	*
4.15	2.01	2.04	1.97	1.48	12.3	12.5	12.3	0.90	381	242	63.6
5.12	1.91	1.39	1.89	1.26	13.2	12.9	12.6	0.61	261	187	71.8
5.13	1.76	1.32	1.72	1.71	12.8	*	12.3	0.53	284	211	74.2
6.12	0.00	0.00	1.79	1.47	12.4	12.3	12.4	0.60	294	232	79.1
6.13	0.00	0.00	1.84	1.58	12.4	12.2	11.7	0.75	286	201	70.2
6.14	0.00	0.00	1.71	1.65	13.1	*	*	0.93	339	222	65.7
6.15	0.00	0.00	1.79	1.45	11.9	12.0	11.9	0.74	308	219	71.3
7.12	1.64	1.39	1.71	1.29	11.7	12.4	12.3	0.56	189	146	77.4
7.13	1.67	1.52	1.73	1.30	13.3	13.6	13.4	0.70	246	174	70.4
9.12	1.70	1.25	1.89	1.30	12.0	12.8	12.4	0.59	251	179	71.5
9.13	1.74	1.36	1.76	1.31	11.6	11.7	12.1	0.61	245	173	70.6
9.14	1.69	1.34	1.67	1.23	11.5	12.4	11.9	0.62	277	196	70.7
10.12	1.85	1.59	1.67	1.21	10.0	10.4	12.3	0.59	260	176	67.7
10.13	1.93	1.13	1.78	1.43	*	11.7	12.8	*	*	*	*
10.14	1.87	1.48	1.79	1.42	11.2	11.9	11.7	0.56	264	203	77.1
11.12	1.74	1.45	1.61	1.26	11.2	12.3	12.3	0.58	208	156	74.9
11.13	1.73	1.28	1.81	1.43	*	11.6	13.1	*	*	*	*
12.12	1.75	1.38	1.83	1.27	11.7	11.7	12.3	0.54	225	171	75.7
12.13	1.71	1.37	1.79	1.20	12.1	12.1	12.6	0.54	237	175	73.6
13.12	1.73	1.11	1.93	1.27	12.8	12.3	12.5	0.55	254	194	76.4
13.13	1.88	1.41	1.92	1.33	12.5	11.8	12.1	0.54	285	219	76.9
13.14	1.67	1.58	1.73	1.24	12.2	11.9	11.5	0.67	256	178	69.3
13.15	1.74	1.64	1.72	1.36	12.2	11.8	11.6	0.61	252	185	73.6
14.12	1.88	1.54	2.00	1.45	13.4	12.8	12.7	0.67	301	208	69.2
14.13	1.78	1.25	1.71	1.30	11.4	11.2	12.5	0.71	278	189	68.0
16.12	1.78	1.17	1.63	1.13	*	10.7	12.4	*	*	*	*
16.13	1.87	1.38	1.62	1.13	*	11.0	12.3	*	*	*	*

Farm Field ID	Flowering Ear N (% DM)	Flowering WP N (% DM)	M. Ripe Ear N (%DM)	M. Ripe WP N (%DM)	Grain protein sample area by ADAS (% DM)	Grain protein sample area by grower (%DM)	Grain protein whole field by grower (%DM)	Straw and Chaff N (%DM)	Total N uptake (kg/ha)	Grain N offtake (kg/ha)	NHI
16.14	1.76	1.34	1.63	1.32	11.3	10.9	12.5	0.65	309	216	69.9
16.15	1.93	1.65	1.69	1.33	11.6	10.7	12.6	0.60	239	182	76.2
17.12	1.66	1.31	1.83	1.44	14.8	13.6	13.9	0.70	279	191	68.7
17.13	1.73	1.32	1.83	1.46	14.6	13.6	13.7	0.64	339	263	77.5
17.14	1.79	1.47	1.84	1.35	*	13.7	14.2	*	*	*	*
18.12	1.62	1.37	1.73	1.46	12.7	10.6	12.8	0.56	211	168	79.7
18.13	1.81	1.55	1.68	1.55	11.4	12.2	13.1	0.61	170	127	75.0
19.12	1.75	1.37	1.72	1.43	12.2	12.4	12.2	0.63	279	206	73.9
19.13	1.85	1.84	1.90	1.48	13.0	12.2	12.5	0.71	290	217	74.9
19.14	1.75	1.61	1.72	1.30	12.3	12.5	12.4	0.56	288	220	76.4
20.12	0.00	0.00	1.91	1.40	13.3	12.9	12.1	0.60	328	237	72.4
20.13	0.00	0.00	1.79	1.32	12.8	12.5	13.1	0.62	314	227	72.3
23.12	2.18	1.49	1.86	1.67	12.4	12.1	12.0	0.88	281	197	69.9
23.13	2.05	1.97	1.75	1.59	13.1	12.4	12.2	0.89	340	228	67.1
23.14	2.05	1.44	1.72	1.73	13.1	12.4	12.5	0.76	385	258	67.0
23.15	2.13	1.62	1.73	1.62	14.4	13.8	13.6	0.70	381	265	69.5
24.12	1.72	1.63	1.74	1.43	12.6	12.3	12.5	0.67	282	209	73.9
24.13	2.09	2.30	1.73	1.63	13.7	13.3	13.5	0.73	290	211	72.9
24.14	1.93	1.54	1.70	1.44	10.9	10.6	10.7	0.55	173	137	79.7
24.15	1.83	1.53	1.69	1.27	10.2	11.3	11.2	0.58	188	135	71.9
25.12	2.04	1.82	1.75	1.53	12.2	11.6	12.7	0.62	240	179	74.3
25.13	2.02	1.51	1.79	1.39	12.0	11.6	12.7	0.66	249	179	71.8
25.14	1.91	1.50	1.83	1.61	12.3	12.0	12.7	0.60	239	173	72.4
25.15	1.74	1.70	1.79	1.59	12.7	12.1	12.5	0.63	247	178	72.0
28.12	1.78	1.69	1.89	1.50	12.6	11.6	12.2	0.60	266	202	75.9
28.13	1.93	1.62	1.81	1.58	11.9	12.4	13.2	0.59	231	182	78.9
28.14	1.81	1.54	1.77	1.44	11.2	11.5	12.1	0.58	258	194	75.3
28.15	1.65	1.53	1.71	1.39	11.9	11.8	12.2	0.62	301	221	73.2
29.12	1.94	1.48	2.09	1.56	14.1	13.2	12.5	0.73	254	187	73.5

Farm Field ID	Flowering Ear N (% DM)	Flowering WP N (% DM)	M. Ripe Ear N (%DM)	M. Ripe WP N (%DM)	Grain protein sample area by ADAS (% DM)	Grain protein sample area by grower (%DM)	Grain protein whole field by grower (%DM)	Straw and Chaff N (%DM)	Total N uptake (kg/ha)	Grain N offtake (kg/ha)	NHI
29.13	1.73	1.41	1.76	1.34	12.6	11.5	12.4	0.64	303	220	72.6
29.14	1.73	1.49	1.90	1.51	11.7	10.9	11.2	0.72	227	155	68.4
30.12	2.01	1.67	1.79	1.39	12.0	11.7	12.1	0.74	306	188	61.7
30.13	1.93	1.73	1.81	1.33	11.9	11.7	12.2	0.71	251	171	68.1
30.14	1.69	1.48	1.79	1.34	12.8	11.8	12.7	0.63	293	209	71.4
31.12	1.66	1.90	1.76	1.42	12.4	11.7	12.4	0.60	274	208	75.9
31.13	1.80	1.49	1.74	1.33	11.8	11.9	12.9	0.62	*	*	*
31.14	1.75	1.86	1.80	1.36	12.7	12.3	12.1	0.58	248	186	74.7
31.15	1.78	1.64	1.74	1.44	12.6	12.2	12.6	0.59	344	260	75.7
33.12	1.56	1.54	1.74	1.15	10.4	*	*	0.58	244	160	65.8
33.13	1.82	1.27	1.72	0.99	11.0	*	*	0.46	215	155	72.1
34.12	1.79	1.64	1.67	1.27	*	9.9	10.8	*	*	*	*
34.13	2.10	1.27	1.75	1.45	10.6	10.7	11.2	0.59	191	141	73.7
35.12	1.73	1.45	1.81	1.39	11.2	11.1	12.3	0.53	190	141	74.4
35.13	1.68	1.37	1.74	1.25	11.1	10.3	12.5	0.53	222	164	73.7
35.14	1.75	1.77	1.87	1.33	13.0	12.9	13.1	0.56	207	150	72.6
36.12	1.83	1.10	1.68	1.36	11.0	10.8	11.5	0.57	250	180	71.9
36.13	1.76	1.56	1.82	1.54	12.3	12.2	13.0	0.60	292	219	75.2
36.14	1.89	1.62	1.71	1.46	12.0	10.7	11.8	0.66	326	236	72.4
36.15	1.83	1.04	1.77	1.57	12.4	11.7	11.7	0.55	231	181	78.4

