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Using grain N% as a signature for good N use

By

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Contents

1. Abstract

Recent fertiliser recommendations suggest that grain nitrogen (N) analysis can be used to monitor the precision of N management for wheat crops. In this project, datasets with up to 443 experiments (including those used to revise the fertiliser recommendations) were analysed to gauge the confidence to place in this approach, and whether it should be extended to barley and oilseed rape.

Average grain N (% in dry matter) at the optimum amount of fertiliser N (assuming a 'break-even' N:grain price ratio of 5) was 2.0% (11.5% protein) for wheat, and 1.9% for barley, both winter and spring types. It was significantly greater for breadmaking than feed wheats by 0.17%, significantly less for malting than feed barleys (by 0.16% for winter and 0.05% for spring types), and significantly less after break crops than after cereal crops by 0.08% in both winter wheat and winter barley; some soil type effects were significant but inconsistent. Unexpectedly, grain N% with optimum N supplies tended to increase as optimum fertiliser N increased; this reduces the value of grain N% as a signature of good N use. Consistency in grain N% of barley with optimum N was greater than if one fixed N amount had been applied everywhere, but this did not apply for wheat or oilseed rape.

Responses in grain N% to applied N were relatively consistent in the region of the optimum N amount; a difference of 0.1 in grain N% could be taken to indicate a difference of about 30 kg/ha in N applied to wheat and spring barley, 25 kg/ha in N applied to winter barley and 50 kg/ha in N applied to oilseed rape.

It was concluded that grain N (or protein) analysis is useful as a retrospective check on the N management of feed varieties of wheat and barley, but not oilseed rape. For feed wheats it can be taken that grain protein around 11.5% signifies optimal N management, and so does grain N around 1.9% for feed barleys. Differences from these 'standards' were only 70-80% successful in identifying crops that had been over- or under-fertilised with N. Hence comparisons on several fields or over several seasons will be needed before confident conclusions can be drawn about accuracy of N management. Grain N analysis could probably prove useful in accrediting the green-house gas emissions associated with biofuel production, but it appeared less useful in judging N management of breadmaking or malting varieties because these crops

generally have specifications (with attendant financial incentives) that encourage N use that is non-optimal for yield, including late urea sprays. A similar approach may be applicable outside the UK but would need different standards since grain N% in Danish experiments was 0.4% less than in the UK; this difference is not explained.

It is suggested that these conclusions should be transferred to the UK arable industry through the forthcoming HGCA publication on ‘Nitrogen for winter wheat – management guidelines’, and that they should inform the next revision of national fertiliser recommendations.

2. Summary

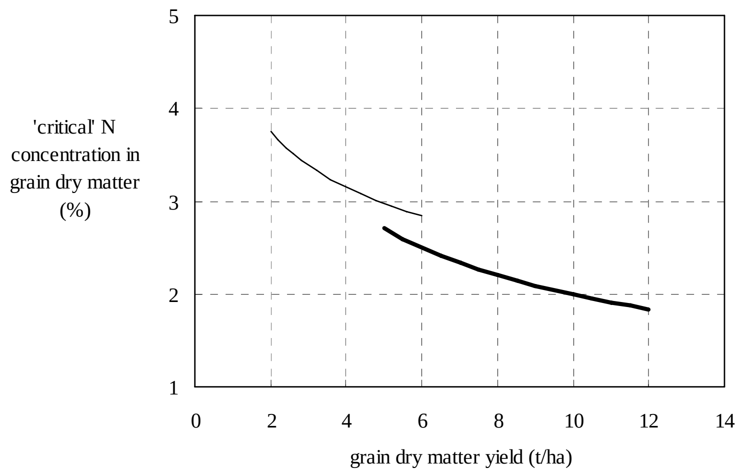
2.1 Objectives

This project was set up to assess how grain nitrogen (N) analysis might best be used to support optimum N use, and possibly GHG accreditation, in the production of cereals and oilseed in the UK. It considered the biological basis for grain N% being stable at optimum levels of N supply, and detectably different at non-optimal levels, and then sought to deduce for wheat, barley and oilseed rape growers how best to use grain analysis to support N management and GHG accreditation.

2.2 Background

Crop N concentration has commonly been used as a diagnostic, high concentrations indicating N excess and low concentrations N deficiency. Crop analysis for N can be used for trouble-shooting particularly with high-value crops, but it is also used to predict fertiliser requirements of arable crops in France. Since 2000, N analysis of grain was recommended as a retrospective check on the N status of wheat crops in England & Wales (Anon., 2000, page 78); growers were advised that grain N was relatively constant (around 2% of grain dry matter) where N supply was optimal, but that it differed by 0.1% for every 30 kg/ha that N supply differed from the optimum. However, evidence for this advice was never published, so this project reconsiders the basis for using grain N analysis as a retrospective check on N management of wheat, and extends the investigation to barley and oilseed rape.

Fig. 2.1 Critical N dilution curves predicted from the literature for wheat grain (bold line) assuming harvest indices are 0.5 for DM and 0.7 for N, and rape seed (fine line) assuming harvest indices are 0.4 for DM and 0.5 for N.



Greenwood *et al.* (1991) described how in theory the ratio of N to dry matter in a crop (where it is *just not* limited by N supply, i.e. the 'critical N%') should follow a 'dilution curve'. Justes *et al.* (1994) determined a 'critical N dilution curve' for wheat and Colnenne *et al.* (1998) did the same for oilseed rape, but no dilution curve has been described for barley. Extrapolation of dilution curves for whole crops indicates that grain N may also follow 'dilution curves' and that these would be fairly 'flat' over the normal range of grain yields for UK farms (Fig. 2.1).

Many growers have already adopted grain N as a retrospective check on N management of wheat, driven in part by a need to demonstrate responsible N management in Nitrate Vulnerable Zones. A further use for grain N analysis may arise in the emerging UK biofuels industry, where feedstock producers will need to demonstrate that their N management has reduced greenhouse gas (GHG) emissions. Hence a resolution of how closely grain N concentrations relate to optimal N management, and what levels of certainty should be applied to any relationships, has become important both for commercial purposes, as well as to improve theoretical explanation of optimum crop nutrition.

2.3 Datasets and their analysis

Seven datasets were collated comprising replicated N response experiments carried out using five or six N fertiliser treatments (including nil N). There were 337 experiments on wheat in the UK, 443 on wheat in Denmark, 75 on winter barley, 97 on spring barley and 39 on oilseed rape. Data on harvest year, cultivar types, previous crops and soil types were also collated. Other than the

Danish data, the majority of these data were used in the recent revision of the fertiliser recommendations (Anon., 2009).

Responses of yield to N were estimated for each experiment by fitting the linear plus exponential function (LEXP; George, 1984), as used in the preparation of RB209.

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

where y is yield in t/ha at 85%DM, N is total fertiliser N applied in kg/ha, and a, b, c and r are parameters determined by statistical fitting. Optimum N rates (Nopt) were then derived for breakeven ratios of 5 for cereals and 2.5 for oilseed rape, as in the new RB209 revision. Standard errors (se) of each Nopt estimate were determined, and experiments were discarded if this exceeded 120 kg/ha N.

A grain N (%) response curve was then fitted to the data from each experiment using either the Gompertz function, a Normal Type curve with Depletion function (Murray & Nunn, 1987) or a straight line function, depending on which had been used previously on the dataset, or which fitted the data better. Grain N% estimates were then derived for each Nopt estimate and forward stepwise all-subsets regression analyses were carried out on each dataset separately to determine the important site factors affecting grain N% at Nopt. In addition, fitted grain N% was calculated for a range of fixed N amounts to test whether grain N% at Nopt was less variable. Fitted values were excluded where the fixed N level would have been outside the range of N levels tested. The slopes of the grain N% curves around the optimum were determined from the fitted curves for each experiment and a similar step-wise regression analysis was used to determine the most important factors affecting these.

2.4 Results

A summary of the results of the data analyses is shown in Table 2.1. Grain N for cereals ranged from 1.00% to 3.84% depending particularly on levels of N applied. Generally oilseed rape showed larger concentrations than the cereals. There was little difference between wheat and barley, but wheat in Denmark clearly showed lower grain N concentrations than wheat in the UK. The response in grain N% to applied N was well described by the sigmoid type or linear functions in most experiments. Thus the main uncertainty in determining grain N% at Nopt was in determining Nopt.

Table 2.1 A summary of the analysis of grain N concentration data from series of experiments testing five or more N levels (including nil) on wheat, barley and oilseed rape. ND = no data.

Result	**UK wheat**	**DK wheat**	**Spring Barley**	**Winter Barley**	**Oilseed Rape**
No. experiments included	337	443	97	75 (57)	39
Variation at Nopt accounted for by crop type, soil type and previous crop	25%	30%	23%	21%	21%
Mean grain N at nil N (*%DM*)	1.60	1.35	1.55	1.52	2.77
Mean grain N% at 300 kg/ha N (*%DM*)	2.30	1.93	2.27	2.45	3.35
Mean grain N% at Nopt (*%DM*)	2.02	1.62	1.90	1.89	3.20
Statistically significant (P<0.05) effects on grain N at Nopt (*%DM*)					
crop type bread or malting cf feed	0.17	ND	-0.05	-0.16	ND
after break crop cf after cereal	-0.08	-0.05	No	-0.08	ND
soil type	Yes	Yes	Yes	Yes	Yes
N% per 100 kg/ha opt N	0.13	0.17	No	Yes	No
Mean grain yield at Nopt (t/ha)	8.87	8.08	5.76	6.45	4.03
Mean Nopt (kg/ha)	156	162	115	131	189
SD of grain N% at Nopt (*%DM*)	0.211	0.171	0.228	0.193	0.265
SD of grain N% at fixed N = mean Nopt	0.204	0.177	0.275	0.229	0.269
Mean grain protein % at Nopt (*%DM*)	11.51	9.23	10.83	10.77	20.00
Mean grain N% response around Nopt (*%N per 100 kg/ha*)	0.299	0.301	0.310	0.417	0.204
Mean grain N% response around Nopt (*kg/ha N per 0.1%N*)	33.4	33.2	32.3	24.0	49.0
Significant effects on grain N% response (*%N per 100 kg/ha*)					
premium crop type	-0.07	ND	No	0.24	ND
after break crop	No	No	No	No	ND
soil type	Yes	Yes	No	Yes	Yes

There was less variation in grain N% at Nopt than at non-optimal (both large and small) N supplies, however there was more variation than was expected and the difference was not marked. When grain N% at Nopt was examined in relation to yields (Fig. 2.2) there were no explanatory relationships. Mean N concentrations were similar to those predicted from published dilution curves for UK wheat and oilseed rape, but grain N% for barley crops was generally less than for wheat, and wheat in Denmark showed grain N approximately 0.4% less than in the UK; the explanation for this large effect is not clear, but it was not due to different levels of N applied or different yield levels.

Regression analysis of grain N% at Nopt according to variety type, previous crop and soil type accounted for only 20-30% of variation (Table 2.1); much variation remained unexplained. Regression analysis often showed soil type to have some effect on grain N% at Nopt, but effects were not consistent, and they often interacted with other factors. Previous crop was identified as a consistent factor affecting grain N% in UK and Danish winter wheat, and winter barley, grain N%

being higher after a cereal than after a break crop, as is often reported (e.g. Vaidyanathan *et al.*, 1987); this may be due to take-all affecting grain yield whilst not affecting N capture.

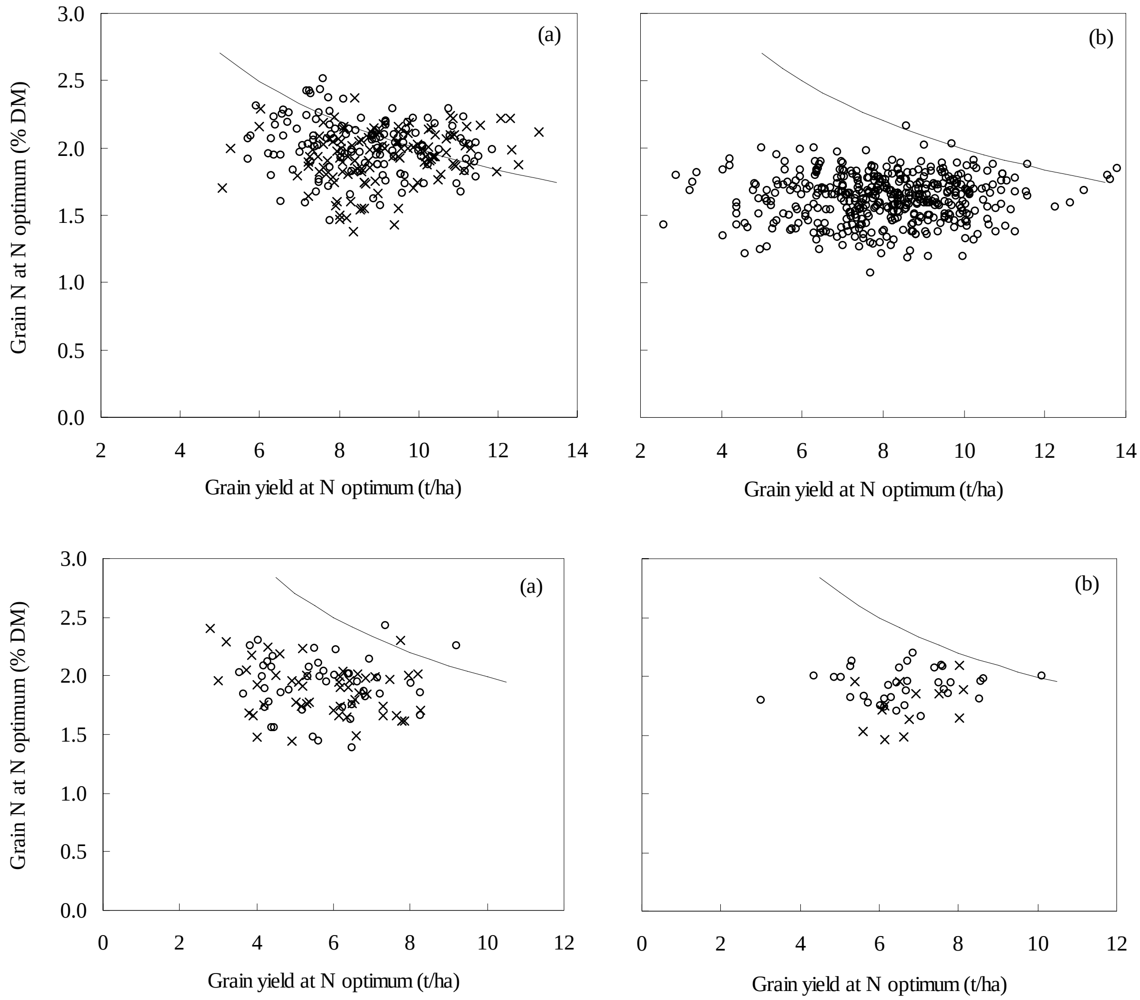


Fig. 2.2 Relationship between grain N (% DM) and grain yield both with the optimum N supply in experiments on UK wheat (top, a), Danish wheat (top, b), winter barley (bottom, a) and spring barley (bottom, b), with feed varieties (circles) and malting varieties (crosses). The line is the predicted relationship for wheat, extrapolated from Justes et al.,(1994), assuming harvest indices were stable at 0.5 for DM and 0.7 for N.

If, as hypothesised, grain N% were a good measure of appropriate N use, it would be expected to show less variation at Nopt than at other N levels. This appeared to be the case for spring and winter barley crops when whole datasets were considered (Table 2.1). However, standard deviations of grain N% at Nopt were little different from those at fixed levels of N for wheat and oilseed rape (Table 2.1). There was no systematic pattern in the variability of grain N% as fixed applications of N increased: variability tended to decrease in UK wheat experiments but it increased in Danish wheat experiments and in spring barley experiments.

It was unexpected that, for wheat and winter barley, some of the variation in grain N% at Nopt was accounted for by Nopt itself. Clearly this compromises the prospects of using grain N% to indicate differences (= error) between the N rate used for a crop and the actual Nopt.

The average response in grain N% around Nopt was the same in both the UK and Danish wheat experiments, and was consistent with guidance in fertiliser recommendations (Anon., 2009), namely that a 0.1% deviation in grain N from the expected indicates a 30 kg/ha deviation in N use. However, responses indicated greater adjustments (40 kg/ha N per 0.1%N) were needed for breadmaking wheats. Average responses for spring barley were similar to feed wheat, but winter barley required only 25 kg/ha N per 0.1%N whilst oilseed rape required an adjustment of 50 kg/ha N per 0.1%N. Where responses were affected by soil type (UK wheat and winter barley) this was due to sandy soils requiring greater adjustments to N rates per 0.1%N than other soil types.

Analyses of yields and N optima from the UK dataset were undertaken to explore why grain N% is greater at Nopt for breadmaking than feed varieties of wheat. Although not included in the new revision of fertiliser recommendations, Nopt for yield of breadmaking types was found to be greater than for feed types by ~20 kg/ha, despite grain yields being less. It appears that the greater grain N% in breadmaking varieties is associated with both greater Nopts and smaller grain yields.

Mean grain N% of wheat at Nopt when converted to protein was 12.2% DM, clearly less than the 13% protein normally specified in contracts for breadmaking grain. Hence this analysis indicates that on average an even greater quantity of ‘extra’ fertiliser N is required to meet a breadmaking specification than is to be recommended in the new Fertiliser Manual (Anon., 2009): about 20 kg/ha more N is needed than for a feed variety to achieve the optimum yield and then, assuming a response rate (from Table 5.3) of 1.4% protein per 100 kg/ha N applied, a further 55 kg/ha N will be needed to raise grain protein from 12.2% to 13% protein, giving a total extra N requirement of 75 kg/ha compared to that of a feed variety. Less extra N may be needed if it is applied later (at flag leaf or milky ripe stages) than in these experiments (at early stem extension).

