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

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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

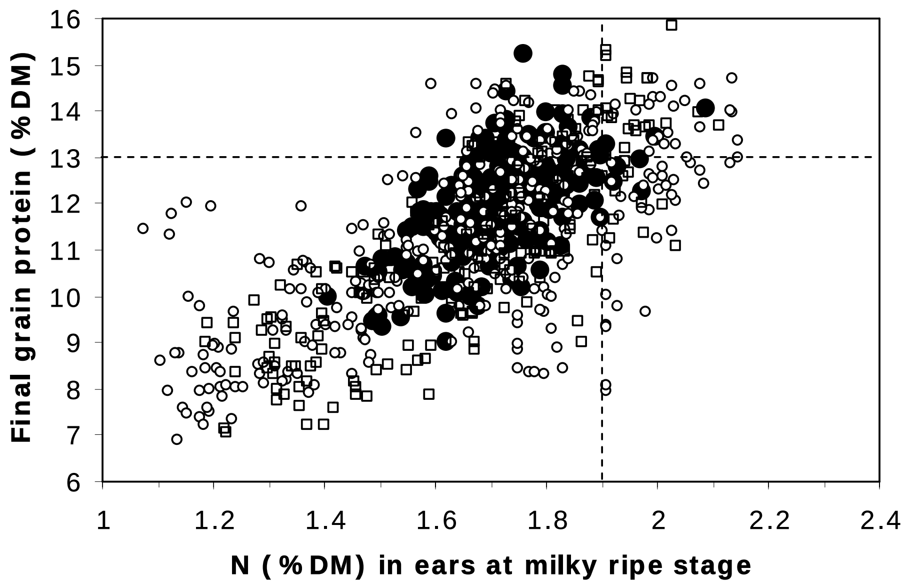
NIR predicts N and moisture in the immature plant by comparing spectra from scanned samples to measures using lab methods. In the present work, N (dry basis) and moisture in fresh plant material were matched with spectral data and added to the NIR calibration dataset developed in the first MALNA project. 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

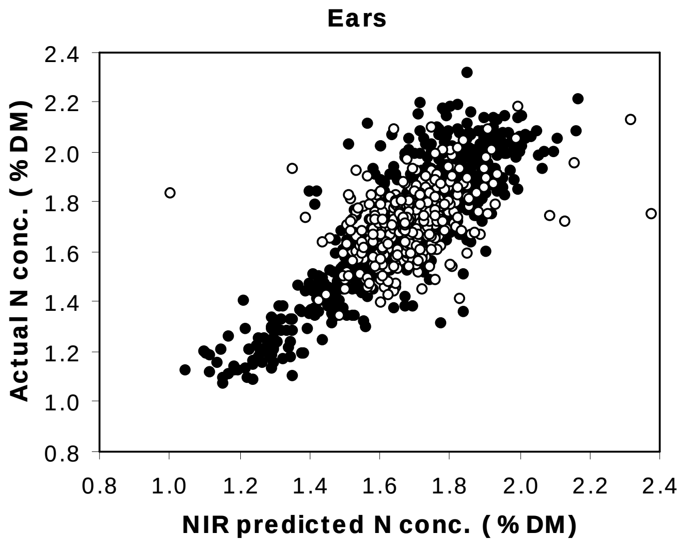
2.3.2. Comparison between field trials and commercial crops

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

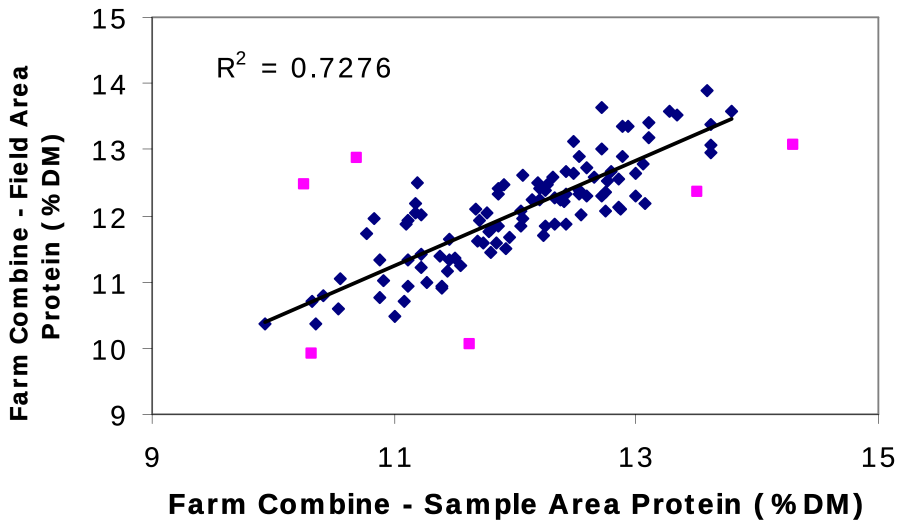
The first MALNA project built NIR calibrations on 219 immature plant samples (each of ears and whole plant, at MR stage only). These were from four seasons and only from field experiments on first wheats. The current project collected many more samples (1,210 each of ears and whole plant) representing 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.

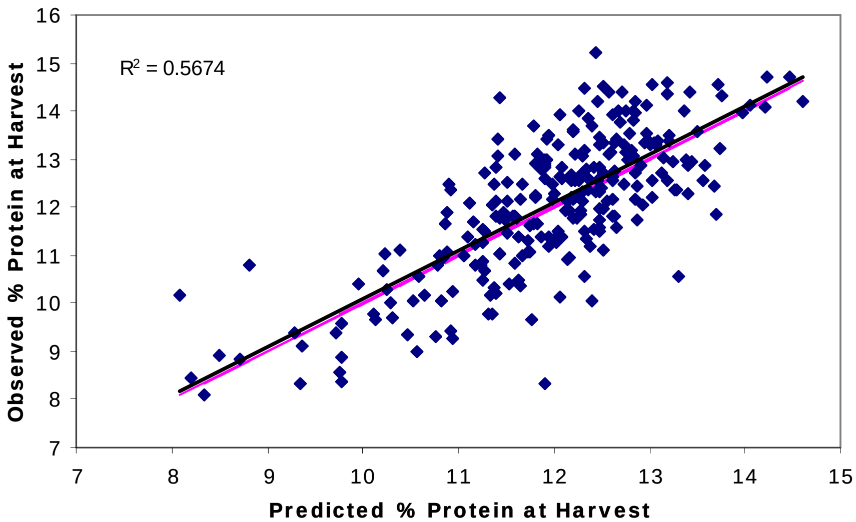
(i) The range of N contents in whole plant material was greater than in ears alone. Hence, whole plant data generally performed better in grain protein prediction. However, this advantage was marginal and, given the extra effort (hence cost) in taking large samples for analysis compared to the relative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