ANNEX 9. CROP DM, GRAIN YIELD AND YIELD COMPONENTS FOR GROWERS SAMPLES

Farm Field ID	M. Ripe Ear DM (t/ha)	M. Ripe WP DM (t/ha)	Straw DM (t/ha)	Chaff DM (t/ha)	Grain yield (t/ha 100% DM)	Grain yield (t/ha, 85% DM)	Total_DM (t/ha)	HI (%)
2007								
1.1	6.6	14.2	7.3	2.2	11.0	13.0	20.5	53.8
1.2	9.8	20.2	6.5	1.9	10.0	11.7	18.4	54.2
2.1	8.6	18.8	6.5	2.4	10.6	12.5	19.6	54.3
2.2	8.5	16.3	6.7	2.9	11.5	13.6	21.1	54.5
3.1	8.4	19.9	7.8	1.8	9.2	10.9	18.9	48.9
3.2	7.3	22.9	9.3	2.1	11.0	12.9	22.4	49.1
3.3	8.6	19.0	6.3	2.1	9.2	10.8	17.7	52.0
4.1	7.8	20.8	10.1	2.5	11.6	13.6	24.1	47.8
4.2	7.1	15.2	8.4	2.8	11.1	13.0	22.3	49.8
4.3	8.6	20.3	8.3	2.3	10.7	12.6	21.3	50.2
5.1	6.6	18.5	5.5	1.9	7.9	9.3	15.2	51.8
5.2	7.0	14.7	5.5	1.8	8.7	10.2	16.0	54.1
6.1	7.8	16.3	5.9	2.3	10.5	12.3	18.7	56.2
6.2	6.7	15.7	6.4	2.3	8.6	10.1	17.4	49.5
6.3	7.2	17.3	8.2	2.6	11.9	13.9	22.7	52.2
6.4	6.5	16.2	5.3	2.1	9.4	11.0	16.8	55.7
7.1	6.0	17.2	7.5	2.1	9.6	11.2	19.1	50.1
7.2	6.5	13.9	5.3	1.6	6.6	7.8	13.5	48.9
7.3	6.4	14.3	7.2	2.6	9.2	10.8	19.1	48.3
8.1	10.5	21.0	10.0	2.8	11.9	14.0	24.7	48.1
8.2	11.4	23.7	8.8	2.1	10.4	12.2	21.3	48.8
8.3	8.9	20.4	8.2	2.5	11.1	13.1	21.9	50.8
9.1	7.2	19.4	9.3	1.9	8.8	10.4	20.0	44.1
9.2	7.6	19.4	6.8	2.1	8.5	9.9	17.3	48.8
10.1	8.4	19.2	6.6	2.4	10.4	12.2	19.3	53.7

Farm Field ID	M. Ripe Ear DM (t/ha)	M. Ripe WP DM (t/ha)	Straw DM (t/ha)	Chaff DM (t/ha)	Grain yield (t/ha 100% DM)	Grain yield (t/ha, 85% DM)	Total_DM (t/ha)	HI (%)
10.2	8.1	19.7	9.6	2.4	9.7	11.4	21.7	44.7
11.1	9.0	21.8	9.0	2.2	8.3	9.7	19.5	42.5
11.2	6.5	19.4	9.9	2.3	8.5	10.0	20.7	41.1
11.3	8.4	23.9	9.6	2.4	9.8	11.5	21.8	44.7
11.4	9.8	21.3	0.0	2.4	9.8	11.5	12.1	80.4
12.1	5.7	12.0	4.6	1.5	7.4	8.7	13.6	54.5
12.2	6.3	13.5	6.1	1.8	8.9	10.5	16.8	53.1
13.1	6.5	13.9	8.0	2.2	11.5	13.6	21.7	53.1
13.2	8.1	18.2	7.0	2.0	9.7	11.4	18.6	52.0
13.3	7.5	19.8	9.0	2.1	9.9	11.7	21.0	47.2
13.4	7.9	23.1	9.2	2.0	10.6	12.5	21.8	48.7
14.1	8.5	20.2	6.9	2.0	9.6	11.3	18.5	51.9
14.2	10.9	24.6	7.5	2.4	11.4	13.4	21.2	53.5
15.1	5.8	14.1	6.3	1.9	8.6	10.1	16.8	51.0
15.2	5.8	16.2	6.7	1.9	8.7	10.3	17.4	50.2
15.3	5.9	17.6	6.4	1.7	8.3	9.8	16.4	50.7
15.4	6.2	14.2	5.8	1.9	8.0	9.4	15.8	50.8
16.1	5.6	14.4	6.4	2.0	8.8	10.4	17.2	51.3
16.2	6.5	14.0	5.0	2.0	8.9	10.5	16.0	55.8
17.1	8.1	18.0	7.9	2.0	10.2	12.0	20.1	50.8
17.2	8.4	19.0	7.6	2.0	9.8	11.5	19.4	50.3
17.3	7.6	21.1	7.3	2.1	10.3	12.1	19.7	52.3
17.4	7.7	16.9	6.0	2.0	9.8	11.5	17.9	54.9
18.1	5.4	14.1	6.0	2.1	6.8	8.0	15.0	45.5
18.2	4.3	10.5	4.7	2.0	5.7	6.7	12.3	45.9
19.1	9.0	23.1	8.0	2.1	9.2	10.8	19.2	47.7
19.2	6.6	16.1	7.4	2.3	10.4	12.2	20.1	51.9
19.3	9.0	19.8	6.9	2.1	9.5	11.2	18.5	51.5

Farm Field ID	M. Ripe Ear DM (t/ha)	M. Ripe WP DM (t/ha)	Straw DM (t/ha)	Chaff DM (t/ha)	Grain yield (t/ha 100% DM)	Grain yield (t/ha, 85% DM)	Total_DM (t/ha)	HI (%)
20.1	7.0	14.7	7.0	2.5	11.8	13.9	21.2	55.6
20.2	8.2	19.2	8.3	2.9	12.0	14.2	23.2	51.8
20.3	8.9	20.1	10.5	2.9	12.3	14.4	25.7	47.7
21.1	5.9	16.6	7.0	2.5	8.7	10.2	18.1	47.8
21.2	9.7	29.6	*	*	*	*	*	*
21.3	5.6	25.6	10.4	2.0	7.9	9.2	20.3	38.7
21.4	5.2	18.2	10.1	2.2	8.7	10.3	21.1	41.5
22.1	6.8	23.6	10.6	2.5	8.5	10.0	21.7	39.4
22.2	4.4	19.7	9.7	2.5	5.9	6.9	18.1	32.4
22.3	6.7	22.0	8.8	2.3	7.7	9.1	18.8	41.1
22.4	6.2	24.0	11.7	2.5	8.1	9.6	22.3	36.5
23.1	9.2	25.5	8.2	2.1	9.8	11.5	20.1	48.5
23.2	5.5	22.1	9.3	2.3	7.7	9.1	19.3	40.1
23.3	8.8	21.1	7.1	2.0	9.7	11.5	18.9	51.6
23.4	6.6	19.9	9.0	2.2	10.0	11.8	21.2	47.2
24.1	4.8	13.7	5.5	1.5	5.7	6.7	12.7	45.1
24.2	6.2	12.8	5.3	1.7	6.7	7.9	13.7	49.0
24.3	4.7	12.9	5.5	1.6	6.6	7.8	13.7	48.1
25.1	3.9	11.3	3.9	1.7	6.0	7.1	11.7	51.7
25.2	4.6	11.6	4.7	1.7	7.5	8.8	13.9	53.7
25.3	4.7	11.3	3.8	1.3	6.7	7.8	11.8	56.5
25.4	5.9	15.2	5.0	2.0	8.0	9.4	14.9	53.5
28.1	7.2	15.8	6.1	1.8	7.5	8.8	15.4	48.8
28.2	6.2	15.9	7.7	1.8	8.8	10.3	18.2	48.1
28.3	8.1	19.1	7.1	2.1	9.2	10.9	18.4	50.1
2008								
1.5	7.1	15.7	5.3	1.8	7.8	9.1	14.9	52.3
1.6	7.2	16.4	4.6	1.8	7.6	8.9	14.0	54.1