This finding clearly has economic implications for growers, and ultimately for the breadmaking industry, since it seems that the costs of growing breadmaking varieties to match the requirements of the end-user are even greater than previously anticipated. It also has environmental and regulatory implications since most of the 75 kg/ha extra N applied to wheat crops for breadmaking will not be harvested but will add to the N load in the arable environment. These results highlight an urgent need to develop breadmaking genotypes, agronomic practices and breadmaking technologies that allow manufacture of acceptable bread products whilst minimising requirements for additional use of fertiliser N. Because extra N will so commonly be needed it will also be difficult to infer optimum N management for yield from grain N analysis of breadmaking varieties, especially if the extra N is applied late (Dampney *et al.*, 2006a).

Malting barleys gave lower grain N concentrations at the optimum N rate than feed barleys but more so in winter than spring barley experiments; average grain N concentrations of feed varieties were 1.92% in both spring and winter barley, and of malting varieties were 1.87% in spring barley and 1.76% in winter barley. As with breadmaking wheat varieties, grain N concentrations for the malting varieties commonly differ from those required by the end-user. Thus N management for malting varieties tends to be sub-optimal and the scope for grain N analysis to indicate the extent of any deviation from optimum N levels for yield is reduced. Given this, and the variability around these mean concentrations, grain N analysis will be most valuable for feed varieties, and it is questionable whether adoption of different guideline concentrations for the different barley types would be justified.

2.5 Conclusions and Research Suggestions

There are implications of this work for commercial practice and for subsequent research. It is clear that the variability found in grain N concentrations precludes its use in any exacting way. However, the datasets assembled showed that grain analysis could have correctly identified in 70-80% of cases whether feed varieties of winter wheat and barley (spring or winter) in the UK had been under- or over-fertilised. The 50% success rate for oilseed rape was not useful. Thus whilst analysis of one grain sample may not be sufficiently trustworthy to form conclusions about N management in a single crop, several analyses, if showing a consistently low or high grain N% compared to a guideline 'standard', could be used to deduce the success of recent N management. Similarly a number of samples, perhaps taken at successive stages through the supply-chain for bioethanol production, could be used to indicate the extent to which N use in growing that grain had deviated from being optimal.

It appears that samples from breadmaking varieties of wheat and malting varieties of barley will not be useful in indicating whether N management was approximately optimal because financial premiums encourage non-optimal N use. However, samples taken from feed crops, if analysed in sufficient numbers – perhaps 5-10 per season, should prove useful in indicating any financially important deviation from optimal N use. Standard grain concentrations for feed varieties of wheat and barley are suggested in Table 2.2. In setting these values it was judged that the differences due to site characteristics such as previous crop were small (<0.1%N) compared to the background variability, so they did not justify recognition. Values for winter wheat have been converted to protein (N x 5.7) for conformity with current commercial practice.

In conclusion, this study has shown that grain N% can be used as a crude retrospective check on N management of feed crops of wheat and barley. Where grain N concentrations from several samples consistently deviate by more than 0.1% from standard grain N concentrations (Table 2.2), it should be deduced that fertiliser N rates differed by at least 30 kg/ha from the optimum N rate.

Table 2.2 Proposed 'standard' values for use in judging whether N management of cereal crops has approximated to the economic optimum, and the extent to which it may have deviated from the optimum, assuming a N:grain price ratio of 5.

Guideline		**Winter Feed Wheat**	**Feed Barley**
	units	***grain protein (grain N x 5.7)***	***grain N***
Expected grain concentration with optimum N applied	*% DM*	11.5%	1.9%
Approx. correction around optimum N	*kg/ha N applied per 0.1% difference*	6	30

Topics that would merit further research are as follows:

- A review of the methods available for on-farm N management (such as previous grain N% analysis, field assessment of soil N supplies, soil mineral N analysis and canopy assessment) would enable growers to see how best to devise an *integrated* N management strategy.
- The large amount of extra N (~75 kg/ha) required to meet the normal specification for breadmaking wheat indicates an urgent need to develop new genetic, agronomic and processing technologies that minimise the true economic and environmental costs of bread production.
- For oilseed rape, seed N concentrations were too variable to prove useful as a guide to N management or GHG emissions but the dataset was small. More work with larger datasets, such as may be available from other countries, might account for more of the variability in the N% at Nopt, and allow standard values to be adopted.
- Further work is needed to understand the large differences in the grain N concentrations between the UK and Denmark. It seems likely that this effect arises from climatic and soil differences, so the further work would most usefully involve extended comparisons with other European countries such as France and Ireland from which more comprehensive climatic contrasts can be examined.
- Grain N concentration is a major component of the N conversion efficiency of cereals and oilseed crops, and N conversion efficiency is a major component of overall N Use Efficiency (Sylvester-Bradley & Kindred, 2009). The large variation in grain N% at Nopt found here, and the large proportion of this variation that is still unexplained, are considerable causes of concern in the quest to improve the N Use Efficiency of arable crops in Europe. It will be important that this variation is subjected to further research so that all possible practical means of improving N Use Efficiency can be identified.

3. Project Objectives and Background

3.1 Project objectives

To assess how grain N analysis can best support optimum N use, and GHG accreditation, in UK cereal and oilseed production.

Specific objectives were:

1. Review the biological basis for grain N% being stable at optimum levels of N supply, and detectably different at non-optimal levels.
2. Recommend for wheat, barley and oilseed rape growers the best way to use grain or whole-crop analysis to support their N management, and GHG accreditation.
3. Publish the basis for using N analysis to support N use and GHG accreditation in the UK.

3.2 Background

Crop nitrogen (N) concentration has commonly been used as a diagnostic, high concentrations indicating N sufficiency or excess and low concentrations indicating N deficiency. Initially, N analysis of vegetative tissues was used for trouble-shooting particularly with high-value horticultural crops (see review by Sylvester-Bradley *et al*., 2004), then in the 1990s it was adopted to predict fertiliser requirements of arable crops in France, through the N Nutrition Index (Greenwood *et al.*, 1991; Justes *et al.*, 1994; Gastal & Lemaire 2002), the ratio of current N% to 'critical' N%. Since 2000 N analysis of grain was recommended as a retrospective check on the N status of wheat crops in England & Wales (Anon., 2000, page 78). This was based on initial observations by Vaidyanathan *et al.* (1987) and then evidence compiled by Goodlass & Sylvester-Bradley (1999, unpublished); data from N response experiments on wheat in the 1980s and 1990s were interpreted to show that grain N was relatively constant (around 2% of grain dry matter) where N supply was optimal, but that it differed by 0.1% for every 30 kg/ha that N supply differed from the optimum. However, this evidence and its interpretation were never published, so the aim of this report is to reconsider the basis for using grain N analysis as a retrospective check on N management of modern wheat crops in the UK, to extend the investigation to barley and oilseed rape, and to make the evidence open for public scrutiny.

Greenwood *et al.* (1991) describe the development of a quantitative explanation for crop N concentration in dry matter whereby (crudely) crop N represents a crop's photosynthetic capacity and its dry matter represents the outcome of its photosynthesis. It is clear that the ratio of N to dry matter in a crop (where it is *just not* limited by N supply, i.e. the 'critical N%') will reflect a quantity of N that is just sufficient to provide for photosynthesis, and that stays constant through time, and then an accumulation of dry matter that increases through time, hence a 'dilution curve'. Justes *et al.* (1994) determined a 'critical N dilution curve' for wheat from data taken prior to reproductive growth. This described how, until flowering, crop N is invested just in leaf and stem tissues and that a consistent minimum amount of N related to each amount of total dry matter (Fig. 3.1): a small or young crop with only 2 t/ha DM had a critical N content of 4% (80 kg/ha N), whereas a large or older crop with 10 t/ha dry matter had a critical N content of 1.9% (190 kg/ha N).

Critical N dilution curves have also been described for forage maize (Herrmann & Taube, 2005), alfalfa (Lemaire *et al.*, 1985), grain legumes (Ney *et al.*, 1997), seed crops of ryegrass (Gislum & Boelt, 2009), linseed (Flénet *et al.*, 2006) and oilseed rape (Colnenne *et al.*, 1998; showing higher critical N concentrations than wheat; Fig. 3.1), but there appear to be no reports of similar work undertaken on barley.

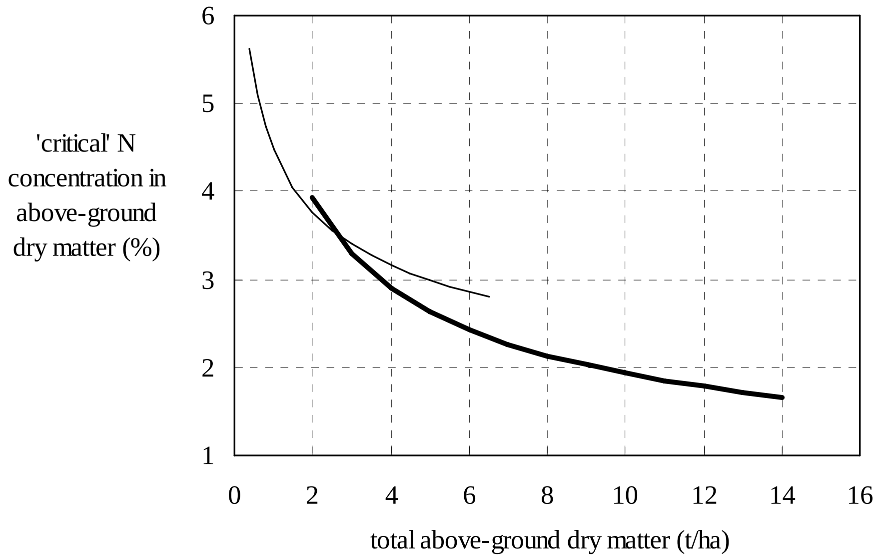


Fig. 3.1 Critical N dilution curves for crops of wheat (bold line; Justes et al., 1994) and oilseed rape (fine line; Colnenne et al., 1998) before grain filling.

The theoretical basis for expecting grain tissues also to show a critical N concentration is weaker than for vegetative tissues because grains do not represent the whole crop, and their major function is assimilate storage rather than photosynthesis. However, a large and relatively stable proportion of the N taken into the canopy is subsequently redistributed to the grain (Sylvester-Bradley *et al.*, 2008), and optimum canopy size relates to the yield potential of the particular variety-environment combination in question (Sylvester-Bradley & Kindred, 2009), so grain N concentrations with optimum N supplies might remain fairly constant over a range of yield levels.

If it is assumed that harvest indices remain stable across a range of yield levels, the relationships for vegetative crops (Fig. 3.1) can be used to derive expected critical N concentrations for both wheat grain and rape seed (Fig. 3.2). These show relatively small ranges (<1%N) for wide ranges of yields, predicted N concentrations being 3% at 5 t/ha oilseed rape DM and 2% at 10 t/ha wheat grain DM. Hence, given that large datasets are available from past N response experiments, it seems important to test the extent to which grain N concentrations for optimally fertilised crops show any consistency.

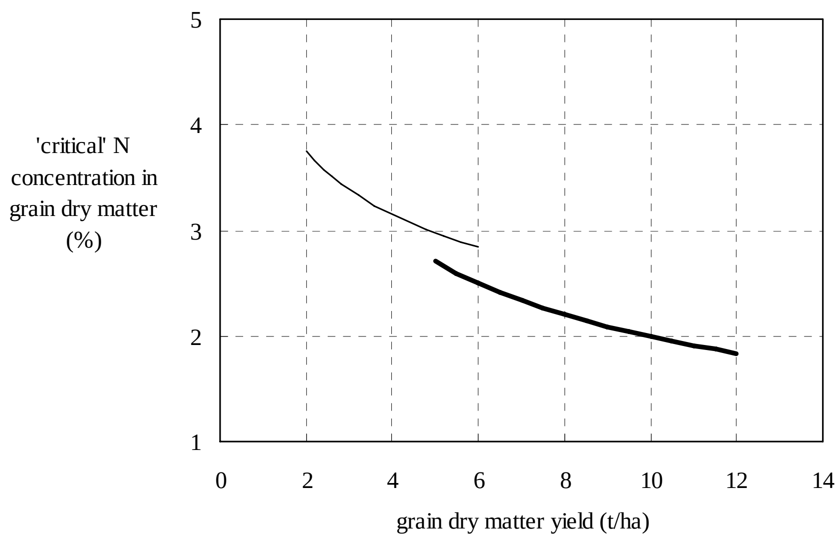


Fig. 3.2 Critical N dilution curves predicted from Fig. 1 for wheat grain (bold line) assuming harvest indices are 0.5 for DM and 0.7 for N, and rape seed (fine line) assuming harvest indices are 0.4 for DM and 0.5 for N.

Notwithstanding the indirect theoretical background and the lack of documentary evidence, grain N analysis has been adopted widely as a retrospective check on N management by UK wheat growers. This has been driven in particular by a need to demonstrate responsible N management to Environment Agency inspectors in Nitrate Vulnerable Zones, an advantage being that grain N data can be presented as independent and auditable. A further use for grain N analysis may arise in the emerging UK biofuels industry, where feedstock producers will need to demonstrate that their N management has reduced greenhouse gas (GHG) emissions (Sylvester-Bradley & Kindred, 2008; Kindred *et al*., 2008); since fertiliser N constitutes the majority of the GHG costs of crop production, good N management is critical to GHG savings. Hence a resolution of how closely grain N concentrations relate to optimal N management, and what levels of certainty should be applied to any relationships, has become important both for commercial purposes, as well as to improve theoretical explanation of optimum crop nutrition.

4. Experimental Data and Analysis

4.1 Data

Seven datasets (Table 4.1) were collated comprising replicated Nitrogen (N) response experiments that had been carried out using five or six N fertiliser treatments (including nil N), and had included grain yield (t/ha 85% DM) and grain N concentration (100% DM) measurements. For the purposes of this study, an experiment comprises replicated data for a particular cultivar at a particular site.

Table 4.1 Sources of data used in this project, years, sites and crops on which experiments were carried out (ww = winter wheat, wb = winter barley, sb = spring barley, osr = oilseed rape).

Name of dataset	**# Exp'ts used**	**Years**	**Region**	**Crops**	**Reference to experimental detail**
Nitric database	297	1981-93	UK	ww, wb, sb, osr	Goodlass *et al.* (2002)
Optimising N for modern cereal crops	185	2005-07	UK	ww, sb	Sylvester-Bradley *et al.* (2008)
N management for new group 1 & 2 wheat varieties	35	2003-05	England	ww	Dampney *et al.* (2006a)
Crop response to different N fertiliser materials	44	2004-05	UK	ww, wb	Dampney *et al.* (2006b)
Canopy management & late N to improve OSR yield	22	2006-07	England	osr	Berry and Spink (2009)
Danish N response experiments	443	1988-2008	Denmark	ww	Pedersen (2008)
Scottish data	13	2007	Scotland	ww, sb	See Appendix A

Table 4.2 Definition of soil codes for Danish winter wheat experiments

Soil index no.	Percent clay	Percent coarse sand	Percent organic matter	No. experiments
1	0-5	>50	<10	17
2	0-5	<50	<10	12
3	5-10	>50	<10	19
4	5-10	<50	<10	68
5	10-15	>50	<10	30
6	10-15	<50	<10	118
7	15-25		<10	110
8	25-40		<10	8
9	>40		<10	1
10	Lime		<10	4
11	Organic		>10	7
12	Special			2

For the majority of experiments, additional information about the experiments was collected, namely: the harvest year of the experiment; the crop at the site immediately prior to the experiment (cereal or break); the crop type (breadmaking or feed for wheats, malting or feed for barley); and the soil type. For UK data, five soil categories were used: sand, shallow, medium, clay and silt. The soil types associated with the Danish data were split into twelve categories which could not easily be allocated to the UK soil categories so were considered 'as is' (Table 4.2).

Data were then separated into different crops: UK winter wheat, Danish winter wheat, winter barley, spring barley and oilseed rape.

4.2 Data analysis

4.2.1 Fitting N response curves and deriving economic optimum N rates

The fitting of functions to the grain yield and N concentration data had already been carried out on four of the seven datasets. There were some small differences in methods used but a thorough check of the data ensured that the parameters estimated were appropriate for use as part of this study. The method below describes the analysis carried out on all experiments.

The response of yield to N was estimated for each experiment using the linear plus exponential function (LEXP). This has been used as the standard method since a comparison of approaches by George (1984), including in the preparation of RB209.

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

where y is yield in t/ha at 85%DM, N is total fertiliser N applied in kg/ha, and a, b, c and r are parameters determined by statistical fitting. Occasionally there is a difficulty in estimating the parameter r. Therefore, if r was outside an acceptable range, the function was re-fitted using an r value of 0.99.

Optimum N rates (Nopt) were then derived from the fitted LEXP parameters using:

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

where k is the breakeven price ratio between fertiliser N (£/kg) and grain (£/tonne). The breakeven ratios used in this study were 5 for cereals and 2.5 for oilseed rape, so that direct comparisons could be made with the new RB209 revision (to be published in 2009). Standard errors (se) of each Nopt estimate were determined, and experiments were discarded if this was greater than 120.

A grain N (%) response curve was then fitted to the data from each experiment. The method differed among the datasets. For example, the 'Optimising N for modern cereal crops' data were fitted either with a Normal Type curve with Depletion or a straight line function, depending on which fitted the data better (by choosing the smaller Residual Mean Squares of the two fits). The function for the normal with depletion curve is:-

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

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

The straight line function is:-

$$\mathrm{N}\% = a + b.\mathrm{N}$$

Gompertz curves were used on other datasets, for example, the Nitric database. The Gompertz function is:

$$\mathrm{N}\% = a + c * \mathrm{EXP}(-\mathrm{EXP}(-b * (\mathrm{N}-m)))$$

where *a, b, c* and *m* are parameters determined by fitting, and N is applied N (kg/ha)

Grain N% estimates were then derived for each Nopt estimate.

4.2.2 Secondary analysis of datasets

Forward stepwise all-subsets regression analyses were carried out on the grain N% at Nopt of each dataset separately using Genstat 11 (VSN International, 2008), to determine the important factors that affect grain N% at Nopt. The explanatory data included all or a selection of year, previous crop, crop type and soil type, depending on the crop being analysed.

Fitted grain N% was calculated for a range of fixed N amounts, and these were analysed to give means and standard deviations. Fitted values were excluded where these would have been outside the range of N amounts tested.

The slopes of the grain N% curves around the optimum (from minus to plus 50 kg N/ha from the optimum) were determined for each experiment from the fitted curves. Experiments were excluded where minus to plus 50 kg N/ha from the optimum was outside the range of N amounts tested.

Forward stepwise all-subsets regression analysis was again used to determine the most important factors affecting the slopes.

Grain N% at Nopt data were plotted against Nopt for each crop type and linear or quadratic functions were fitted where appropriate.

5. Results

5.1 Winter wheat

5.1.1 UK experiments

The overall average grain N concentration at the optimum N fertiliser rate (calculated using a 5:1 break even ratio) was 2.02%. This was associated with an average optimum fertiliser rate of 156 kg N/ha. Average fitted grain N% at fixed N amounts ranged from 1.60% at 0 kg N/ha to 2.30% at 300 kg N/ha (Table 5.1).

Information about crop type (breadmaking or feed), previous crop (cereal or break), soil type and year were included in a regression analysis to investigate which were important factors in determining grain N% at the optimum N rate. When a forward stepwise all-subsets regression was carried out, the model that explained most of the variation included all of the available factors:

Constant + Year + Crop type + Soil type + Previous crop [R^2 (adj.) = 24.9]

Although Year was included in the model, the variation in grain N% among years was small and only one out of 16 years was identified as being different. Since there were only four experiments included in that year, and all at one site, Year effects are not presented in this report.

The average grain N concentration at the optimum N rate for breadmaking varieties (2.15%) was 0.17% higher than for feed varieties (1.98%; Table 5.1). Indeed, the grain N concentrations of breadmaking varieties were higher than those of the feed varieties at all fertiliser levels from 0 to 300 kg N/ha. Experiments that had been grown after a cereal crop had, on average, slightly (0.08%) higher grain N concentrations at the optimum N rate and also higher N concentrations at all other fertiliser levels than those grown after a break crop (Table 5.1).

Soil type appeared to interact with previous crop and crop type effects. For example, sandy soils gave the highest grain N% at the optimum N rate of all the soil types with breadmaking varieties following a break crop, but the lowest grain N% with feed varieties following a break crop (Table 5.1).

Table 5.1 Fitted mean grain nitrogen concentrations (%) at different levels of fertiliser N (including the optimum N level) applied to UK winter wheat experiments using breadmaking or feed varieties grown after a cereal or break crop on different soil types.

Prev. crop	Crop type	Soil type	No. expts.	Mean Nopt kg/ha	Opt. N	0	50	100	150	200	250	300
					Mean grain N% at levels of fertiliser N applied (kg N/ha)							
					Previous crop effects							
Break			163	128	1.98	1.63	1.69	1.84	2.03	2.17	2.26	2.32
Cereal			172	183	2.06	1.58	1.63	1.76	1.94	2.11	2.22	2.29
					Crop type effects							
	Bread		82	175	2.15	1.70	1.75	1.89	2.06	2.21	2.30	2.36
	Feed		255	150	1.98	1.58	1.63	1.77	1.96	2.11	2.22	2.29
					Soil type effects							
		Sand	30	131	1.93	1.55	1.62	1.75	1.96	2.15	2.28	2.36
		Shallow	42	202	2.12	1.59	1.62	1.75	1.93	2.11	2.21	2.27
		Medium	63	142	2.02	1.69	1.74	1.86	2.01	2.15	2.25	2.32
		Clay	152	143	1.99	1.60	1.67	1.82	2.01	2.15	2.24	2.30
		Silt	49	191	2.06	1.55	1.59	1.74	1.94	2.10	2.22	2.28
					Prev. crop x crop type x soil type interactions							
Break	Bread	Sand	4	130	2.22	1.95	1.97	2.04	2.24	2.41	2.49	2.53
		Shallow	5	202	2.09	1.58	1.63	1.78	1.96	2.10	2.18	2.22
		Medium	2	101	2.28	2.05	2.05	2.10	2.17	2.21	2.23	2.23
		Clay	20	139	2.16	1.69	1.78	1.98	2.18	2.31	2.39	2.43
		Silt	6	112	2.00	1.84	1.83	1.91	2.07	2.20	2.30	2.37
	Feed	Sand	17	125	1.81	1.44	1.53	1.68	1.92	2.13	2.28	2.37
		Shallow	11	173	2.00	1.51	1.57	1.74	1.93	2.06	2.14	2.18
		Medium	27	116	2.00	1.74	1.77	1.91	2.05	2.17	2.25	2.31
		Clay	54	102	1.89	1.62	1.69	1.84	2.02	2.15	2.24	2.29
		Silt	17	177	2.02	1.52	1.57	1.73	1.93	2.11	2.23	2.30
Cereal	Bread	Sand	0									
		Shallow	7	213	2.18	1.77	1.74	1.79	1.93	2.16	2.26	2.30
		Medium	2	81	2.00	1.79	1.91	2.05	2.18	2.27	2.34	2.40
		Clay	20	185	2.16	1.71	1.77	1.91	2.07	2.21	2.31	2.38
		Silt	14	248	2.20	1.49	1.53	1.69	1.89	2.07	2.19	2.26
	Feed	Sand	9	142	2.04	1.57	1.63	1.75	1.92	2.07	2.20	2.28
		Shallow	19	215	2.16	1.57	1.59	1.73	1.92	2.12	2.24	2.32
		Medium	31	171	2.02	1.62	1.68	1.78	1.95	2.11	2.24	2.33
		Clay	57	168	1.97	1.52	1.57	1.72	1.92	2.07	2.17	2.23
		Silt	12	184	2.00	1.50	1.58	1.74	1.92	2.07	2.17	2.25
All data			337	158	2.02	1.60	1.66	1.80	1.98	2.14	2.24	2.30

The variation associated with the grain N concentrations tended to decrease with increasing levels of fertiliser from 0 to 300 kg N/ha, i.e. as grain N concentrations increased (Table 5.2). This was also the case at the optimum N rate; breadmaking varieties with higher grain N concentrations than feed varieties had a lower standard deviation (by 0.03; Table 5.2). The same was true of experiments that followed a cereal *vs.* a break crop. Generally, the variation at the optimum N rates after cereal and break crops (average 183 & 128 kg N/ha) were similar to those found at fixed N rates of around 100-150 kg N/ha (Table 5.2), but this was not always the case; some standard deviations at the optimum were greater than those found for all the fixed fertiliser rates (0-300 kg N/ha).

Table 5.2 Standard deviations (s.d.) of mean grain N concentrations (Table 5.1) at different levels of fertiliser N (including the optimum N level) applied to UK winter wheat experiments using breadmaking or feed varieties grown after a cereal or break crop on different soil types.

Prev. crop	Crop type	Soil type	No expts	Standard deviation of grain N% at levels of fertiliser N (kg N/ha) Opt. N	0	50	100	150	200	250	300
				Previous crop effects							
Break			163	0.213	0.256	0.258	0.248	0.209	0.186	0.185	0.200
Cereal			172	0.203	0.198	0.197	0.194	0.192	0.176	0.165	0.167
				Crop type effects							
	Bread		82	0.174	0.231	0.224	0.215	0.200	0.167	0.152	0.153
	Feed		255	0.204	0.221	0.226	0.222	0.200	0.182	0.179	0.189
				Soil type effects							
		Sand	30	0.301	0.290	0.312	0.303	0.253	0.221	0.207	0.212
		Shallow	42	0.165	0.161	0.162	0.150	0.161	0.141	0.142	0.153
		Medium	63	0.194	0.261	0.254	0.254	0.230	0.205	0.194	0.198
		Clay	152	0.212	0.226	0.228	0.221	0.203	0.189	0.187	0.197
		Silt	49	0.158	0.175	0.169	0.172	0.162	0.134	0.112	0.103
				Prev. crop x crop type x soil type interactions							
Break	Bread	Sand	4	0.335	0.408	0.410	0.403	0.333	0.295	0.274	0.268
		Shallow	5	0.074	0.052	0.145	0.166	0.161	0.159	0.159	0.164
		Medium	2	0.099	0.429	0.382	0.262	0.120	0.004	0.072	0.118
		Clay	20	0.181	0.212	0.215	0.196	0.148	0.116	0.113	0.121
		Silt	6	0.159	0.191	0.206	0.230	0.221	0.160	0.129	0.133
	Feed	Sand	17	0.269	0.196	0.246	0.275	0.238	0.209	0.191	0.184
		Shallow	11	0.097	0.103	0.180	0.179	0.144	0.121	0.110	0.109
		Medium	27	0.165	0.290	0.270	0.253	0.203	0.175	0.177	0.197
		Clay	54	0.176	0.247	0.254	0.235	0.203	0.197	0.214	0.243
		Silt	17	0.176	0.152	0.178	0.190	0.163	0.129	0.108	0.101
Cereal	Bread	Sand	0								
		Shallow	7	0.145	0.168	0.189	0.178	0.217	0.122	0.091	0.085
		Medium	2	0.402	0.400	0.411	0.388	0.380	0.406	0.457	0.520
		Clay	20	0.191	0.201	0.166	0.161	0.166	0.151	0.132	0.129
		Silt	14	0.063	0.094	0.072	0.101	0.105	0.093	0.081	0.075
	Feed	Sand	9	0.231	0.242	0.302	0.261	0.176	0.128	0.162	0.216
		Shallow	19	0.191	0.165	0.130	0.123	0.159	0.156	0.160	0.173
		Medium	31	0.207	0.197	0.212	0.234	0.241	0.227	0.207	0.192
		Clay	57	0.193	0.189	0.188	0.183	0.185	0.174	0.162	0.160
		Silt	12	0.129	0.143	0.128	0.148	0.168	0.157	0.125	0.099
All data			337	0.211	0.229	0.231	0.225	0.204	0.183	0.176	0.183

When the slopes of the grain N% curves around the optimum (+/- 50 kg N/ha from the optimum) were examined, the overall average slope was 0.30 grain N%

per 100 kg/ha N applied. This indicated that for every 0.1% difference in grain N% from the expected level, fertiliser applications should be adjusted by ~30 kg N/ha. Regression analysis showed that the slopes differed with crop type and soil type, but not previous crop. Breadmaking varieties generally had shallower slopes (0.25) than feed varieties (0.32; Table 5.3). The difference in slopes between soil types was mainly due to the curves for sandy soils, which were steeper (0.39) than those of other soil types: average 0.28 (Table 5.3).

Table 5.3 Mean slope of grain N concentration curves around the optimum N rate from UK winter wheat experiments grown on different soil types with breadmaking or feed varieties

Category	No. expts.	Mean slope *grain N% per 100 kg N/ha*	SD
Crop Type			
Bread	82	0.250	0.1167
Feed	255	0.315	0.1431
Soil Type			
Sand	30	0.386	0.1709
Shallow	42	0.275	0.0963
Medium	63	0.277	0.1567
Clay	152	0.309	0.1305
Silt	49	0.264	0.1358
All data	337	0.299	0.1398

Grain N concentrations at the optimum N rate for all UK winter wheat experiments were plotted against their optimum N rates and a linear trendline fitted (Fig. 5.1a). A significant ($P < 0.001$) positive relationship was found. The slope was 0.0013, i.e. for an increase of 100 kg N/ha in the optimum N rate, N% increased by 0.13%.

When instead fitted grain N concentrations at N rates of 0 to 300 kg N/ha of all experiments were plotted the linear relationship fitted (Fig. 5.1b) had a slope double that of the previous graph (0.0026). The fitted grain N% curves were then co-located to the optimum N rate for each experiment, and grain N concentrations plotted at N rates from minus to plus 150 kg N/ha from the optimum (again a range of 300 kg N/ha) (Fig. 5.1c). In this case, the slope of the linear relationship was 0.0024, similar to the slope in N% with fixed N rates, but greater than the slope with optimum N rates.

The relationship between grain N% at optimum N and the optimum N rate was unexpected, so further data analysis was undertaken to try to explain this. The experiments were split into those using breadmaking varieties and those using feed varieties due to their difference in grain N% at the optimum N rate. The data were then further split into previous crop and soil type categories: the earlier regression analysis had identified that clay soils differed most from the other soil types, and so these were also separated out.

A quadratic relationship fitted slightly better than a linear one when grain N% at the optimum N rate was plotted against optimum N rate of the breadmaking varieties (Fig. 5.2). No relationship between grain N% and optimum N rate was found for the experiments carried out on breadmaking varieties on non-clay soils after a break crop, but a significant ($P < 0.05$) positive linear relationship was found with experiments after cereals (Fig. 5.2). Significant ($P < 0.05$) quadratic relationships were found with the clay soil experiments (Fig. 5.2).

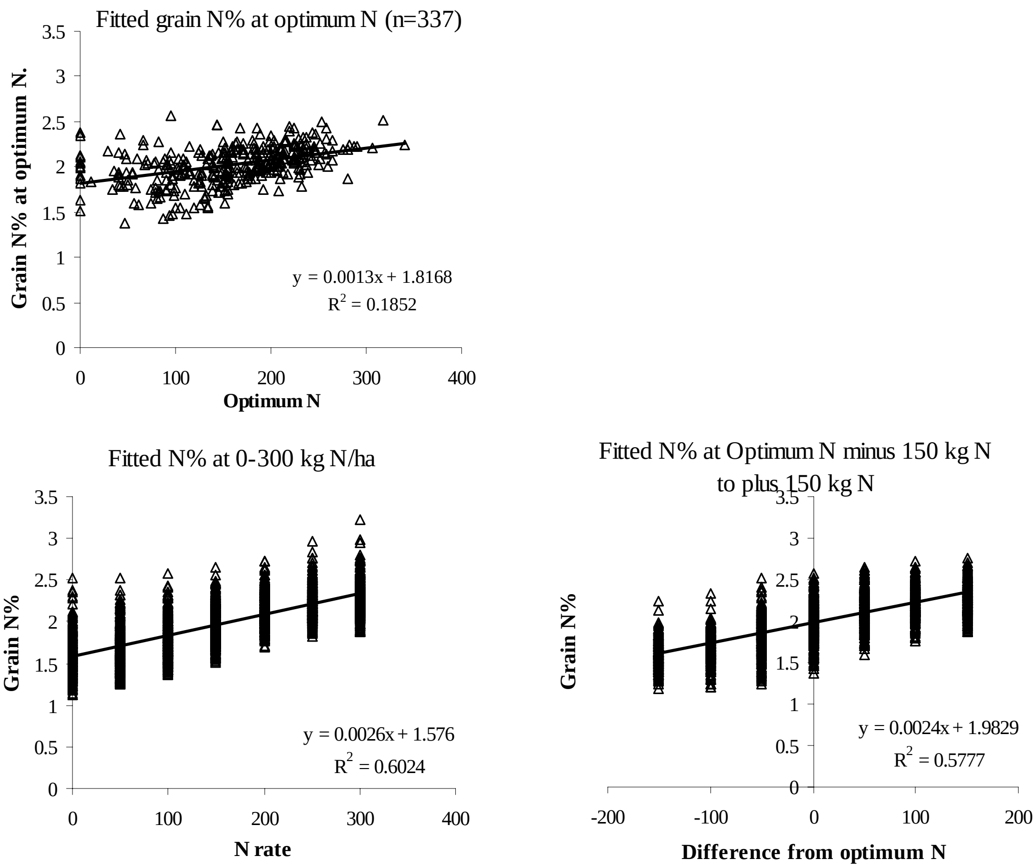


Fig. 5.1 *Fitted grain N concentrations of all UK winter wheat experiments at: optimum N rates; fixed fertiliser rates 0-300 kg N/ha; and fertiliser rates minus to plus 150 kg N/ha from the optimum.*

Quadratic relationships fitted best to the grain N% at optimum N data of the combined feed experiments, and those carried out after a break crop (Fig. 5.3). The feed experiments after cereal crops, though, showed significant ($P < 0.05$) linear relationships (Fig. 5.3).

The quadratic relationships found in Figs 5.2 and 5.3 were generally due to the grain N concentrations at low and 0 kg N/ha optima. These low optima occurred more often after a break crop, hence where cereals had been the previous crop, relationships were more often linear (Figs 5.2 & 5.3). Had the data been restricted to optima greater than 100 kg N/ha, linear relationships would have resulted.