Farm Field ID	M. Ripe Ear DM (t/ha)	M. Ripe WP DM (t/ha)	Straw DM (t/ha)	Chaff DM (t/ha)	Grain yield (t/ha 100% DM)	Grain yield (t/ha, 85% DM)	Total_DM (t/ha)	HI (%)
2.5	6.1	14.8	7.0	2.2	8.8	10.4	18.0	49.0
3.5	6.8	17.6	7.6	2.2	10.7	12.6	20.5	52.3
3.6	8.9	23.0	7.6	2.2	11.0	13.0	20.8	53.0
3.7	8.3	22.3	7.1	2.0	10.5	12.3	19.6	53.4
4.5	7.1	20.4	6.5	2.1	10.8	12.7	19.3	55.9
4.6	7.4	20.6	7.1	2.3	11.1	13.1	20.6	54.1
4.7	6.7	19.7	8.1	2.5	12.4	14.6	23.0	53.9
4.8	7.4	20.0	6.3	1.6	9.2	10.9	17.1	53.8
5.5	6.9	19.6	5.7	2.1	9.1	10.7	16.9	53.9
5.6	6.6	20.6	*	*	*	*	*	*
5.7	8.9	22.4	6.4	2.1	10.3	12.1	18.8	54.7
5.8	4.9	13.9	7.3	2.1	9.4	11.1	18.8	50.0
6.5	6.6	16.1	4.7	1.5	8.1	9.5	14.3	56.3
6.6	5.1	14.9	6.1	1.9	8.5	10.0	16.5	51.4
6.7	5.7	13.2	4.3	1.6	7.7	9.1	13.7	56.4
6.8	6.2	15.2	4.9	1.7	7.5	8.8	14.1	53.0
7.5	7.9	17.4	6.3	2.2	8.9	10.5	17.4	51.2
7.6	7.0	18.8	7.8	2.4	8.6	10.1	18.8	45.7
8.5	6.8	17.8	6.4	2.0	10.4	12.3	18.8	55.5
8.6	6.5	18.1	5.9	1.9	9.7	11.4	17.5	55.5
8.7	6.9	17.0	5.4	1.8	9.2	10.8	16.4	55.9
8.8	7.2	17.9	6.1	2.1	9.0	10.6	17.2	52.3
9.5	8.7	18.7	6.8	2.1	9.4	11.1	18.3	51.6
9.6	7.6	19.7	7.6	2.3	10.3	12.1	20.2	51.0
9.7	8.1	18.8	6.4	2.2	9.6	11.3	18.2	52.8
9.8	9.4	19.1	7.9	2.3	9.4	11.0	19.6	47.8
10.5	9.1	21.4	8.1	2.2	11.2	13.2	21.5	52.1
10.6	8.4	19.4	7.7	*	11.4	13.4	19.1	0.0

Farm Field ID	M. Ripe Ear DM (t/ha)	M. Ripe WP DM (t/ha)	Straw DM (t/ha)	Chaff DM (t/ha)	Grain yield (t/ha 100% DM)	Grain yield (t/ha, 85% DM)	Total_DM (t/ha)	HI (%)
10.7	10.1	23.3	8.4	2.3	11.0	12.9	21.7	50.7
10.8	8.1	18.5	6.3	2.1	10.1	11.9	18.5	54.8
11.5	7.1	19.6	7.5	2.3	10.7	12.6	20.6	52.1
11.6	6.6	15.3	5.0	1.8	7.5	8.8	14.2	52.5
11.7	8.6	17.3	6.3	2.4	9.1	10.7	17.9	50.9
11.8	8.2	19.7	7.6	2.3	10.2	12.0	20.0	51.0
12.5	7.4	16.9	6.4	1.8	9.1	10.7	17.3	52.5
12.6	7.2	16.9	5.7	1.8	7.6	8.9	15.1	50.2
13.6	10.8	21.6	4.9	1.8	6.3	7.5	13.1	48.5
13.8	9.3	20.9	7.1	2.1	10.4	12.2	19.5	53.1
13.9	7.9	17.7	7.1	2.3	9.7	11.4	19.0	50.9
13.10	6.6	17.5	7.9	2.3	10.4	12.2	20.5	50.5
13.11	8.3	19.1	7.6	2.2	10.1	11.9	19.9	50.7
14.5	7.5	21.2	7.0	2.1	11.2	13.2	20.4	55.2
14.6	6.1	18.3	6.6	2.1	10.5	12.4	19.2	54.7
14.7	7.4	20.4	7.2	2.2	11.4	13.4	20.8	54.8
14.8	7.7	22.3	7.2	2.1	11.0	12.9	20.3	54.2
16.5	9.6	20.6	6.7	2.2	10.8	12.7	19.6	54.8
16.6	9.5	19.6	7.2	2.3	11.2	13.1	20.6	54.1
16.7	7.4	18.3	6.4	2.1	9.2	10.9	17.7	52.4
16.8	7.4	19.6	6.8	2.3	9.6	11.3	18.7	51.3
17.5	10.4	24.4	8.8	2.4	11.5	13.5	22.7	50.7
17.6	8.6	19.4	7.1	2.1	11.2	13.2	20.3	55.0
17.7	9.1	17.9	6.4	2.0	9.4	11.1	17.9	52.6
18.5	5.5	19.4	8.5	2.4	9.4	11.1	20.3	46.4
18.6	5.1	15.5	6.6	2.1	8.0	9.4	16.7	48.1
19.5	8.5	22.9	8.4	2.3	11.8	13.9	22.6	52.4
19.6	9.2	22.5	8.0	2.4	11.0	13.0	21.3	51.6