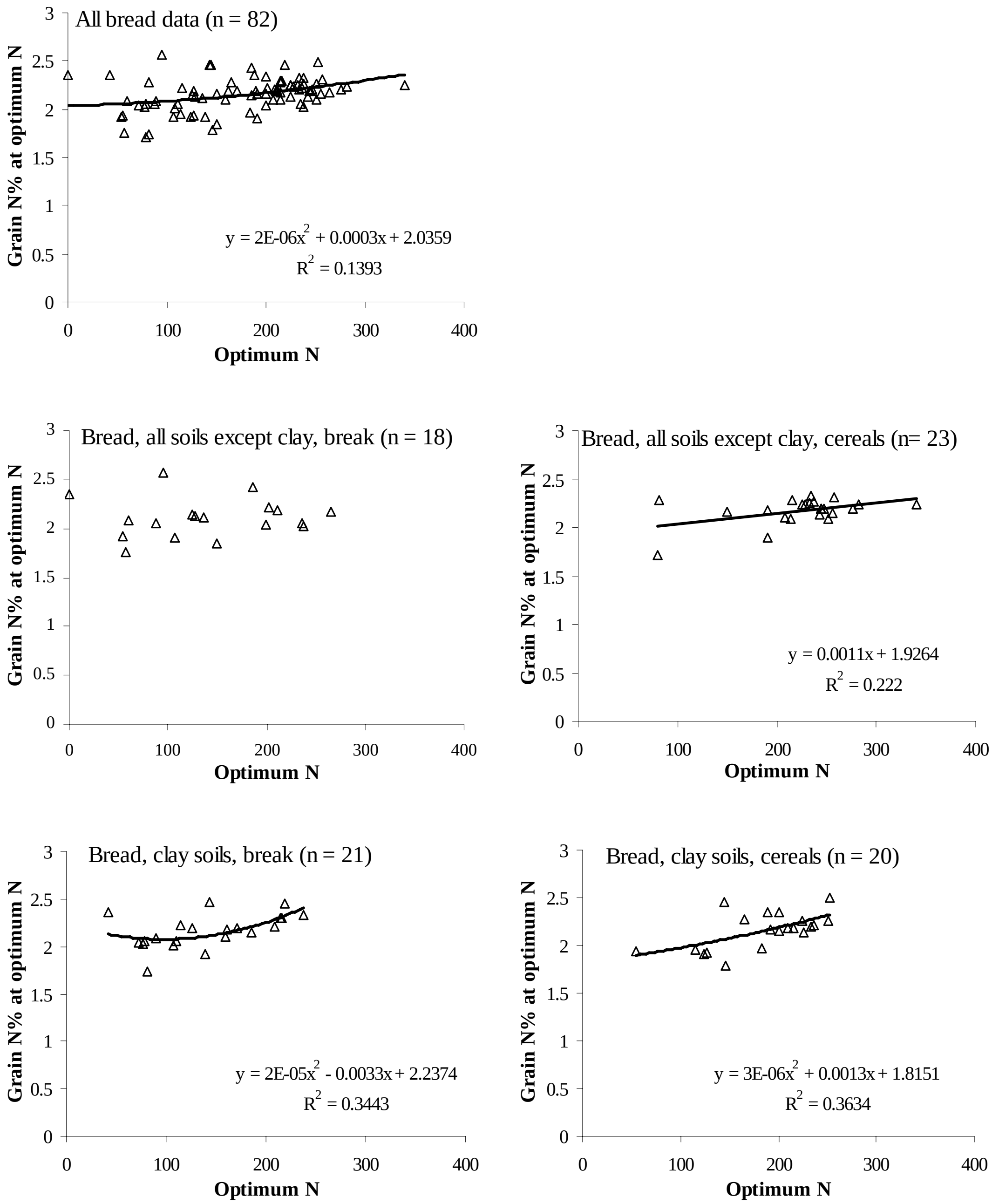


Fig. 5.2 Grain N concentrations at optimum fertiliser N levels of UK winter wheat experiments using breadmaking varieties grown after a break or cereal crop on different soil types.

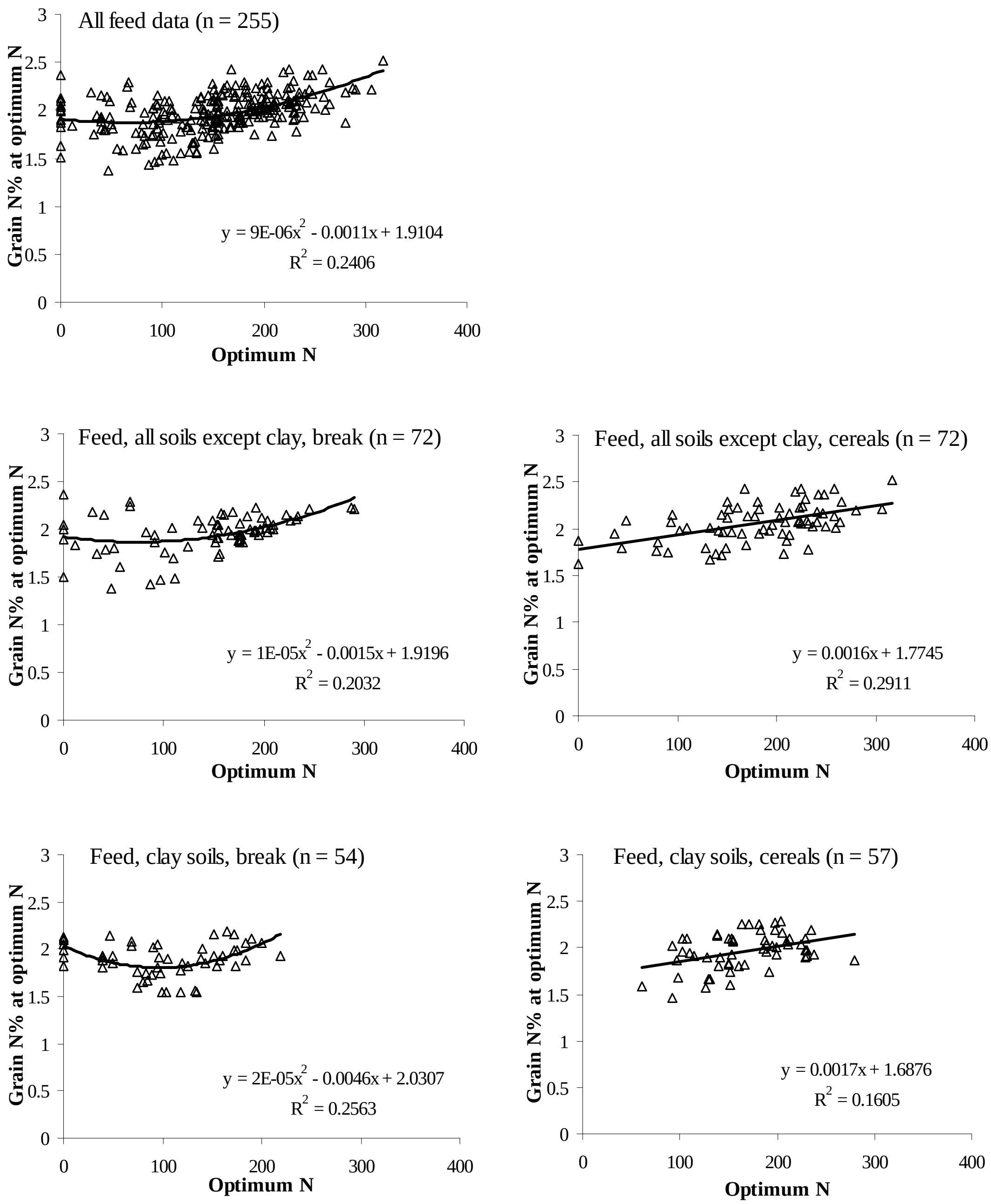


Fig. 5.3 Grain N concentrations at optimum fertiliser N levels of UK winter wheat experiments using feed varieties grown after a break or cereal crop on different soil types.

5.1.2 Danish experiments

On average, the grain N concentration at the optimum N rate was lower in the Danish than the UK winter wheat, at 1.62% (Table 5.4). The Danish grain N concentrations were also lower at each of the seven N levels from 0 to 300 kg N/ha.

A regression analysis of the Danish experiments included information about the years, previous crop, and soil types (Table 4.2) of the experiments. Information about the crop type (breadmaking or feed) was not available, although most Danish varieties are feed varieties.

The forward stepwise all-subsets regression showed that the model that explained most of the variation was:

Constant + Year + Soil type + Previous crop (R^2 adj. = 30.3%)

Overall, the grain N concentration at the optimum N rate was slightly higher after a cereal (1.65%) than after a break crop (1.60%; Table 5.4). This was associated with higher average optimum N rate for experiments after a cereal (178 kg N/ha) than after a break (144 kg N/ha); conversely grain N concentrations at fixed N rates of 0-300 kg N/ha were greater after a break than after a cereal (Table 5.4). These trends are similar to those found in the UK data.

Average grain N% at the optimum N rate of soil types differed by up to 0.22%, with soil type 2 (0-5% clay, <50% sand, <10% organic matter) giving the lowest grain N% at the optimum N rate (1.51%), and soil type 9 (> 40% clay, <10% organic matter) the highest (1.73%; Table 5.4), although this was based on one experiment only.

The variation associated with the grain N% data tended to increase with fixed N levels between 50 and 300 kg N/ha (Table 5.5), in contrast with the variation in the UK data which tended to do the opposite. The variation at the optimum N rate for a particular crop type or soil type category was generally within the range of standard deviations found for that category.

The average slope of the grain N% curves around optimum was 0.30, the same as was found in the UK data. Regression analysis showed that the slopes were affected by soil type, but not previous crop. A significant (P = 0.002) relationship between slope and soil code was found whereby slopes became shallower as clay contents increased (soil codes 1 to 9).

Table 5.4 Fitted mean grain nitrogen concentrations (%) at different levels of fertiliser N (including the optimum N level) applied to Danish winter wheat experiments grown after a cereal or break crop on different soil types. For an explanation of soil codes see Table 4.2.

Prev. crop	Soil type	N obs-erved	Mean Nopt kg/ha	Grain N% at levels of fertiliser N (kg N/ha)							
				Opt. N	0	50	100	150	200	250	300
				Previous crop effects							
Break		203	144	1.60	1.35	1.33	1.44	1.62	1.77	1.88	1.96
Cereal		240	178	1.65	1.35	1.30	1.40	1.56	1.71	1.82	1.90
				Soil type effects							
	1	17	141	1.58	1.35	1.30	1.41	1.63	1.85	1.99	2.08
	2	12	144	1.51	1.37	1.29	1.35	1.52	1.70	1.85	1.95
	3	19	156	1.63	1.41	1.36	1.44	1.62	1.79	1.93	2.16
	4	68	151	1.62	1.39	1.33	1.44	1.62	1.77	1.86	1.90
	5	30	151	1.62	1.35	1.31	1.42	1.61	1.77	1.89	2.01
	6	118	155	1.65	1.36	1.34	1.46	1.63	1.78	1.88	1.95
	7	110	185	1.60	1.29	1.26	1.34	1.50	1.65	1.76	1.83
	8	8	195	1.64	1.32	1.31	1.42	1.55	1.65	1.70	1.73
	9	1	224	1.73	1.39	1.40	1.46	1.56	1.68	1.78	1.87
	10	4	135	1.64	1.38	1.38	1.51	1.67	1.78	1.85	1.92
	11	7	77	1.66	1.55	1.60	1.69	1.79	1.86	1.92	2.16
	12	2	134	1.71	1.44	1.48	1.62	1.78	1.93	2.03	2.10
				Previous crop x Soil type interactions							
Break	1	15	133	1.57	1.34	1.30	1.42	1.65	1.86	2.01	2.09
	2	9	151	1.53	1.33	1.28	1.36	1.52	1.69	1.84	1.95
	3	12	145	1.59	1.34	1.29	1.40	1.61	1.81	1.98	2.16
	4	37	141	1.59	1.35	1.32	1.44	1.63	1.77	1.86	1.90
	5	14	133	1.58	1.37	1.33	1.45	1.63	1.78	1.88	1.95
	6	52	134	1.63	1.37	1.37	1.50	1.67	1.81	1.90	1.95
	7	31	159	1.57	1.32	1.31	1.41	1.54	1.69	1.80	1.86
	8	3	166	1.51	1.18	1.19	1.30	1.45	1.57	1.65	1.70
	11	1	64	1.74	1.74	1.74	1.74	1.74	1.76	1.93	3.39
	12	1	112	1.44	1.31	1.29	1.40	1.59	1.80	1.98	2.11
Cereal	1	2	195	1.69	1.40	1.28	1.33	1.52	1.72	1.87	1.96
	2	3	121	1.42	1.49	1.32	1.32	1.50	1.72	1.88	1.95
	3	7	176	1.68	1.53	1.47	1.51	1.63	1.74	1.84	2.17
	4	31	163	1.66	1.43	1.35	1.44	1.62	1.77	1.86	1.90
	5	16	167	1.65	1.33	1.29	1.40	1.58	1.76	1.91	2.06
	6	66	172	1.67	1.35	1.31	1.42	1.60	1.76	1.87	1.94
	7	79	196	1.61	1.28	1.23	1.32	1.48	1.63	1.74	1.81
	8	5	213	1.72	1.40	1.38	1.50	1.62	1.69	1.73	1.75
	9	1	224	1.73	1.39	1.40	1.46	1.56	1.68	1.78	1.87
	10	4	135	1.64	1.38	1.38	1.51	1.67	1.78	1.85	1.92
	11	6	80	1.65	1.52	1.58	1.69	1.80	1.87	1.92	1.95
	12	1	156	1.99	1.58	1.68	1.84	1.98	2.05	2.08	2.09
	All data	443	162	1.62	1.35	1.32	1.42	1.59	1.74	1.85	1.93

Table 5.5 Standard deviations (s.d.) of mean grain N concentrations (Table 5.4) at different levels of fertiliser N (including the optimum N level) applied to Danish winter wheat experiments grown after a cereal or break crop on different soil types. For an explanation of soil codes see Table 4.2.

Prev. crop	Soil type	N obs-erved	Standard deviation of grain N% at levels of fertiliser N (kg N/ha) Opt. N	0	50	100	150	200	250	300
			Previous crop effects							
Break		203	0.187	0.165	0.159	0.176	0.182	0.187	0.208	0.287
Cereal		240	0.154	0.168	0.152	0.164	0.169	0.164	0.173	0.270
			Soil type effects							
	1	17	0.145	0.136	0.136	0.130	0.152	0.209	0.260	0.297
	2	12	0.228	0.152	0.085	0.084	0.096	0.103	0.117	0.179
	3	19	0.190	0.169	0.156	0.170	0.192	0.193	0.201	0.562
	4	68	0.193	0.152	0.128	0.154	0.169	0.173	0.182	0.197
	5	30	0.168	0.176	0.193	0.182	0.162	0.154	0.199	0.407
	6	118	0.166	0.152	0.152	0.180	0.184	0.177	0.186	0.242
	7	110	0.154	0.172	0.147	0.151	0.155	0.156	0.168	0.193
	8	8	0.211	0.139	0.109	0.133	0.110	0.095	0.109	0.123
	9	1	*	*	*	*	*	*	*	*
	10	4	0.167	0.192	0.192	0.199	0.213	0.230	0.263	0.333
	11	7	0.183	0.268	0.204	0.139	0.097	0.093	0.109	0.560
	12	2	0.388	0.193	0.272	0.311	0.274	0.179	0.073	0.012
			Previous crop x soil type interactions							
Break	1	15	0.148	0.142	0.146	0.134	0.154	0.215	0.271	0.314
	2	9	0.248	0.147	0.095	0.095	0.110	0.112	0.118	0.193
	3	12	0.196	0.093	0.105	0.157	0.183	0.169	0.200	0.520
	4	37	0.187	0.152	0.129	0.157	0.172	0.183	0.199	0.216
	5	14	0.184	0.182	0.215	0.199	0.169	0.154	0.168	0.206
	6	52	0.186	0.173	0.177	0.200	0.198	0.191	0.201	0.229
	7	31	0.208	0.174	0.158	0.176	0.185	0.189	0.205	0.228
	8	3	0.303	0.129	0.027	0.056	0.011	0.090	0.132	0.149
	11	1	*	*	*	*	*	*	*	*
	12	1	*	*	*	*	*	*	*	*
Cereal	1	2	0.004	0.090	0.030	0.030	0.068	0.139	0.126	0.066
	2	3	0.165	0.104	0.051	0.038	0.045	0.089	0.134	0.161
	3	7	0.178	0.206	0.170	0.181	0.220	0.237	0.181	0.672
	4	31	0.196	0.144	0.128	0.152	0.168	0.163	0.163	0.176
	5	16	0.150	0.175	0.178	0.169	0.157	0.158	0.227	0.526
	6	66	0.149	0.134	0.124	0.155	0.165	0.162	0.174	0.253
	7	79	0.127	0.171	0.138	0.134	0.138	0.139	0.149	0.177
	8	5	0.105	0.042	0.068	0.102	0.087	0.076	0.099	0.119
	9	1	*	*	*	*	*	*	*	*
	10	4	0.167	0.192	0.192	0.199	0.213	0.230	0.263	0.333
	11	6	0.197	0.279	0.213	0.151	0.104	0.091	0.119	0.153
	All data	443	0.171	0.167	0.156	0.171	0.177	0.177	0.192	0.279

Table 5.6 Mean slope of grain N concentration curves around the optimum N rate (optimum N rate +/- 50 kg N/ha) from Danish winter wheat experiments grown on different soil types

Soil type	Percent clay	Percent coarse sand	N observed	Mean slope around optimum N rate	Standard deviation.
1	0-5	>50	17	0.385	0.1963
2	0-5	<50	12	0.305	0.1350
3	5-10	>50	19	0.333	0.1227
4	5-10	<50	68	0.314	0.1358
5	10-15	>50	30	0.318	0.1210
6	10-15	<50	118	0.310	0.1277
7	15-25		110	0.290	0.1271
8	25-40		8	0.163	0.0798
9	>40		1	0.231	*
10	Lime		4	0.217	0.0649
11	Organic		7	0.218	0.2056
12	Special		2	0.233	0.0433
All data			443	0.301	0.1355

When the grain N concentrations at the optimum N rate of the experiments carried out after a break crop were plotted against the optimum N rates, a significant ($P < 0.001$) positive relationship was found (Fig. 5.4) with a slope of 0.17% N compared to 0.13% for UK data.

Significant differences were found between soil types ($P < 0.05$) in the slopes of the N% responses around optimum N amounts (Fig. 5.4), with grain N concentrations increasing by 0.16% to 0.33% with a 100 kg/ha increase in N rate. There was an indication of shallower slopes with heavier soils.

A shallower (0.1% grain N increase with 100kg N/ha increase in optimum N), but still significant ($P < 0.001$) positive relationship between grain N% and optimum N rate was found when the experiments that followed a cereal were examined (Fig. 5.5). However, when the data was separated by soil type, only soil types 4 (5-10% clay, <50% sand), 6 (10-15% clay, <50% sand) and 7 (15-25% clay) showed significant ($P < 0.05$) positive relationships (Fig. 5.5).

Where they were significant, relationships between grain N% and the optimum N rate were always linear (Figs 5.4 and 5.5), differing from the UK data. The Danish experiments had fewer instances where the optimum N rate was less than 50 kg N/ha or 0 kg N/ha, which may explain this.

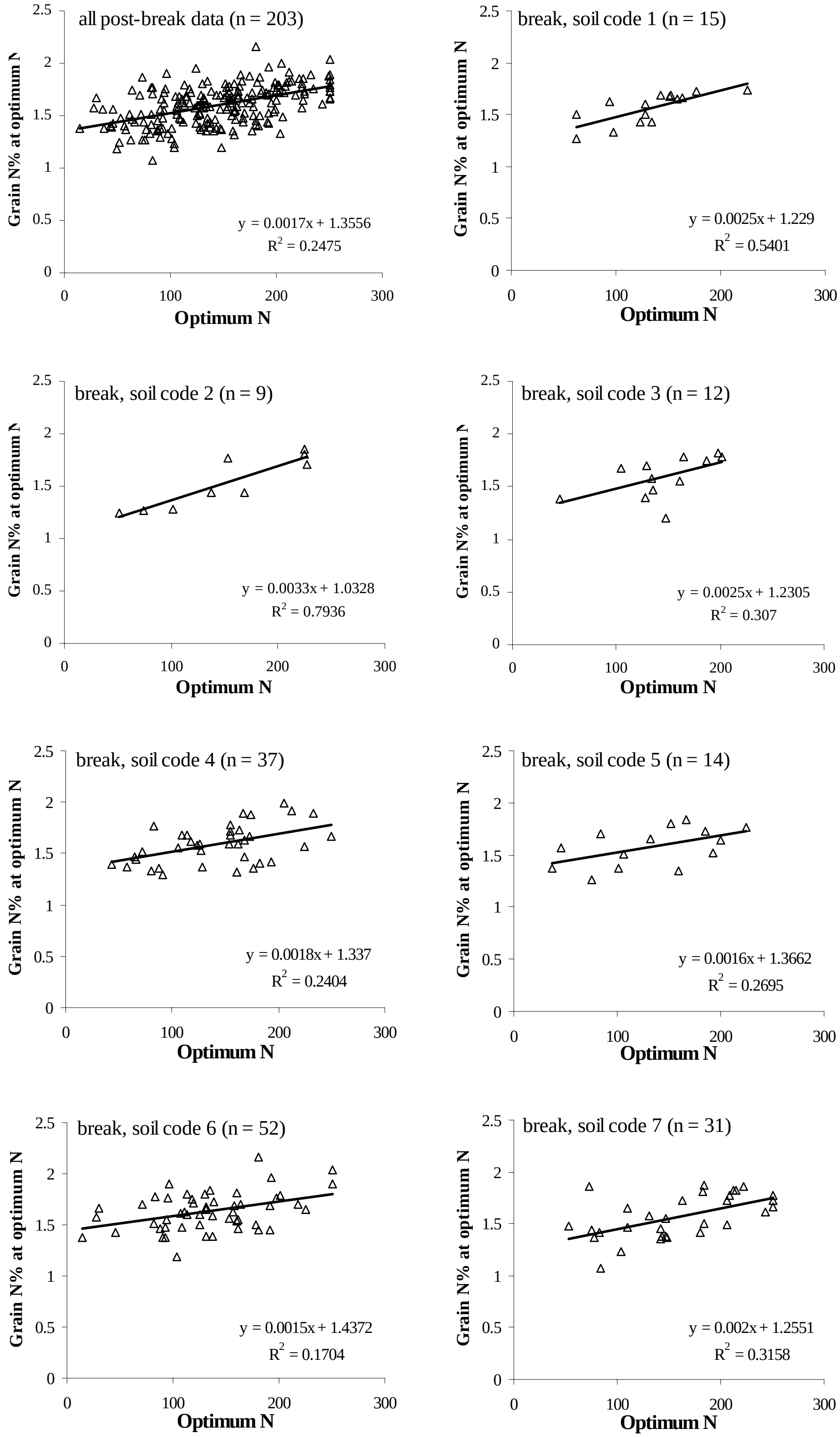


Fig. 5.4 Grain nitrogen concentrations at optimum fertiliser nitrogen levels of Danish winter wheat experiments grown after a break crop on different soil types. For an explanation of the soil codes see Table 4.2.

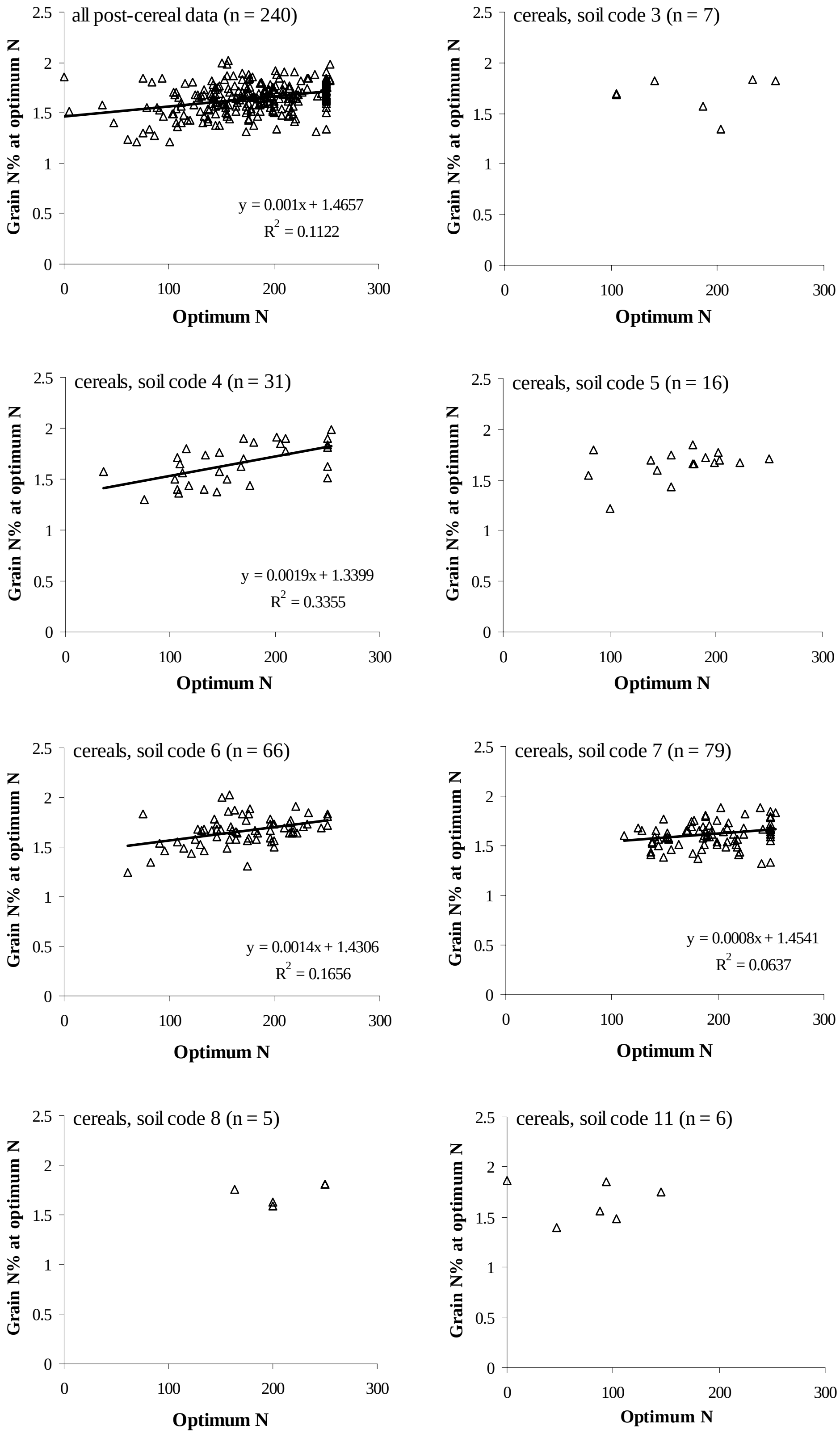


Fig. 5.5 Grain nitrogen concentrations at optimum fertiliser nitrogen levels of Danish winter wheat experiments grown after a cereal crop on different soil types. For an explanation of the soil codes see Table 4.2.

5.2 Spring Barley

Nearly one hundred spring barley experiments were included in the analysis, although there were no experiments carried out on silty soils, and only one experiment carried out on clay soil. The overall average grain N concentration at the optimum N rate was 1.90%. Average fitted grain N concentrations increased with fixed rates of applied N from 1.55% at 0 kg N/ha to 2.27% at 300 kg N/ha (Table 5.7).

Information about the years, previous crop, crop types (malting or feed) and soil types of the experiments was included in a regression analysis. When the forward stepwise all-subsets regression was carried out on the spring barley data, the model that explained most of the variation was:

Constant + Year + Soil type + Crop type (malting or feed) (R^2 adj. = 22.7%)

Including previous crop as a factor did not improve the model so previous crops have not been separated in the tables.

The average grain N concentration at the optimum N rate was higher for feed (1.92%) than malting (1.87%) barleys. Grain N concentrations of the two crop types were similar up to a fixed N rate of 150 kg N/ha, beyond which the feed varieties had higher grain N concentrations (Table 5.7).

Average N% at the optimum N rate was the same for shallow and sandy soils because their different responses to N application compensated for their different N optima (shallow = 115 kg N/ha; sand = 155 kg N/ha) (Table 5.7). The medium soil type gave smaller grain N concentrations but, unlike the shallow and sandy soils, grain N concentrations were not less for malting varieties (Table 5.7).

The variation in the overall mean grain N% data at the optimum N rate was generally less than at fixed N rates of 0 to 300 kg N/ha (Table 5.8). Only in the case of shallow soils was the standard deviation associated with the N% at the optimum N rate greater than that at most of the fixed N levels.

The average slope of the grain N% curves around the optimum N rates was 0.31% per 100 kg N/ha. Regression analysis showed that the slope was not affected by soil type, previous crop or crop type. Therefore, for every 0.1% that a crop deviates from the expected grain N%, fertiliser rates should be adjusted by approximately 30 kg N/ha.

Table 5.7 Fitted mean grain nitrogen concentrations (%) at different levels of fertiliser N (including the optimum N level) applied to spring barley experiments using feed and malting varieties grown on different soil types

Crop type	Soil type	N observed	Mean Nopt Kg/ha	Opt. N	Grain N% at levels of fertiliser N applied (kg N/ha) 0	50	100	150	200	250	300
							Crop type effects				
Feed		45	119	1.92	1.57	1.67	1.84	2.02	2.17	2.27	2.35
Malting		52	113	1.87	1.54	1.66	1.84	2.01	2.11	2.17	2.21
							Soil type effects				
	Sand	17	156	1.94	1.44	1.52	1.70	1.90	2.04	2.13	2.18
	Shallow	21	115	1.94	1.59	1.70	1.90	2.10	2.24	2.33	2.39
	Medium	58	104	1.87	1.57	1.69	1.86	2.01	2.13	2.20	2.26
	Clay	1	105	2.00	1.75	1.79	1.97	2.18	2.30	2.35	2.38
							Crop type x soil type interactions				
Feed	Sand	8	158	2.01	1.50	1.55	1.73	1.95	2.11	2.21	2.26
	Shallow	9	128	1.99	1.58	1.71	1.88	2.06	2.19	2.29	2.36
	Medium	27	104	1.87	1.59	1.69	1.85	2.03	2.17	2.28	2.37
	Clay	1	105	2.00	1.75	1.79	1.97	2.18	2.30	2.35	2.38
Malting	Sand	9	154	1.88	1.40	1.50	1.68	1.86	1.99	2.06	2.11
	Shallow	12	105	1.90	1.59	1.69	1.91	2.13	2.27	2.36	2.41
	Medium	31	104	1.86	1.56	1.70	1.87	2.01	2.09	2.13	2.16
	Clay	0	*	*	*	*	*	*	*	*	*
	All data	97	115	1.90	1.55	1.66	1.84	2.01	2.14	2.22	2.27

Table 5.8 Standard deviations (s.d.) of mean grain N concentrations at different levels of fertiliser N (including the optimum N level) applied to spring barley experiments using feed and malting varieties grown on different soil types.

Crop type	Soil type	N observed	Standard deviations of grain N% at levels of fertiliser N (kg N/ha) Opt. N	0	50	100	150	200	250	300
						Crop type effects				
Feed		45	0.237	0.273	0.291	0.293	0.297	0.304	0.336	0.409
Malting		52	0.220	0.223	0.267	0.262	0.253	0.265	0.299	0.346
						Soil type effects				
	Sand	17	0.264	0.293	0.304	0.274	0.268	0.276	0.296	0.325
	Shallow	21	0.190	0.191	0.171	0.170	0.183	0.194	0.199	0.207
	Medium	58	0.230	0.246	0.292	0.298	0.295	0.307	0.355	0.439
	Clay	1	*	*	*	*	*	*	*	*
						Crop type x soil type interactions				
Feed	Sand	8	0.303	0.389	0.383	0.363	0.372	0.382	0.389	0.396
	Shallow	9	0.157	0.215	0.199	0.189	0.168	0.154	0.148	0.158
	Medium	27	0.236	0.261	0.293	0.306	0.318	0.329	0.377	0.480
	Clay	1	*	*	*	*	*	*	*	*
Malting	Sand	9	0.227	0.186	0.233	0.183	0.135	0.129	0.179	0.248
	Shallow	12	0.208	0.181	0.157	0.161	0.195	0.220	0.232	0.242
	Medium	31	0.228	0.236	0.297	0.296	0.279	0.286	0.324	0.380
	Clay	0	*	*	*	*	*	*	*	*
	All data	97	0.228	0.247	0.277	0.275	0.273	0.284	0.319	0.382

When the grain N concentrations of all the feed barley experiments were plotted against their associated optimum N rates, no significant relationship was found (Fig. 5.6). Nor were there any significant relationships when the feed barley data were split into the different soil types (Fig. 5.6). When the same graphs were plotted with the malting barley data (Fig. 5.7) again there was no significant relationship found in the combined data. However, when data were split into the different soil types, the shallow soil data showed a significant ($P<0.05$) increase in grain N% with an increase in optimum N rate, although the slope was very small (Fig. 5.7).

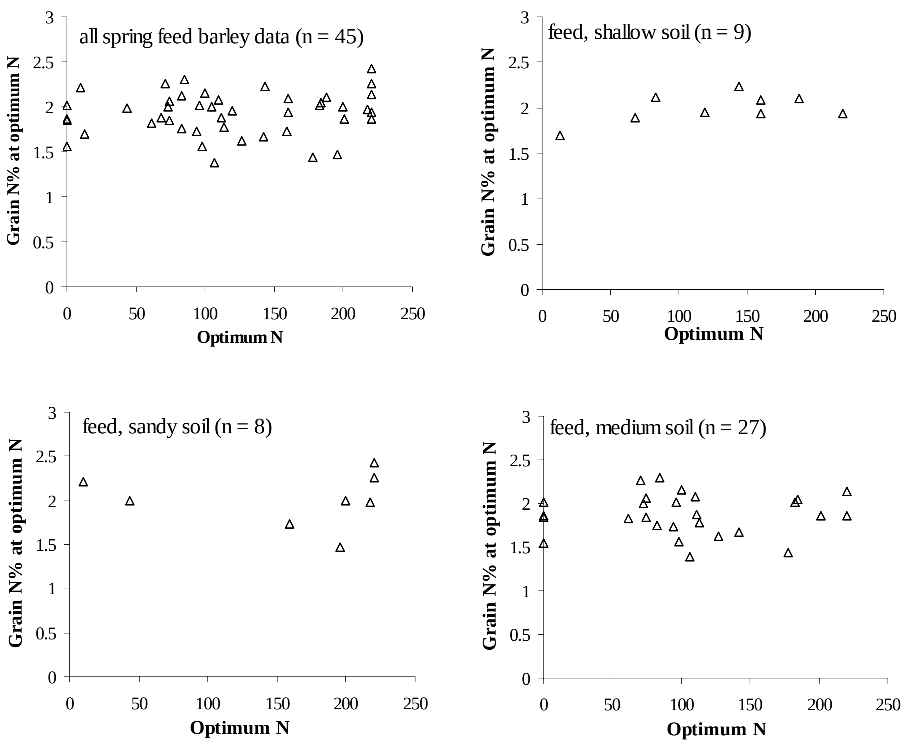


Fig. 5.6 Grain nitrogen concentrations at optimum fertiliser nitrogen levels of spring feed barley experiments grown on different soil types.