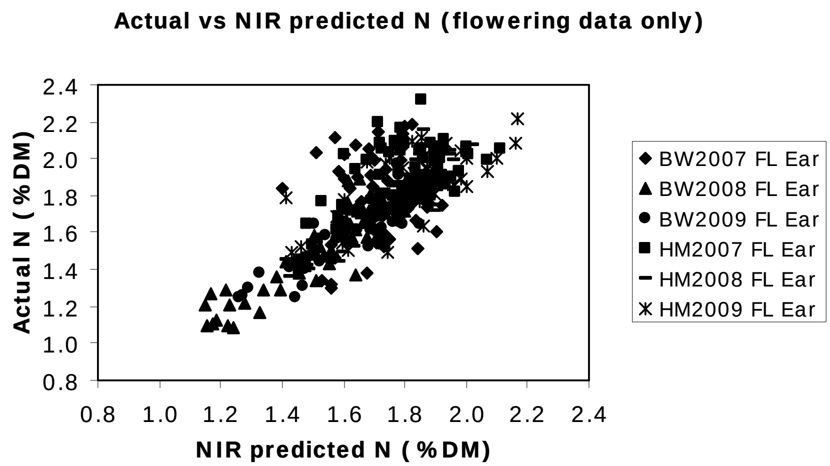
Farm Field ID	M. Ripe Ear DM (t/ha)	M. Ripe WP DM (t/ha)	Straw DM (t/ha)	Chaff DM (t/ha)	Grain yield (t/ha 100% DM)	Grain yield (t/ha, 85% DM)	Total_DM (t/ha)	HI (%)
19.7	8.3	20.1	7.7	2.3	11.4	13.4	21.5	53.2
19.8	7.8	20.8	6.9	2.2	10.7	12.6	19.8	54.0
23.5	8.0	19.1	6.8	2.0	10.1	11.9	18.9	53.4
23.6	6.1	18.0	9.0	2.2	9.9	11.6	21.0	46.9
23.7	7.0	20.9	9.4	2.2	10.1	11.9	21.7	46.7
23.8	7.1	22.1	8.8	2.3	10.7	12.6	21.9	49.1
24.5	6.0	15.7	6.3	1.9	8.0	9.4	16.1	49.3
24.6	6.4	18.1	*	*	*	*	*	*
24.7	5.7	17.7	7.4	2.5	10.7	12.6	20.5	52.2
24.8	6.5	20.1	6.7	2.3	10.3	12.2	19.3	53.5
25.5	6.7	18.4	4.1	1.9	8.5	10.0	14.5	58.7
25.6	6.2	16.5	7.4	2.0	8.3	9.7	17.6	46.9
25.7	5.8	14.9	5.1	1.5	6.5	7.7	13.1	49.7
28.5	6.8	17.6	6.9	2.4	10.8	12.8	20.2	53.6
28.6	6.5	17.2	6.3	2.2	9.3	10.9	17.8	52.2
28.7	6.5	18.0	8.6	2.6	11.5	13.5	22.7	50.7
28.8	6.6	18.1	7.4	2.5	9.8	11.5	19.6	50.0
29.5	8.1	23.2	8.6	1.9	10.4	12.2	21.0	49.5
29.6	8.0	19.4	6.7	2.1	8.7	10.3	17.5	49.7
29.7	7.0	18.6	7.7	2.2	9.7	11.4	19.6	49.3
30.5	9.3	20.5	6.2	2.1	9.4	11.1	17.8	52.8
30.6	9.2	21.3	6.7	2.4	11.2	13.1	20.2	55.3
30.7	8.5	20.9	7.5	2.5	11.2	13.2	21.3	52.7
31.5	6.6	15.4	4.7	1.9	7.6	8.9	14.2	53.1
32.5	9.1	20.7	6.7	2.0	8.1	9.5	16.8	48.1
2009								
1.12	7.0	16.4	*	*	*	*	*	*
1.13	7.9	18.8	7.3	7.3	11.0	13.0	25.6	53.8

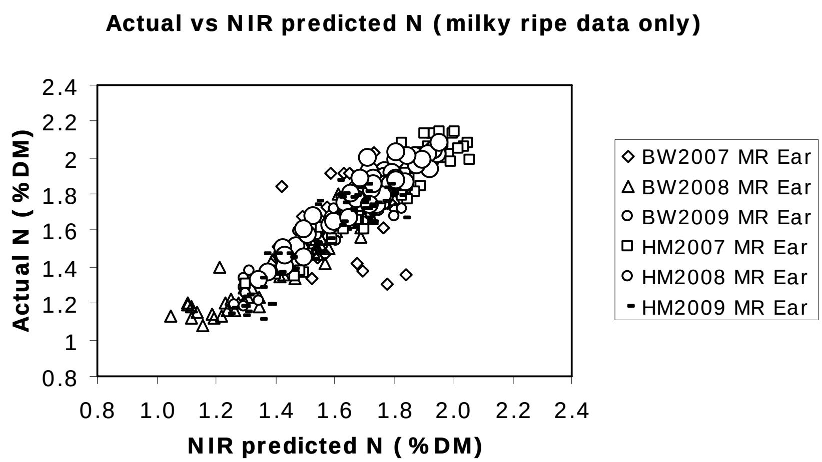
Farm Field ID	M. Ripe Ear DM (t/ha)	M. Ripe WP DM (t/ha)	Straw DM (t/ha)	Chaff DM (t/ha)	Grain yield (t/ha 100% DM)	Grain yield (t/ha, 85% DM)	Total_DM (t/ha)	HI (%)
2.12	11.0	19.3	6.7	6.7	10.4	12.3	23.8	54.0
3.12	9.1	21.3	7.4	7.4	11.4	13.4	26.3	53.9
3.13	6.2	13.3	*	*	*	*	*	*
3.14	7.2	15.8	5.2	5.2	8.4	9.8	18.8	53.5
4.12	6.4	19.4	*	*	*	*	*	*
4.13	6.6	7.2	6.5	6.5	9.4	11.1	22.4	52.5
4.14	6.1	15.5	*	*	*	*	*	*
4.15	6.7	20.1	7.7	7.7	11.2	13.2	26.7	52.2
5.12	4.9	16.3	6.1	6.1	8.1	9.5	20.2	50.1
5.13	6.3	18.0	6.9	6.9	9.4	11.0	23.3	50.5
6.12	8.3	16.3	5.1	5.1	10.7	12.5	20.8	60.0
6.13	9.6	18.1	5.7	5.7	9.3	10.9	20.6	54.8
6.14	9.2	20.2	6.3	6.3	9.7	11.4	22.2	54.3
6.15	10.5	20.3	5.9	5.9	10.5	12.3	22.4	56.3
7.12	5.4	12.0	3.8	3.8	7.1	8.4	14.7	56.7
7.13	6.1	15.3	5.2	5.2	7.5	8.8	17.8	52.4
9.12	7.6	16.7	6.1	6.1	8.5	10.0	20.6	51.8
9.13	7.5	17.1	5.9	5.9	8.5	10.0	20.3	52.5
9.14	7.6	16.6	6.6	6.6	9.7	11.4	22.8	52.8
10.12	6.7	18.2	7.1	7.1	10.0	11.8	24.2	52.0
10.13	8.9	18.3	*	*	*	*	*	*
10.14	8.1	16.8	5.4	5.4	10.3	12.2	21.2	58.6
11.12	5.5	14.7	4.5	4.5	7.9	9.3	16.9	55.4
11.13	5.4	12.5	*	*	*	*	*	*
12.12	6.7	15.4	5.1	5.1	8.3	9.8	18.5	55.1
12.13	5.8	13.9	5.8	5.8	8.2	9.7	19.8	52.2
13.12	8.8	15.7	5.5	5.5	8.7	10.2	19.6	54.2
13.13	10.0	19.0	6.1	6.1	10.0	11.8	22.2	55.4

Farm Field ID	M. Ripe Ear DM (t/ha)	M. Ripe WP DM (t/ha)	Straw DM (t/ha)	Chaff DM (t/ha)	Grain yield (t/ha 100% DM)	Grain yield (t/ha, 85% DM)	Total_DM (t/ha)	HI (%)
13.14	7.7	17.0	5.9	5.9	8.3	9.8	20.2	52.4
13.15	8.0	16.5	5.5	5.5	8.7	10.2	19.7	54.5
14.12	6.2	16.0	6.9	6.9	8.8	10.4	22.7	50.3
14.13	7.0	16.2	6.2	6.2	9.4	11.1	21.9	53.3
16.12	8.1	16.3	*	*	*	*	*	*
16.13	8.9	18.6	*	*	*	*	*	*
16.14	6.8	18.1	7.1	7.1	10.9	12.8	25.2	53.7
16.15	6.5	14.1	4.8	4.8	9.0	10.6	18.5	57.4
17.12	5.8	13.7	6.2	6.2	7.4	8.7	19.9	48.0
17.13	*	*	6.0	6.0	10.3	12.1	22.3	56.5
17.14	9.2	19.6	*	*	*	*	*	*
18.12	*	*	3.8	3.8	7.6	8.9	15.2	56.8
18.13	5.9	11.9	3.5	3.5	6.4	7.5	13.4	54.3
19.12	6.2	14.9	5.8	5.8	9.6	11.3	21.2	54.7
19.13	7.5	15.5	5.1	5.1	9.5	11.2	19.8	57.1
19.14	7.8	19.1	6.1	6.1	10.2	12.0	22.4	55.2
20.12	7.9	18.3	7.5	7.5	10.2	12.0	25.2	51.4
20.13	7.3	17.9	7.0	7.0	10.1	11.9	24.2	52.6
23.12	4.5	12.3	4.8	4.8	9.0	10.6	18.6	57.4
23.13	8.5	18.5	6.3	6.3	9.9	11.7	22.5	54.6
23.14	7.1	21.7	8.3	8.3	11.2	13.2	27.9	51.4
23.15	8.0	20.4	8.3	8.3	10.5	12.3	27.0	48.8
24.12	7.9	16.7	5.5	5.5	9.5	11.1	20.4	56.4
24.13	5.9	14.1	5.4	5.4	8.8	10.4	19.6	55.8
24.14	6.3	12.8	3.2	3.2	7.2	8.5	13.6	59.6
24.15	5.4	12.4	4.5	4.5	7.5	8.9	16.6	54.8
25.12	4.5	11.7	5.0	5.0	8.4	9.8	18.3	54.8
25.13	4.5	4.7	5.3	5.3	8.5	10.0	19.1	54.5

Farm Field ID	M. Ripe Ear DM (t/ha)	M. Ripe WP DM (t/ha)	Straw DM (t/ha)	Chaff DM (t/ha)	Grain yield (t/ha 100% DM)	Grain yield (t/ha, 85% DM)	Total_DM (t/ha)	HI (%)
25.14	6.7	15.1	5.5	5.5	8.0	9.4	18.9	52.0
25.15	5.7	7.3	5.5	5.5	8.0	9.4	19.0	52.0
28.12	7.7	17.2	5.3	5.3	9.2	10.8	19.8	55.5
28.13	6.1	13.4	4.1	4.1	8.7	10.3	17.0	58.7
28.14	6.4	17.2	5.5	5.5	9.9	11.6	20.8	56.7
28.15	5.8	17.8	6.6	6.6	10.6	12.5	23.7	54.7
29.12	6.1	12.6	4.6	4.6	7.6	8.9	16.8	53.1
29.13	5.4	14.4	6.5	6.5	10.0	11.7	22.9	54.0
29.14	4.9	14.8	5.0	5.0	7.6	8.9	17.5	52.8
30.12	7.7	19.3	7.9	7.9	9.0	10.6	24.7	46.0
30.13	6.5	16.4	5.7	5.7	8.2	9.6	19.5	51.0
30.14	6.2	14.5	6.7	6.7	9.3	10.9	22.6	52.0
31.12	6.2	16.6	5.5	5.5	9.5	11.2	20.6	56.7
31.13	7.1	17.8	*	*	*	*	*	*
31.14	5.8	16.1	5.4	5.4	8.3	9.8	19.2	53.9
31.15	5.8	20.0	7.0	7.0	11.7	13.8	25.8	56.3
33.12	9.0	20.7	7.2	7.2	8.8	10.4	23.2	49.3
33.13	7.2	17.2	6.5	6.5	8.0	9.4	21.0	48.4
34.12	7.0	14.3	*	*	*	*	*	*
34.13	5.6	11.1	4.3	4.3	7.5	8.9	16.1	55.0
35.12	6.0	13.1	4.6	4.6	7.2	8.5	16.4	53.1
35.13	7.7	18.4	5.5	5.5	8.4	9.9	19.4	53.4
35.14	5.4	12.0	5.1	5.1	6.6	7.8	16.8	49.1
36.12	7.6	18.6	6.2	6.2	9.4	11.0	21.7	53.3
36.13	9.4	18.6	6.1	6.1	10.2	12.0	22.3	55.4
36.14	8.7	19.0	6.8	6.8	11.2	13.2	24.8	55.5
36.15	7.8	15.6	4.5	4.5	8.3	9.8	17.4	57.1

ANNEX 10. NIR PREDICTIONS AND REFERENCE DATA.





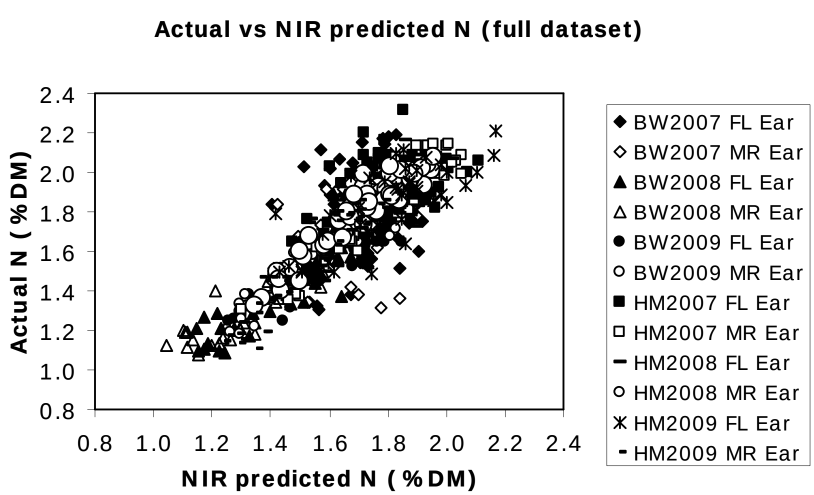
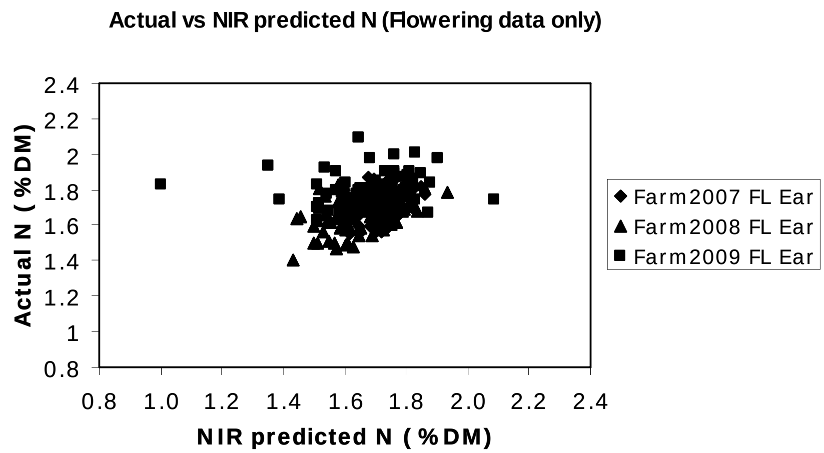
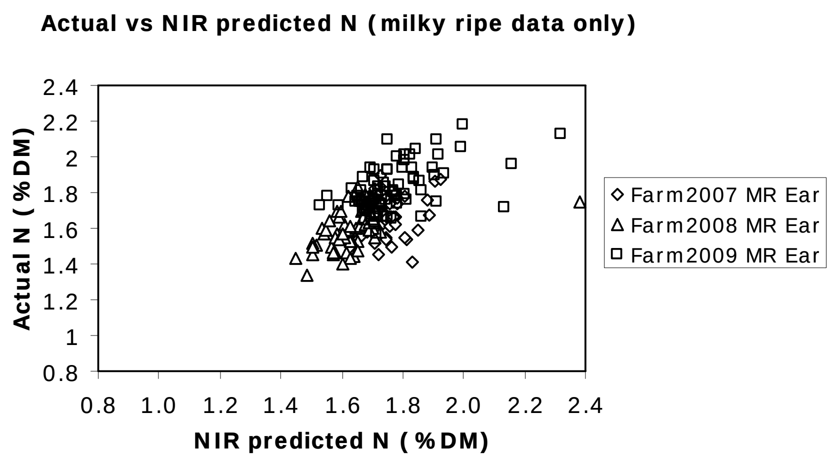


Figure A9. Nitrogen in immature ears at flowering (FL) or milky ripe (MR) for ADAS field experiments 2007-2009.