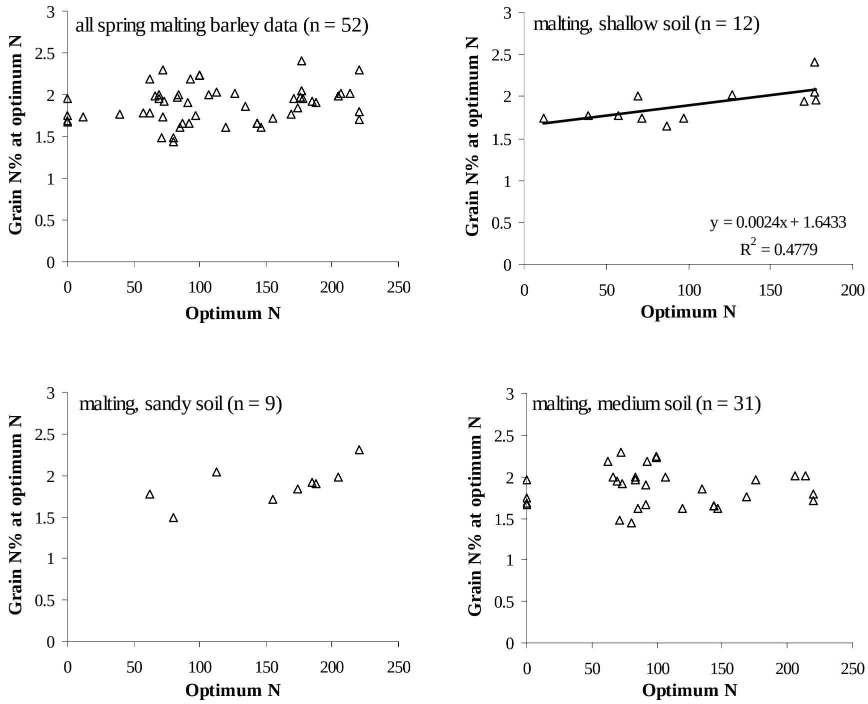


Fig. 5.7 *Grain N concentrations at optimum fertiliser N levels of spring malting barley experiments grown on different soil types.*

5.3 Winter Barley

The average grain N% at the optimum N rate of the 75 winter barley experiments was 1.89% (Table 5.9), very similar to the spring barley average (1.90%). The average optimum N rate associated with this grain N% was 148 kg N/ha. A proportion of the winter barley experiments were missing some or all experimental information so a forward stepwise all-subsets regression was carried out on the winter barley data just using the 57 experiments where information about the crop type and/or soil type and/or previous crop was available. The model that explained most of the variation was:

Constant + Crop type + Previous crop + Soil type (R^2 adj. = 20.9%)

Table 5.9 Fitted mean grain nitrogen concentrations (%) at different levels of fertiliser N (including the optimum N level) applied to winter barley experiments using feed and malting varieties grown on different soil types after a cereal or break crop.

Prev. crop	Crop type	Soil type	N observed	Mean Nopt Kg/ha	Opt. N	Grain N% at levels of fertiliser N (kg N/ha) 0	50	100	150	200	250	300
						Previous crop effects						
Break			13	114	1.76	1.40	1.47	1.65	1.93	2.21	2.42	2.56
Cereal			33	133	1.88	1.51	1.57	1.72	1.96	2.19	2.36	2.47
						Crop type effects						
	Feed		34	122	1.92	1.59	1.66	1.82	2.04	2.24	2.38	2.48
	Malting		13	149	1.76	1.28	1.32	1.46	1.76	2.11	2.37	2.54
						Soil type effects						
		Sand	25	126	1.88	1.46	1.55	1.73	1.99	2.23	2.43	2.56
		Shallow	5	138	1.91	1.57	1.63	1.77	1.99	2.21	2.35	2.42
		Medium	21	126	1.80	1.49	1.54	1.68	1.91	2.14	2.30	2.39
		Clay	2	160	1.98	1.68	1.68	1.72	1.92	2.12	2.23	2.27
		Silt	3	119	1.94	1.70	1.78	1.88	2.03	2.22	2.40	2.56
						Prev. crop x crop type x soil type interactions						
Break	Feed	Sand	6	99	1.84	1.51	1.61	1.80	2.04	2.24	2.39	2.48
	Malting	Sand	1	145	1.65	1.28	1.31	1.42	1.68	2.06	2.47	2.85
		Medium	5	135	1.67	1.24	1.26	1.43	1.78	2.15	2.41	2.56
Cereal	Feed	Sand	10	128	1.91	1.48	1.57	1.76	2.03	2.27	2.46	2.60
		Shallow	3	122	1.93	1.69	1.73	1.87	2.09	2.31	2.43	2.48
		Medium	7	118	1.91	1.62	1.68	1.83	2.04	2.22	2.34	2.42
		Clay	2	160	1.98	1.68	1.68	1.72	1.92	2.12	2.23	2.27
		Silt	1	124	1.75	1.63	1.63	1.67	1.88	2.19	2.46	2.63
	Malting	Sand	4	165	1.96	1.33	1.40	1.55	1.84	2.18	2.43	2.59
		Shallow	1	179	1.85	1.58	1.58	1.60	1.73	1.94	2.11	2.21
		Medium	2	139	1.55	1.15	1.17	1.30	1.62	1.98	2.23	2.39
		All data	75	131	1.89	1.52	1.59	1.75	1.97	2.18	2.34	2.45

The average grain N% at the optimum N rate was lower for malting (1.76%) than feed (1.92%) experiments (Table 5.9), consistent with the spring barley results. The experiments following a cereal gave a higher (1.88%) average grain N% than those following a break crop (1.76%). In both cases grain N concentrations at the optimum were also lower at all fixed N levels (0 to 300 kg N/ha; Table 5.9). On average, the medium soil type experiments gave lowest grain N% at the optimum N rate (1.80%) and the clay experiments the highest (1.98%), although this figure was based on only two experiments (Table 5.9).

Overall, the variation associated with the grain N concentrations at the N optima of winter barley was better than with fixed N rates. Differences in variation did not appear to relate to grain N% or increasing fertiliser N input (Table 5.10) as has been found in other crops.

The average slope of the grain N% curves around the optimum N rate for the winter barley was 0.42% per 100 kg N/ha (Table 5.11), steeper than any of the other crops examined. A regression analysis showed that the slope was affected by crop type and soil type, but not previous crop. The slope around the optimum for malting varieties was very steep (0.64) compared to the feed varieties (0.41; Table 5.11). The differences among the soil type slopes were due to the steep slopes of the sandy soil experiments (0.51) and the shallower slopes of the silty soils experiments (0.29; Table 5.11).

Table 5.10 Standard deviations (s.d.) of mean grain N concentrations at different levels of fertiliser N (including the optimum N level) applied to winter barley experiments using feed and malting varieties grown on different soil types after a cereal or break crop.

Prev. crop	Crop type	Soil type	N obs-erved	Standard deviations of grain N% at levels of fertiliser N (kg N/ha) Opt. N	0	50	100	150	200	250	300
				Previous crop effects							
Break			13	0.165	0.238	0.269	0.274	0.211	0.115	0.078	0.134
Cereal			33	0.158	0.214	0.217	0.237	0.235	0.225	0.241	0.271
				Crop type effects							
	Feed		34	0.139	0.216	0.215	0.209	0.193	0.183	0.199	0.228
	Malting		13	0.198	0.140	0.155	0.182	0.184	0.163	0.169	0.207
				Soil type effects							
		Sand	25	0.147	0.193	0.209	0.229	0.206	0.162	0.152	0.181
		Shallow	5	0.061	0.258	0.229	0.266	0.326	0.338	0.348	0.362
		Medium	21	0.202	0.264	0.275	0.272	0.227	0.198	0.218	0.248
		Clay	2	0.042	0.311	0.309	0.271	0.242	0.192	0.127	0.085
		Silt	3	0.229	0.060	0.142	0.200	0.180	0.137	0.140	0.131
				Prev. crop x crop type x soil type interactions							
Break	Feed	Sand	6	0.154	0.263	0.269	0.246	0.178	0.104	0.082	0.105
	Malting	Sand	1	*	*	*	*	*	*	*	*
		Medium	5	0.166	0.110	0.097	0.097	0.100	0.047	0.055	0.088
Cereal	Feed	Sand	10	0.153	0.188	0.192	0.186	0.155	0.130	0.125	0.143
		Shallow	3	0.069	0.194	0.234	0.323	0.403	0.417	0.452	0.484
		Medium	7	0.116	0.194	0.202	0.222	0.240	0.259	0.283	0.306
		Clay	2	0.042	0.311	0.309	0.271	0.242	0.192	0.127	0.085
		Silt	1	*	*	*	*	*	*	*	*
	Malting	Sand	4	0.100	0.119	0.170	0.275	0.297	0.246	0.216	0.219
		Shallow	1	*	*	*	*	*	*	*	*
		Medium	2	0.119	0.082	0.096	0.140	0.162	0.184	0.226	0.271
		All data	75	0.193	0.217	0.229	0.246	0.229	0.212	0.225	0.252

When the grain N% at the optimum N rate data from all winter barley experiments were plotted against their optimum N rates, a quadratic curve fitted the relationship (Fig. 5.8). However, when the data were plotted by soil type using the 55 (out of 75) experiments that had soil type information, no significant relationships were found (Fig. 5.8). Nor were significant relationships found with the experiments using feed varieties after a break or cereal crop, or with malting variety experiments after a cereal crop (Fig. 5.9). The only significant ($P < 0.05$) relationship was found for malting varieties after a break crop (Fig. 5.9).

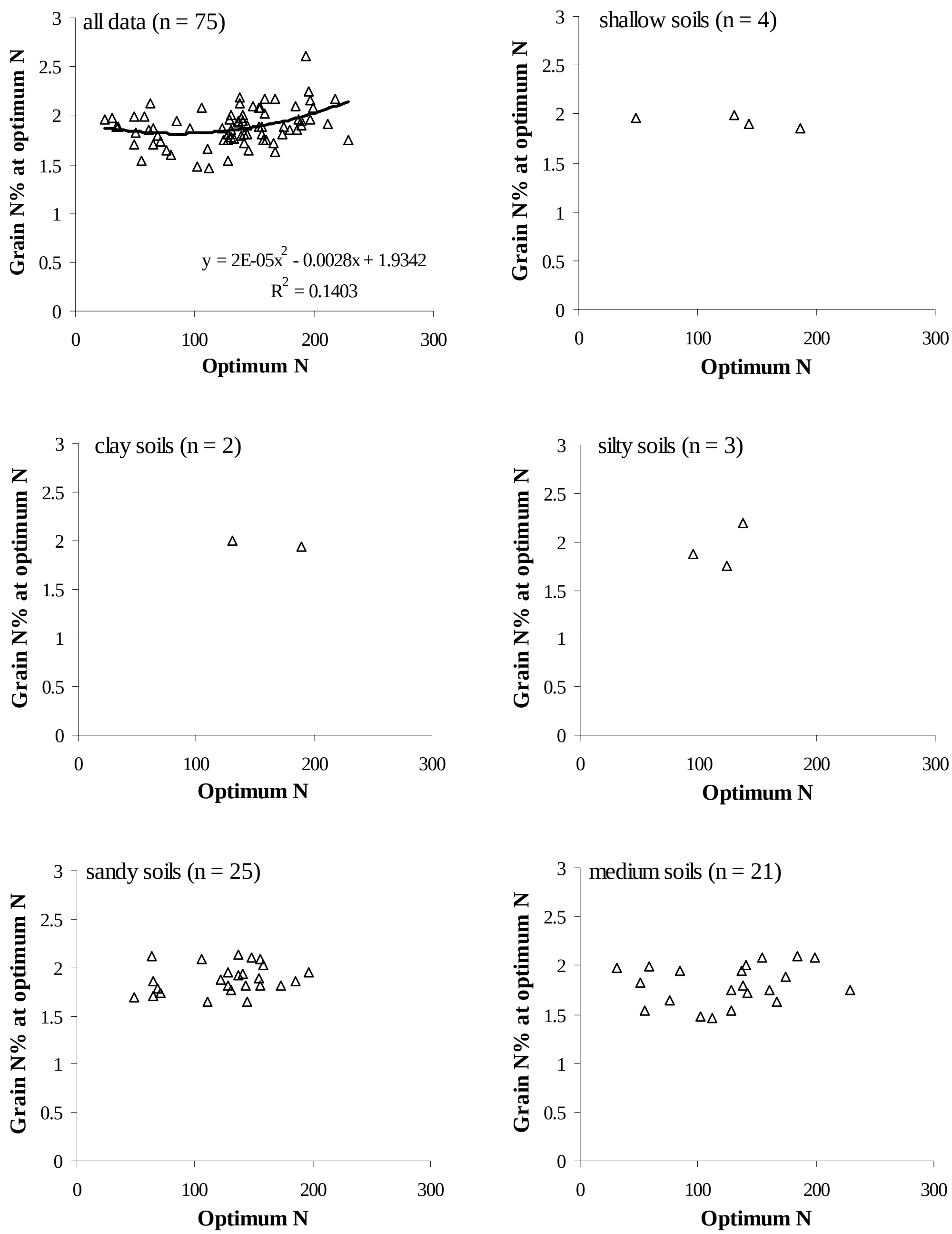


Fig. 5.8 Grain N concentrations at optimum fertiliser N levels (kg/ha) of winter barley experiments – all experiments and those with information about soil types.

Table 5.11 Mean and standard deviation (SD) of slopes of grain N% curves around the optimum N rate (optimum N rate +/- 50 kg N/ha) from winter barley experiments grown on different soil types with malting or feed varieties

Category	No. expts.	Mean slope *(%N per 100kg/ha N)*	SD
Crop type			
Feed	34	0.407	0.1497
Malting	13	0.643	0.1168
Soil type			
Sand	25	0.507	0.1500
Shallow	5	0.445	0.0724
Medium	21	0.417	0.2088
Clay	2	0.362	0.0728
Silt	3	0.293	0.0946
Sand	25	0.507	0.1500
Medium	21	0.417	0.2088
All data	75	0.417	0.1684

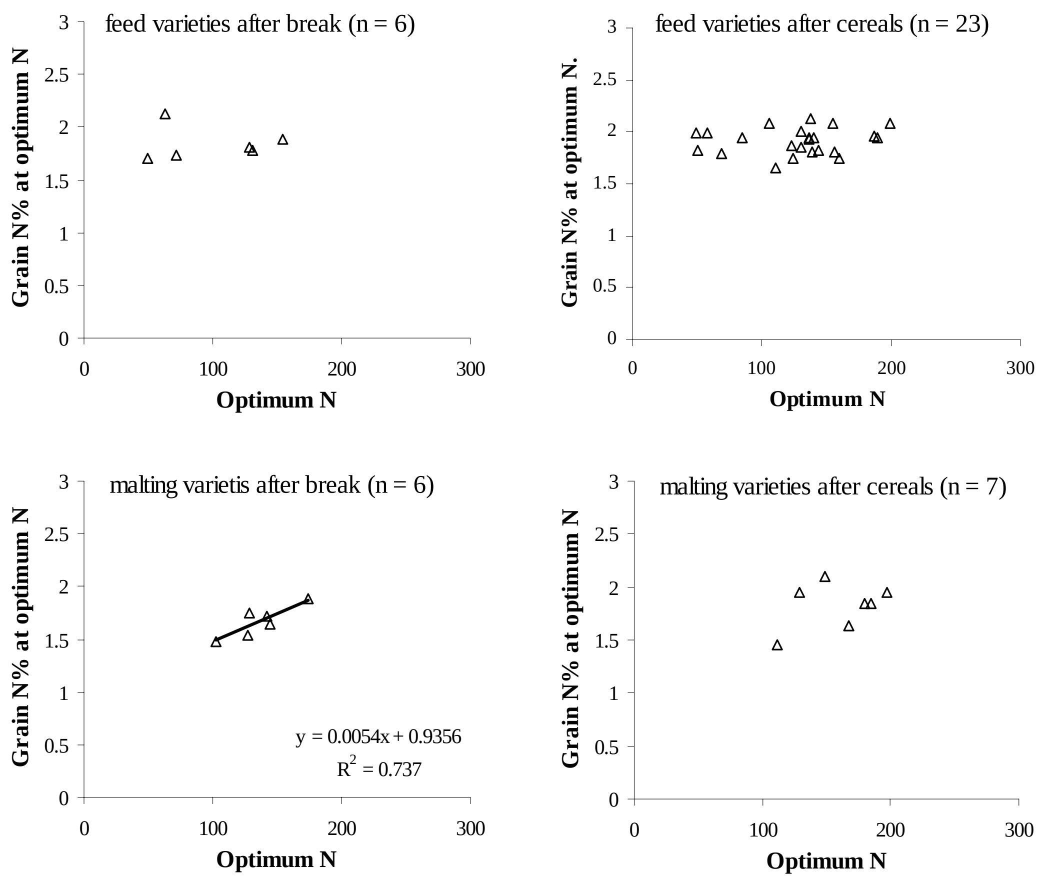


Fig. 5.9 Grain N concentrations at optimum fertiliser N levels (kg/ha) of winter barley experiments – feed or malting varieties grown after a cereal or break crop.

5.4 Oilseed Rape

The average seed N concentration at the optimum N rate for oilseed rape was 3.20%, with concentrations ranging from 2.77 to 3.35% where N applications were fixed from 0 to 300 kg N/ha (Table 5.12). The average optimum N rate was 189 kg N/ha (data not shown).

For regression analysis, information about the years and soil types of the experiments was included but previous crop was not because all the OSR experiments had been preceded by a cereal. When the forward stepwise all-subsets regression was carried out on the oilseed rape data, the model that explained most of the variation was:

Constant + Year + Soil type (R^2 adj. = 20.8%)

It can be seen from Table 5.12 that the experiments carried out on sandy soils gave a high seed N% at the optimum N input (3.41%), with higher seed N% than the other soil types at all levels of N input. However, these results were based on only two experiments. The experiments on clay soils showed a lower average seed N% at the optimum N rate than most other soil types (apart from medium), probably as a result of a lower optimum N rate, rather than lower seed N concentrations at each N level (Table 5.12).