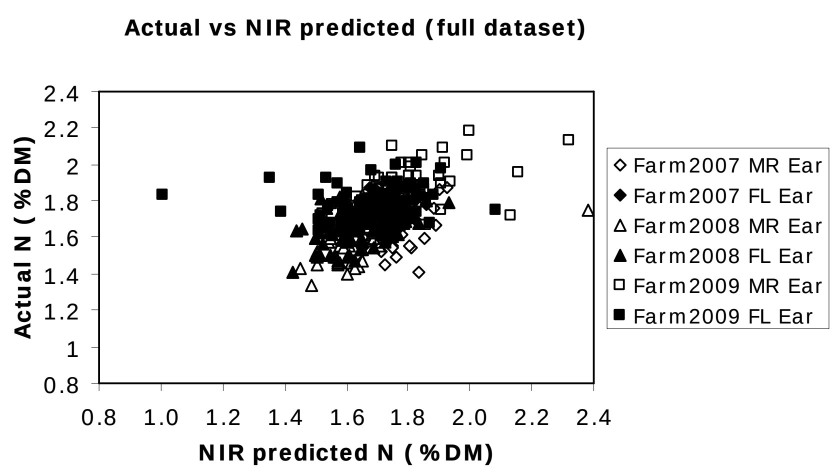
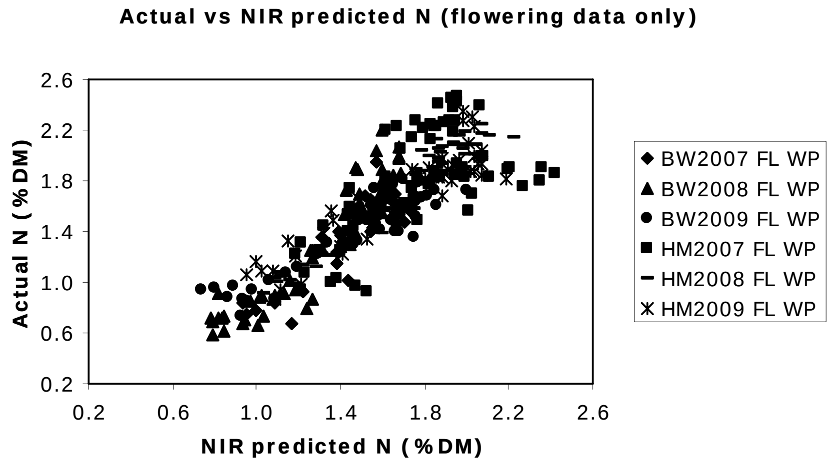
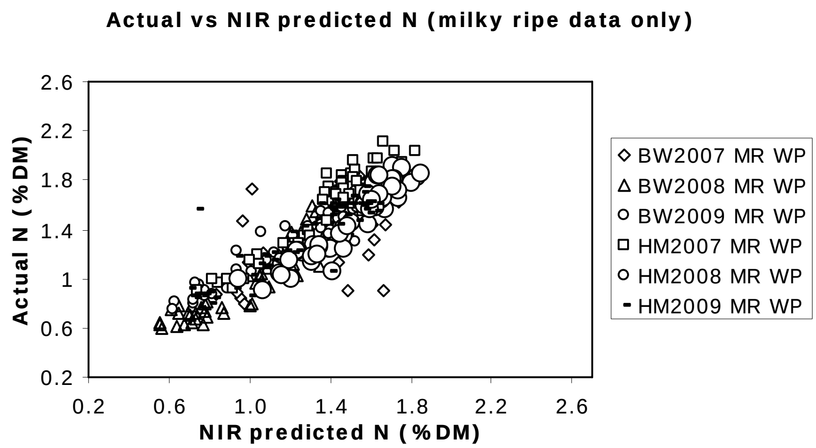


Figure A10. Nitrogen in immature ears at flowering (FL) or milky ripe (MR) for commercial crops 2007-2009.





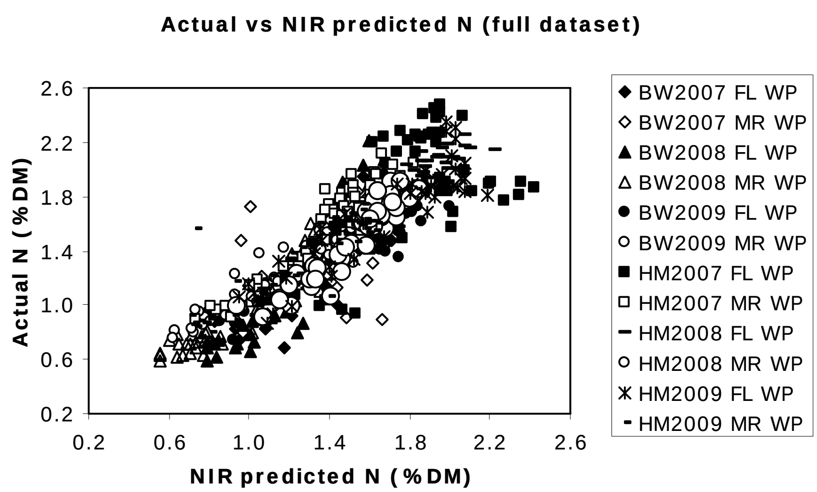
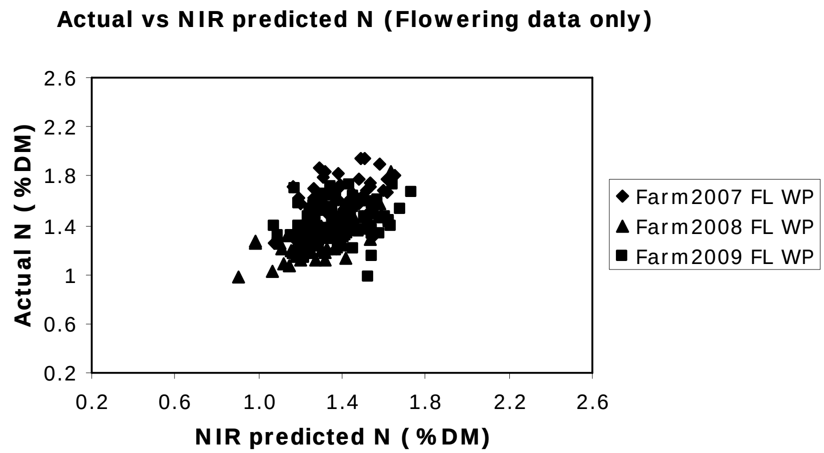
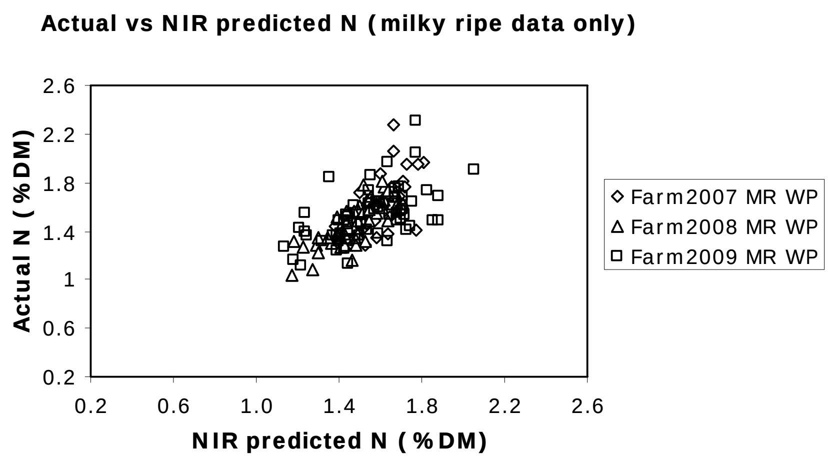


Figure A11. Nitrogen in immature whole plant (WP) at flowering (FL) or milky ripe (MR) for ADAS field experiments 2007-2009.





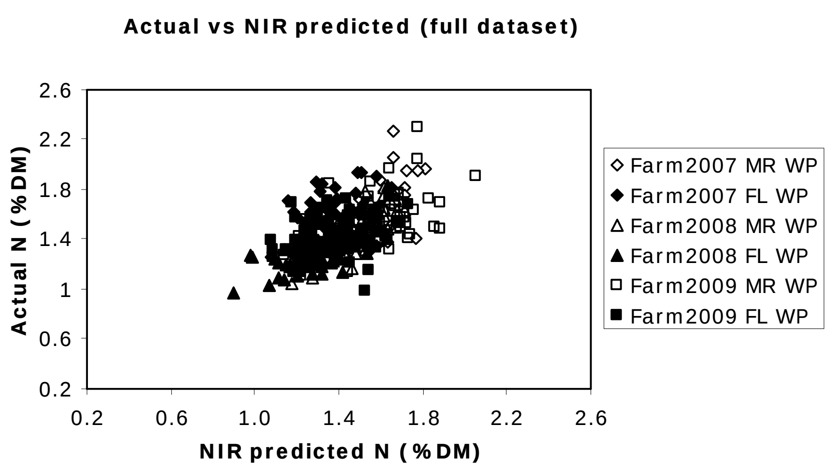


Figure A12. Nitrogen in immature whole plant (WP) at flowering (FL) or milky ripe (MR) for commercial crops 2007-2009.

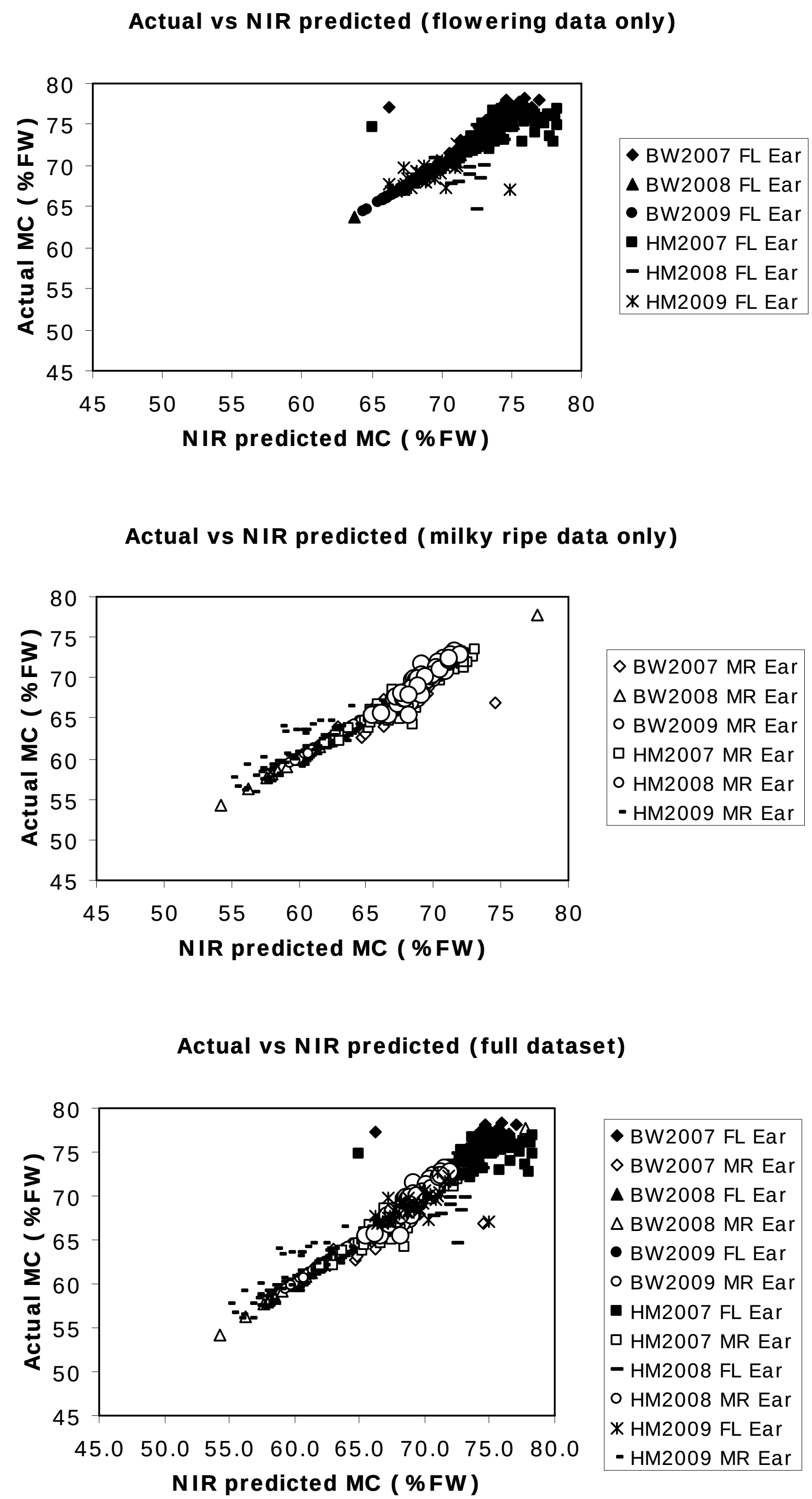
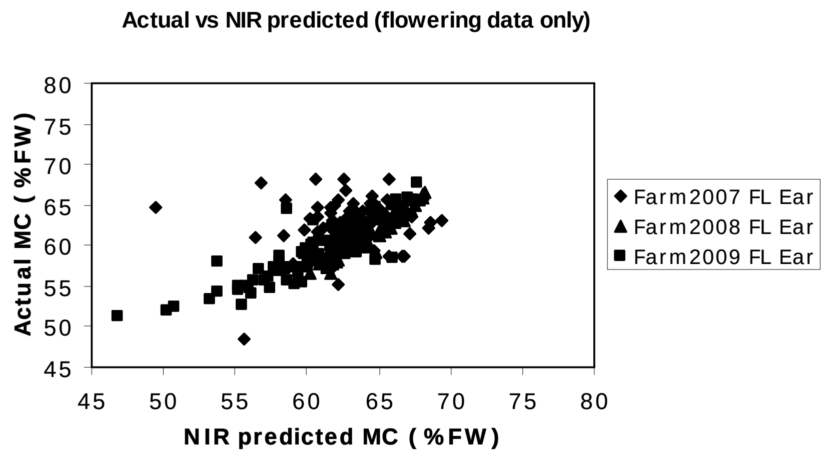
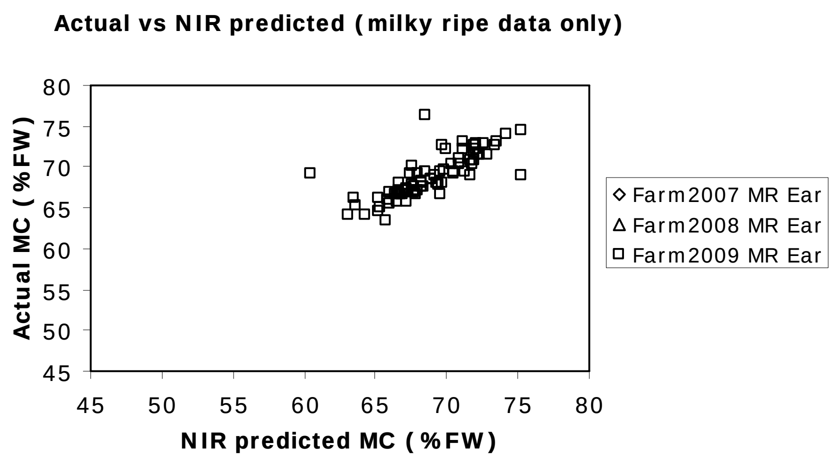


Figure A13. Moisture content (MC) in immature ears at flowering (FL) or milky ripe (MR) for ADAS field experiments 2007-2009.





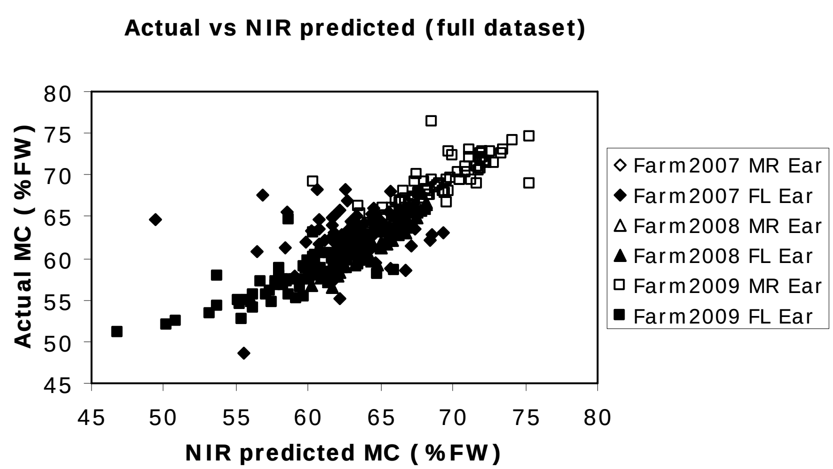


Figure A14. Moisture content (MC) in immature ears at flowering (FL) or milky ripe (MR) for commercial crops 2007-2009.