Table 5.12 Fitted mean seed N concentrations (%) at different levels of fertiliser N (including the optimum N level) applied to oilseed rape grown on different soil types

Soil type	No. expts.	Mean Nopt Kg/ha	Seed N% at levels of fertiliser N (kg N/ha)							
			Opt. N	0	50	100	150	200	250	300
Sand	2	157	3.41	3.04	3.11	3.26	3.39	3.48	3.55	3.60
Shallow	6	219	3.25	2.94	2.96	3.00	3.08	3.20	3.26	3.28
Medium	8	194	3.04	2.63	2.70	2.80	2.99	3.04	3.07	3.09
Clay	14	170	3.21	2.81	2.88	3.00	3.15	3.27	3.37	3.42
Silt	8	217	3.28	2.62	2.78	2.93	3.06	3.17	3.34	3.40
All data	39	189	3.20	2.77	2.85	2.96	3.11	3.21	3.30	3.35

Table 5.13 Standard deviations (s.d.) of mean seed N concentrations at different levels of fertiliser N (including the optimum N level) applied to oilseed rape grown on different soil types

Soil type	No. expts.	Standard deviations of seed N% at levels of fertiliser N (kg N/ha)						
		Opt. N	0	50	100	150	200	250
Sand	2	0.335	0.137	0.244	0.318	0.320	0.279	0.216
Shallow	6	0.317	0.449	0.450	0.425	0.353	0.322	0.314
Medium	8	0.127	0.292	0.289	0.162	0.143	0.143	0.153
Clay	14	0.226	0.243	0.206	0.189	0.179	0.207	0.203
Silt	8	0.360	0.244	0.239	0.250	0.261	0.301	0.315
All data	39	0.265	0.296	0.287	0.258	0.249	0.269	0.278

Table 5.14 Mean change in seed N concentration (%) around the optimum N rate (optimum N rate +/- 50 kg N/ha) from winter oilseed rape grown on different soil types.

Category	No. expts.	Mean slope around optimum N rate	Standard deviation.
Soil type			
Sand	2	0.200	0.0466
Shallow	6	0.116	0.0698
Medium	8	0.120	0.0824
Clay	14	0.271	0.1062
Silt	8	0.233	0.1695
All data	39	0.204	0.1253

The variability of the overall average seed N concentration was less at the optimum N rate than at most fixed levels of applied N (Table 5.13). However, when standard deviations were examined for the different soil types this appeared to be the case for just the shallow and medium soils (Table 5.13).

When the slopes of the seed N% curves around the optimum N rate were examined, the average was 0.20% per 100 kg N/ ha. This slope was affected by soil type (Table 5.14), with shallower slopes for shallow and medium soils (0.12) and a steeper slope for the clay soil category (0.27).

When seed N concentration was plotted against the optimum N rate for all experiments, no significant relationship was found (Fig. 5.10). This was also the case for four of the five soil type categories (Fig. 5.10); the only significant ($P < 0.05$) relationship was found with clay soils, which was positive (an increase of 0.17% grain N with an increase of 100 kg in optimum N).

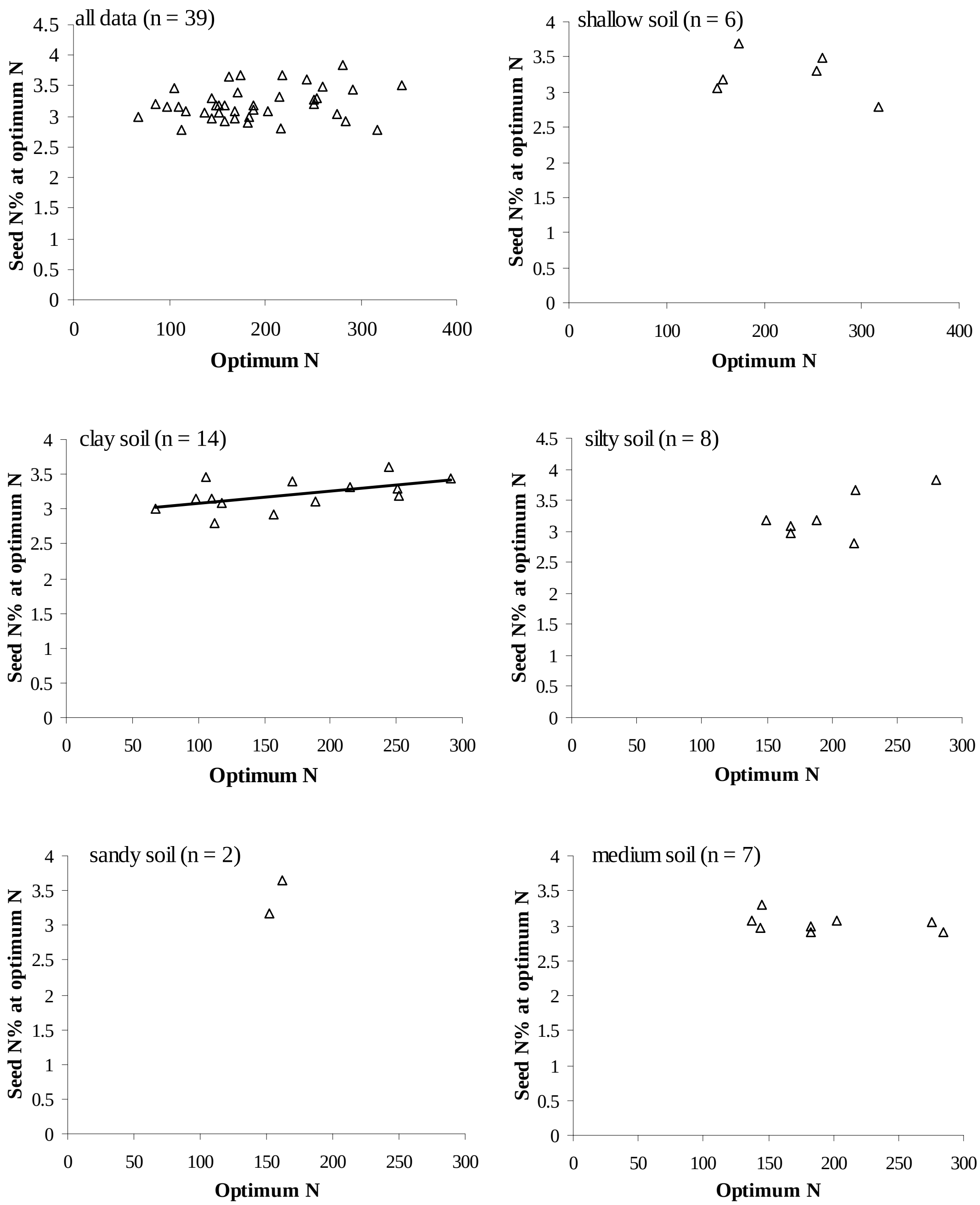


Fig. 5.10 Seed N % at optimum N levels (kg/ha) of oilseed rape grown on different soil types.

6. Discussion

6.1.1 *Derivation of grain (or seed) N concentrations*

Grain N content can be expected to vary in line with variation in both N supplies and grain yield. Clearly both of these are very variable and difficult to predict on farms. Factors which may affect N supplies relate to manure and fertiliser use, but also to soil N supplies resulting from soil organic matter turnover, which is highly subject to soil type and weather, and from atmospheric deposition. Factors which affect grain yield are myriad, but include particularly genotype, soil type, rainfall and diseases. Nevertheless, as explained in the Introduction, there are reasons to expect that grain N concentrations might provide a way of retrospectively diagnosing how close actual N use was to the optimal level of N supply for the particular level of grain yield achieved in a particular circumstance.

Taking wheat as the prime example, grain N concentrations in the experiments described here varied from 1.12% for an unfertilised feed variety grown in Essex in 2006 to 2.77% for an over-fertilised breadmaking variety grown following a cereal at Sutton Bonington, Nottinghamshire in 2005. Generally oilseed rape showed larger concentrations than the cereals. There was little difference between wheat and barley, but wheat in Denmark clearly showed lower grain N concentrations than wheat in the UK.

Grain N responded positively to increasing fertiliser N in each of the many experiments analysed here. In general this response was well fitted by the sigmoid shapes of the Gompertz or Normal type with depletion functions: these generally accounted for over 80% of variation in the data from an experiment. Thus the main uncertainty in determining grain N concentrations with optimum N supplies was in the determination of optimum N rather than in interpolating the grain N concentration. When the standard errors of an optimum were translated into effects on grain N concentration they averaged at 0.07% N for oilseed rape and 0.11%N for wheat and barley.

6.1.2 *'Optimum N' versus 'critical N'*

It is generally the case that determination of optimal levels of fertiliser N has become particularly scrupulous and exacting in the UK compared to other

European countries over recent decades, following the work of statisticians at Rothamsted such as Boyd *et al*. (1976), Wimble (1980) and George (1984) on fitting curves to data from response experiments, then the adoption of these curve fitting procedures such that official recommendations were based on economic optima derived from one common function (the linear plus exponential) fitted to large datasets from multiple experiments (Dampney, 2000), and then the introduction of Nitrate Vulnerable Zones which stipulated these recommended N rates as definitive levels for use on farms. Until the last revision of the official recommendations (Anon., 2000) relative prices of grain and fertiliser N had remained stable. However, price volatility in recent years has caused unprecedented shifts in the 'break-even' N:grain price ratio (from 3 to 12) which, given their derivation from fitted curves, has caused unprecedented changes in economically determined optimum N supplies of up to 100 kg/ha N over recent years.

On the other hand, the attitude taken by Justes *et al.* (1994) and others when determining 'critical' N supplies was more crude. Data were often taken from experiments with only 4 levels of N supply (compared to the 5 or 6 levels used in the UK) and data were fitted with a two line function (rather than one with a continuously changing slope) which gave discrete optima of some biological significance but with no economic validity.

It is therefore important in interpreting the analyses made here that 'optimum N' is not regarded as synonymous with 'critical N'. Optimum N should be recognised as being more commercially meaningful but subject to the vagaries of economics. The favourable economics applying to cropping in the last century (N:grain price ratio = 3) enabled production levels to approximate to biological maxima. With typical recent conditions assumed here (N:grain price ratio = 5) and normal response curves (as described by Sylvester-Bradley *et al.*, 2008) N optima are reduced by about 30 kg/ha, yields by about 0.1 t/ha, and grain N by about 0.1% (Table 6.1). However, the certainty in optima has improved; the mean standard error of the optima determined by Sylvester-Bradley *et al.* (2008) reduced from about ±33 kg/ha N at N:price ratio 3 to about ±25 kg/ha N at N:price ratio 5.

Table 6.1 Effect of N:grain price ratio on optimum N amounts, grain yield (at 85% DM) and grain N or protein concentrations with normal responses for feed varieties of winter wheat after break crops from Sylvester-Bradley *et al.* (2008)

'Break-even' or N:grain price ratio	Optimum N applied	Optimum grain yield at 85% DM	Grain N at N optimum	Protein at N optimum
	kg/ha	*t/ha*	*% DM*	*% DM*
1	260	10.09	2.15%	12.2%
2	240	10.06	2.08%	11.9%
3	222	10.02	2.03%	11.6%
4	207	9.96	1.98%	11.3%
5	193	9.90	1.94%	11.1%
6	181	9.84	1.91%	10.9%
7	170	9.77	1.87%	10.7%
8	160	9.69	1.85%	10.5%
9	151	9.61	1.82%	10.4%
10	143	9.53	1.79%	10.2%

6.1.3 *Variation in grain N% with optimum N supply*

There was less variation in grain N concentrations of optimally fertilised crops than between crops receiving non-optimal (both large and small) N supplies, however the difference was not marked and there was more variation than the theory of Greenwood, Lemaire and others (Greenwood *et al.*, 1991; Lemaire & Gastal, 1997) and extrapolation from it (as outlined in the Introduction) would lead us to expect. When grain N concentrations were presented in relation to grain yields (Figs. 6.1, 6.2 & 6.3) there were no statistically significant relationships of any meaningful slope. Mean concentrations were similar to those predicted in the Introduction for UK wheat and oilseed rape crops; no predictions were possible for barley crops but N concentrations here were evidently less than for wheat.

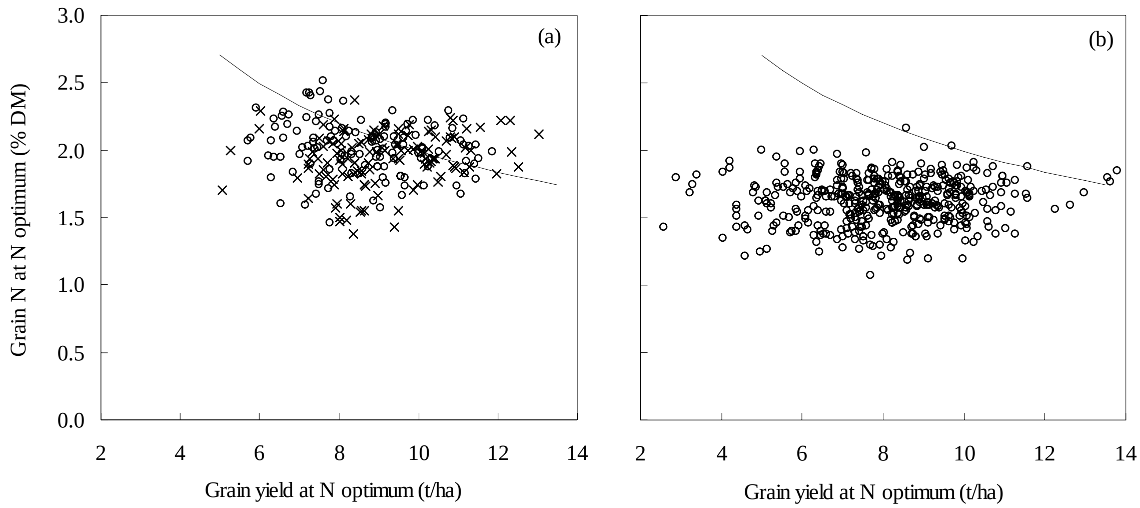


Fig. 6.1 Relationship between grain N (% DM) and grain yield both with the optimum N supply (a) in wheat experiments in the UK after cereals (circles) and after break crops (crosses), and (b) in Danish experiments. The line is the predicted relationship, extrapolated from Justes et al.,(1994), assuming harvest indices were stable at 0.5 for DM and 0.7 for N.

For wheat in Denmark grain N concentrations at the optimum (and at fertiliser levels from 0 to 300 kg N/ha) were approximately 0.4% less than in the UK, and markedly less than the predicted relationship (Fig. 6.1b). The explanation for this large effect is not clear. The average optimum N rate was very similar for the two countries (UK = 156 kg/ha; Denmark = 162 kg/ha) and the ranges of grain yields were similar. Also, some UK varieties were included in the Danish experiments yet did not behave differently to the Danish varieties (data not shown). Information about the N management of the experiments and methods used for N determination indicated no major difference between the countries. More investigations are needed to establish causes of this difference, and whether further differences are evident in other environments, for example in the warmer conditions of France. There are important commercial, environmental and scientific implications of this difference that must be resolved.

Regression analysis of grain N concentrations according to variety type, previous crop and soil type accounted for a portion of the variation but generally this was only 20-30%; much variation remained unexplained. It was also unexpected that, for wheat and winter barley, some of the variation in grain N concentration with optimal N supply was accounted for by the optimum N amount itself (Figs. 5.4, 5.5 & 5.8). Although the trend was not steep it clearly compromises the prospects of using grain N% to indicate difference (= error) between any set

N rate and the optimum N amount. An explanation for this may be that large optimum N amounts are usually associated with small soil N supplies, hence with a disproportionately large part of the optimal N supply being provided by fertiliser: fertiliser N normally effects crop N uptake later in growth than soil N uptake and late N uptake tends to affect grain N concentration more than early N uptake.

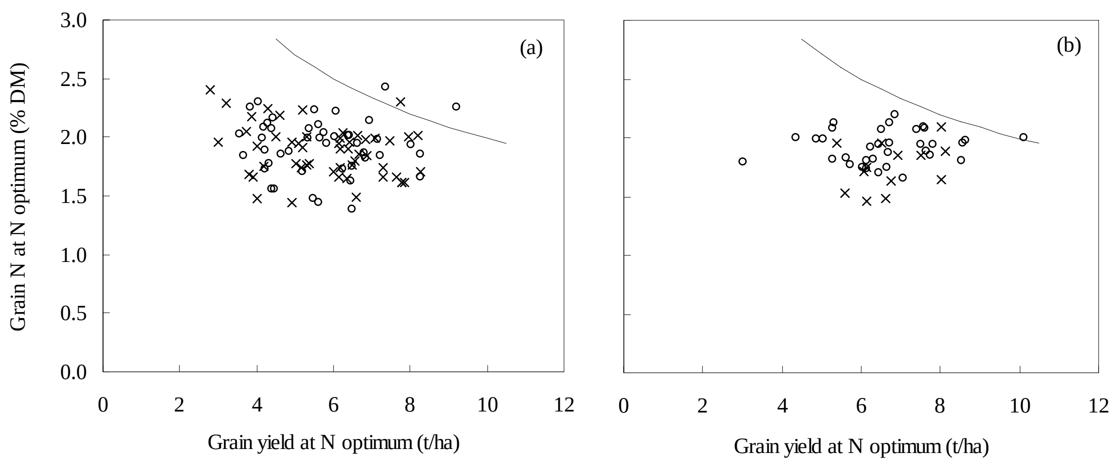


Fig. 6.2 Relationship between grain N (% DM) and grain yield both with the optimum N supply (a) in spring barley experiments and (a) in winter barley experiments with feed (circles) and malting (crosses) varieties. The line is the predicted relationship for wheat, extrapolated from Justes et al.,(1994), assuming harvest indices were stable at 0.5 for DM and 0.7 for N.