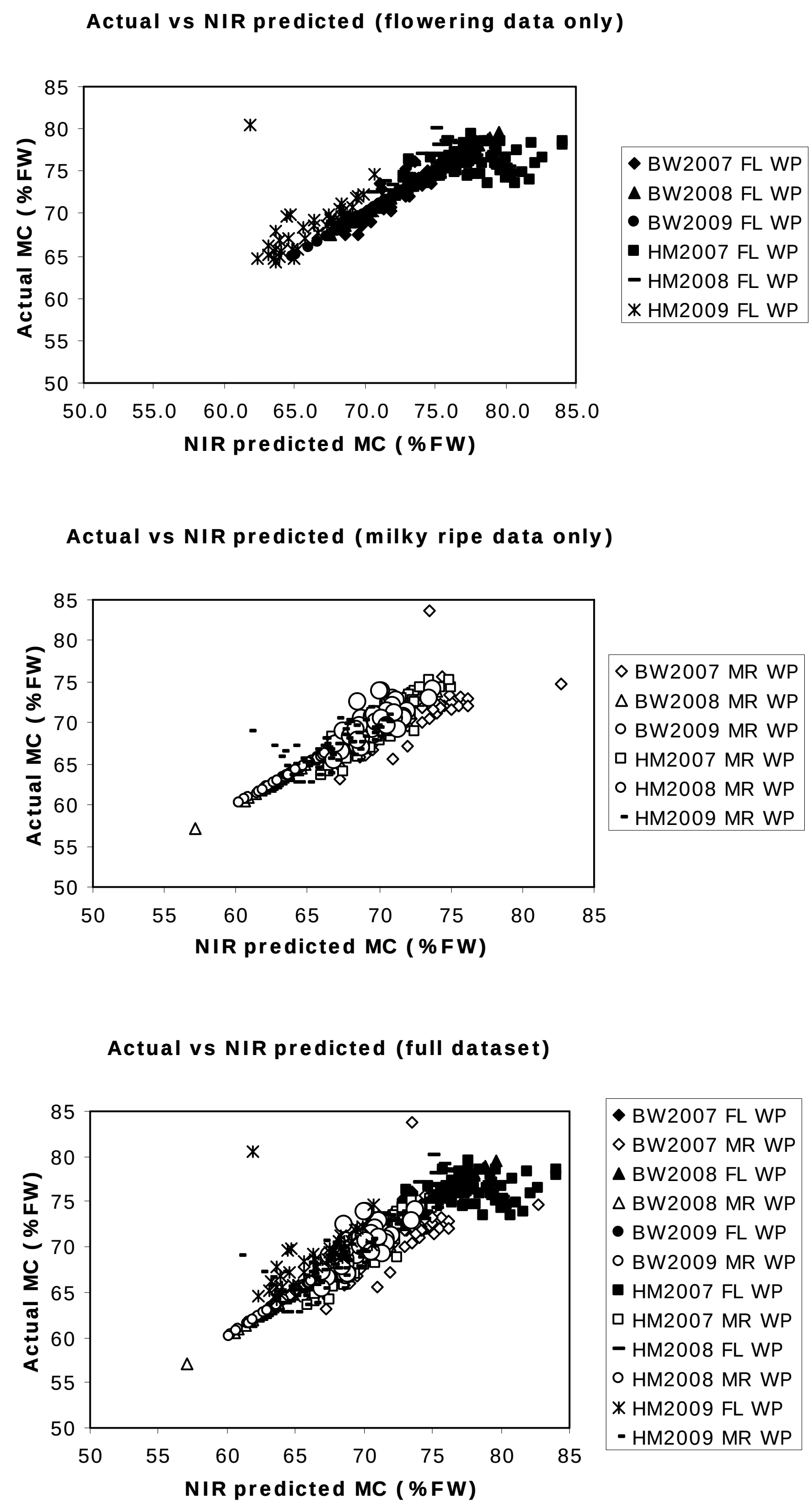
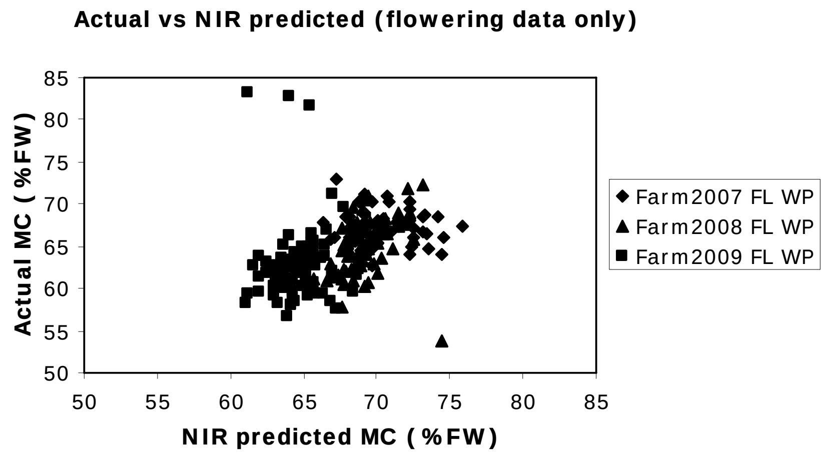
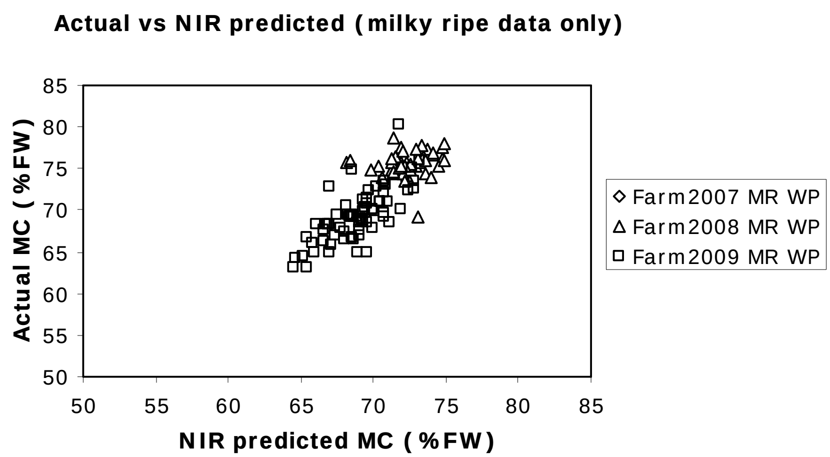


Figure A15. Moisture content (MC) in immature whole plant (WP) at flowering (FL) or milky ripe (MR) for ADAS field experiments.





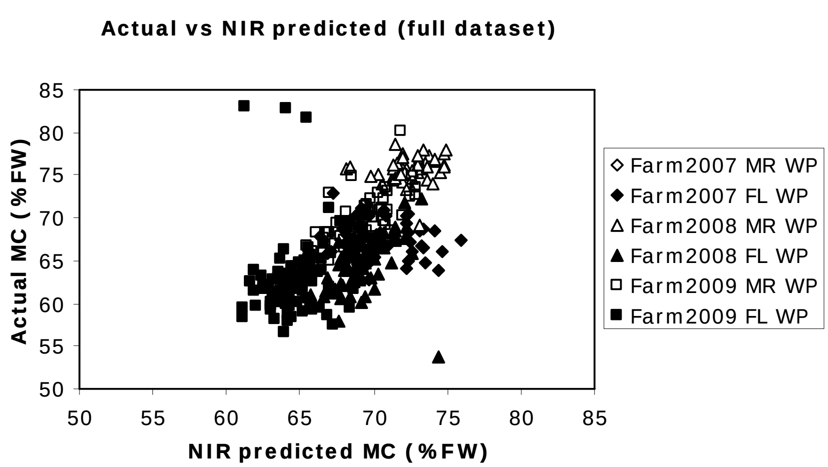


Figure A16. Moisture content (MC) in immature whole plant (WP) at flowering (FL) or milky ripe (MR) for commercial crops 2007-2009.