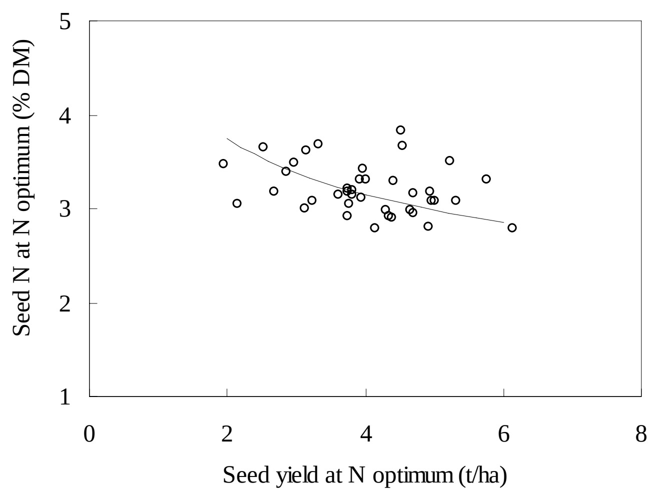


Fig. 6.3 Relationship between seed N (% DM) and seed yield both with the optimum N supply in oilseed rape experiments. The line is the predicted relationship, extrapolated from Colnenne et al.,(1994), assuming harvest indices were stable at 0.4 for DM and 0.5 for N.

Regression analysis often showed soil type to affect grain N% at the optimum N rate, but effects were not consistent, and they often seemed to interact with other factors. In all crops where previous crop was identified as a factor affecting grain N% at the optimum (UK and Danish winter wheat, and winter barley), grain N concentrations at the optimum N rate were higher after a cereal than after a break crop. This is consistent with the analysis of Vaidyanathan *et al.* (1987) and may be due to take-all affecting grain yield but not affecting N capture.

If, as is hypothesised, grain N concentration at the optimum N rate is a good measure of appropriate fertiliser use, it may be expected that the variation in the grain N% would be less at the optimum N rate than other fertiliser levels. This appears to be the case when the whole datasets are considered for spring and winter barley crops (Tables 5.8 & 5.10). However, standard deviations of grain N concentrations at optimum N were little different from those at fixed levels of N (applied at all sites) for wheat or oilseed rape (Tables 5.2, 5.5 & 5.13).

There appeared to be no particular pattern in the variability of grain N concentrations as a fixed amount of N changed: variability tended to decrease as N amounts increased in UK wheat experiments but it increased as amounts increased in Danish wheat experiments and spring barley experiments. Comparing standard deviations for optimum and fixed N rates, grain N concentrations for wheat were generally high at the 0 kg N/ha fertiliser rate and reduced at each fertiliser level to 300 kg N/ha, and the standard deviations at the optimum N rate were similar to those at 100-150 kg N/ha (similar to the average of all optima). The reason for this outcome is not clear, but it may be due to there being different shapes of the N% curves in the wheat experiments.

The quadratic relationships found in the UK winter wheat and winter barley data when grain N% at the optimum was plotted against the optimum N rate was generally due to the low optima (under 100 kg N/ha). For instance, in the Danish wheat, few experiments had low or 0 kg N/ha optima, and relationships were linear. The reason that the grain N concentrations were higher than expected at low optima may have been due to the greater errors associated with determination of small optimum N rates, or that ‘real’ optima of curves with reported optima of zero were negative. However, even when the wheat and winter barley data were restricted to experiments with optima >100 kg N/ha, there was still an increase in grain N% with increasing optimum N, even though small.

As a result of the generally high levels of variability in grain N concentrations it seems that they would not provide levels of certainty necessary for them to be adopted as one-off, quantitative indicators of the degree of imprecision in N management. However, there may be scope for their cruder use – perhaps taking several samples, taking samples from several fields or over several seasons from one field. It is also possible that grain N analysis can usefully augment other N monitoring methods such as soil mineral N analysis and canopy assessment to provide a more robust overall approach to N management.

6.1.4 The rate of grain N response to applied N

The average slope of the N% curves around the optimum N rate was the same in both the UK and Danish wheat experiments, and was consistent with the recommendation in the current edition of RB209, namely that for a 0.1% deviation in grain N% from the expected, fertiliser rates should be adjusted by 30 kg N/ha. The slope was found to be shallower (0.25% N per 100 kg/ha N) for breadmaking than feed (0.32% N per 100 kg/ha N) varieties, perhaps because protein contents at the optima are higher in bread wheats, hence closer to asymptotic protein levels. The average slope was very similar for spring barley, and lower for oilseed rape (25 kg N/ha adjustment required per 0.1% N deviation). Winter barley differed from the other cereals, having a much steeper average slope (0.42% N per 100 kg/ha N). Where the slope around the optimum was affected by soil type (UK wheat and winter barley) this was due, as may be expected, to sandy soils having steeper slopes i.e. requiring smaller adjustments to N rates to effect the same change in N%, probably due to greater fertiliser recovery efficiency.

6.1.5 Breadmaking wheat varieties

The timing of N applications in the UK experiments was the same for both breadmaking and feed varieties so timing cannot explain the greater grain N concentrations with optimum N supplies of the breadmaking varieties. Analyses of yields and N optima from the UK dataset were undertaken to explore this effect (Table 6.2) and unexpectedly (i.e. this is not included in the new revision of fertiliser recommendations) this showed that optimum N amounts for yield (i.e. irrespective of grain N or protein concentrations) were greater for breadmaking than for feed varieties by approximately 20 kg/ha despite grain yields being lower for breadmaking varieties, especially after break crops (Table 6.2). Thus it appears that the greater N concentrations in breadmaking varieties are associated with both the need for greater amounts of fertiliser N and smaller grain yields.

Table 6.2 Numbers of experiments on breadmaking and feed varieties of winter wheat grown in the UK after break crops and after cereals with means (and their standard errors, s.e.) from analysis of optimum N amounts, grain yields and grain N concentrations.

Crop type	No. experiments			Optimum N *(kg/ha)*		Grain yield at optimum N *(t/ha)*		Grain N at optimum N *(% DM)*	
After:	Break	Cereals		Break	Cereals	Break	Cereals	Break	Cereals
Bread	37	43	Mean	140	205	8.97	8.69	2.14	2.17
			s.e.	10.9	8.8	0.222	0.215	0.032	0.025
Feed	126	129	Mean	124	175	9.15	8.66	1.93	2.02
			s.e.	6.2	5.3	0.132	0.140	0.017	0.018

The mean grain N concentrations, when converted to grain protein concentrations expected at optimum N supplies for grain yield (mean 12.2% DM), are clearly less than the protein concentrations (usually 13% DM) specified in contracts for breadmaking grain. Hence this analysis indicates that an even greater quantity of 'extra' fertiliser N is required to meet a breadmaking specification than is to be recommended in the new Fertiliser Manual (Anon., 2009): about 20 kg/ha more N is needed than for a feed variety to achieve the optimum yield and then, assuming a response rate (from Table 5.3) of 0.25 x 5.7 = 1.4% protein per 100 kg/ha N applied, a further 55 kg/ha will be needed to achieve 13% protein, giving a total of 75 kg/ha extra N over that required by a feed variety.

This finding clearly has economic implications for growers, and ultimately for the breadmaking industry, since it seems that the costs of growing breadmaking varieties to match the requirements of the end-user are even greater than previously anticipated. It also has environmental and regulatory implications since most of the 75 kg/ha extra N applied to wheat crops for breadmaking will not be harvested but will add to the N load in the arable environment, and this will be difficult to exploit before it is lost to the wider environment in drainage waters or emissions to the atmosphere. These results highlight the urgent need to develop breadmaking technologies, breadmaking genotypes and agronomic practices that allow manufacture of acceptable bread products whilst minimising requirements for additional use of fertiliser N. Technologies that enable breadmaking from grain with 12.2% protein would markedly improve both economic and environmental efficiencies of the bread-supply chain.

Whilst these findings are important in highlighting future challenges for the breadmaking industry, they indicate difficulties in using grain N analysis to interpret the accuracy of N management with breadmaking varieties. The clear need for additional N on breadmaking varieties (80% of the 82 breadmaking crops analysed here would have needed N additional to the optimal N supply for yield if they were to achieve 13% protein) implies that N applications will normally need to be super-optimal. Whilst a comparison of results from grain analysis with the commercial 13% protein target will indicate the extent to which N management had met its market target, it will be difficult to infer lessons concerning N management for yield in subsequent seasons. Hence the guideline grain N concentration for breadmaking varieties (2.1%; Anon., 2009) in the fertiliser recommendations should be removed.

6.1.6 Barley varieties

Malting barley gave lower grain N concentrations at the optimum N rate than feed barley but more so in winter than spring barley experiments; average grain N concentrations of feed varieties were 1.92% in both spring and winter barley, and of malting varieties were 1.87% in spring barley and 1.76% in winter barley. As with breadmaking wheat varieties, grain N concentrations for the malting varieties are somewhat different from those required for the intended end-use. Thus N management for malting varieties tends to be sub-optimal and the value of grain N analysis to judge the extent of any deviation from optimum N levels for yield is reduced. Given this, and the variability around these mean concentrations, grain N analysis will be most valuable for feed varieties, and it is questionable whether adoption of different guideline concentrations for the different barley types would be justified.

6.1.7 N Use Efficiency

Grain N concentration is a major component of the N conversion efficiency of these crops, and N conversion efficiency is a major component of overall N Use Efficiency (Sylvester-Bradley & Kindred, 2009). Hence the large variation in grain N concentrations with optimum N supplies, and the large proportion of this variation that is still unexplained, must give considerable cause for concern to those wishing to improve the N Use Efficiency of arable crops in Europe. It will be important that this variation is subjected to further research so all possible that means of improving N Use Efficiency are identified.

7. Conclusions & Recommendations

There are implications of this work for commercial practice and for subsequent research. It is clear that the variability in grain N concentrations precludes its use in any exacting way. However, checks with the datasets assembled here showed that analysis could nevertheless prove useful. Figs 7.1 & 7.2 show that grain analysis could have correctly identified whether feed varieties of winter wheat and barley (spring or winter) in the UK had been under- or over-fertilised in 70-80% of cases (however, the success rate for oilseed rape did not prove useful). Thus whilst analyses of a single grain sample may not be sufficiently trustworthy to form conclusions about N management in a recent crop, several analyses, if consistently low or high compared to a guideline 'optimum' standard, could be used to build confidence in a particular conclusion about the success of N management.

Table 7.1 Guideline standard values for use in judging whether N management has approximated to the economic optimum.

Guideline	*units*	**Winter Feed Wheat** *grain protein*	**Feed Barley** *grain N*
Expected grain concentration with optimum N applied	*% DM*	11.5%	1.9%
Approx. correction around optimum N	*kg/ha N applied per 0.1% difference*	6	30

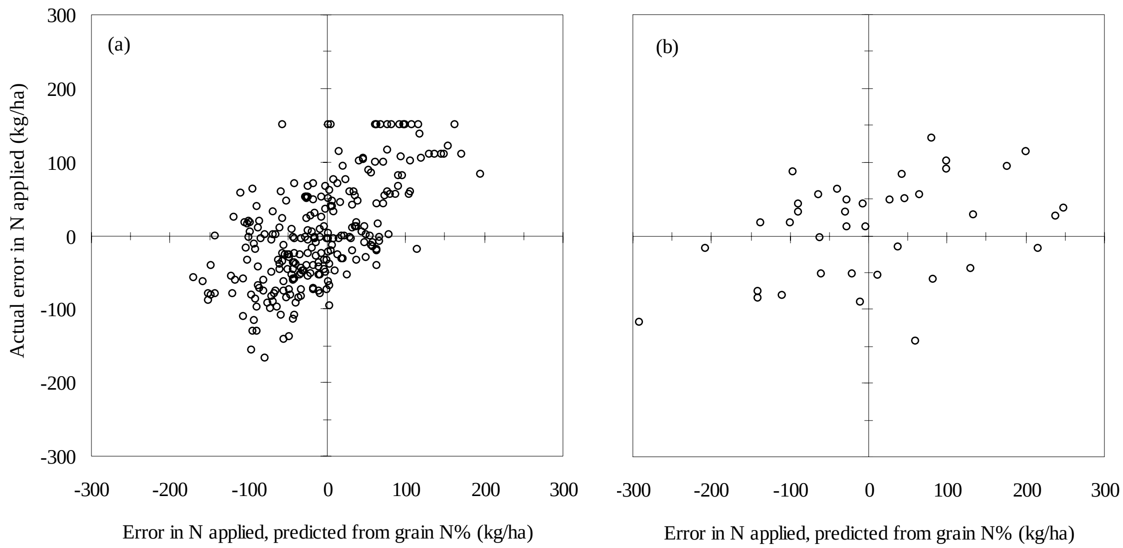


Fig. 7.1 Actual errors in N use if a fixed N rate was applied at each site and errors in N use predicted from grain N analysis. (a) feed wheat in the UK, assuming optimum grain N is 1.94% and response in grain N is 0.1% per 32 kg/ha N applied, and (b) oilseed rape assuming optimum seed N is 3.2% and response in seed N is 0.1% per 49 kg/ha N applied.

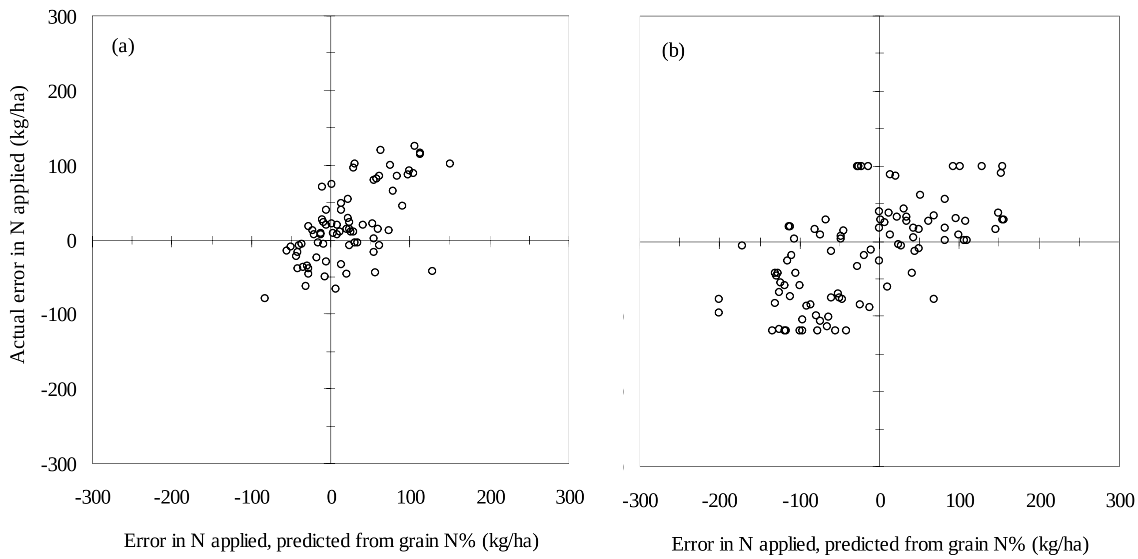


Fig. 7.2 Relationships for feed varieties of (a) winter and (b) spring barley between actual errors in N use if a fixed N rate (of 150 kg/ha for winter and 100 kg/ha for spring) was applied at each site and errors in N use predicted from grain N analysis, assuming optimum grain N is 1.9% and response in grain N is 0.1% per 32 kg/ha N applied.

It must be concluded that samples from crops for which grain analysis affects financial premiums (breadmaking varieties of wheat and malting varieties of barley) will not be useful in indicating whether N management was approximately optimal. However, samples taken from feed crops, if analysed in sufficient numbers – perhaps 5-10 per season, should prove useful in indicating any financially important deviation from optimal N use. Guideline values for feed varieties of wheat and barley are presented in Table 7.1.

Although grain N concentrations in both these species were significantly less after break crops than after cereals, and although there were significant relationships between N% at Nopt and Nopt, it is concluded that these effects were small compared to the background variability, and thus they could be ignored in practice. Similarly values are rounded to provide clear and memorable guidance. Hence values are given for each crop species, without distinguishing growing conditions. Values for winter wheat are converted to protein (N x 5.7) as this is how commercial grain analyses are expressed.

Thus in conclusion, this study has shown that grain N% can be used as a guide to good N use in wheat and barley. In these cases, where grain N concentrations consistently deviate by at least 0.1% from the expected optimum grain N concentration, it can be deduced that fertiliser N rates differed by at least 30 kg N/ha from the optimum N rate. For oilseed rape, seed N concentrations may give a useful indication of whether crops have been fertilised appropriately, but more work is needed to determine the reasons for the variability in the N% data at the optimum N rate. Further work is also needed to understand the large differences in the grain N concentrations between the UK and Denmark. Work is also needed to assess how grain N analysis can best be combined with other methods available for N management on UK farms (such as field assessment of soil N supplies, soil mineral N analysis and canopy assessment) so that most effective and efficient N management strategies can be devised.

8. Knowledge transfer

The main vehicle for dissemination of results from this project will be a new HGCA publication entitled “Nitrogen for winter wheat – management guidelines” due to be published in autumn 2009 (HGCA Project KT-0809-0012).

9. Acknowledgements

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Appendix A: Details of Scottish experiments

Two winter wheat and three spring barley Nitrogen response trial series were carried out in the 2007 harvest season. The winter wheat experiments were carried out in Roxburgshire, Southern Scotland (Grid ref. NT 627 322) and Fife, Central Scotland (Grid ref. NT 260 978) and were drilled in October 2006 after potatoes and winter oilseed rape, respectively. Both sites had sandy loam soils. The spring barley experiments were carried out in: Kelso, Southern Scotland (Grid ref. NT 660 316) after winter wheat; Fife, Central Scotland (Grid ref. NT 251 981) after winter wheat; and Ellon, Northern Scotland (Grid ref. NJ 984 284) after spring barley. The experiments were drilled in March 2007 and all sites had sandy loam soils.

All experiments were set out in a randomised block design. The agronomy of the crop (except N applications) was carried out as per commercial practice. Winter wheat N treatments were as follows: Nil, 120, 150, 180, 210 and 270 kg N/ha. Spring barley N treatments were: Nil, 40, 90, 130, 170 and 220 kg N/ha. Fertiliser application timings were as per commercial practice. After combine harvesting at the end of August/beginning of September (depending on the trial) 2007, grain yield (t/ha at 85% DM) was determined and samples sent for grain N% determination.