August 2018

Project Report No. 596

Using farm experience to improve N management for wheat (LearN)

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This is the final report of a 54 month project (2160005) which started in September 2013. The work was funded with contract for £261,545 from AHDB Cereals & Oilseeds and in-kind contributions from CF Fertilisers and Agrii.

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1. Abstract

Nitrogen (N) requirements of wheat are notoriously variable and difficult to predict, despite much research to develop recommendation systems. Recent studies also show a significant farm effect on grain protein content. This suggests a farm factor may be causing N requirements to differ, even where the RB209 recommendation would be the same. Some fields and farms may be consistently receiving too much or too little N fertiliser and, therefore, losing substantial profit from wasted fertiliser or lost yield, as well as potentially having an impact on the environment. It is also possible that yields on some farms are substantially constrained by N.

Precision farming technologies can be used to test N rates, through tramline comparisons and analysis of yield maps. The LearN project supported 18 self-selecting, engaged farmers to test whether their standard N rates were about right, too high or too low. They used simple trials on their farms, from 2014 to 2017, to test single replicates of 60kg/ha more and less than their standard rate of fertiliser N in alternate tramlines. On a subset of six heavy soil, high-yielding, long-term arable farms in East Anglia, conventional small-plot N response experiments were conducted on three fields per year, alongside the tramline trials.

The small plot trials showed that despite substantial and consistent differences in yields, proteins and soil N between farms, there was no evidence of consistent differences in N optima between farms. N optima varied as much within farms as between farms (overall range: 88 to 356kg/ha; mean 225kg/ha) and were well predicted by RB209 N recommendations with yield adjustment to 11t/ha. Little relation between soil mineral N or grain yield and N optimum was observed.

LearN farmers showed strong engagement; in principle tramline trials were easy to set-up, manage and harvest. However, many challenges had to be overcome, including: ensuring comparable treatment areas; precise recording of tramline wheelings and treatment boundaries; over-lapping fertiliser application by spinning disc spreaders; a need for farm-specific harvest protocols; transfer, processing and cleaning of yield data; statistical analysis to achieve robust conclusions in the face of residual spatial variation; and appropriate interpretation of multi-site results.

Overall, tramline yields were 11.43, 11.07 and 11.74t/ha for farm-standard, -60kgN/ha and +60kgN/ha respectively, giving differences in margin of -£9.81/ha and -£0.55/ha. Differences in yield between two ‘farm standard’ tramlines were used to indicate errors and infer confidence levels. At £140/t for grain and £0.70/kg for N, a difference of 0.3t/ha was required to pay for 60kg/ha difference in N fertiliser. Firm conclusions on N management could be made on around half of the 142 tramline experiments. Underlying spatial variation in yield was usually much greater than the N effect. Overall, around 30% of standard N rates were found to be optimal, 26% were super-optimal and 24% were sub-optimal. No farms were found to be consistently applying too much or too little N. Variation in yield was large within and between fields and farms, but N was not the major driver. The causes for the variation in yield and profitability are a major question for the industry, for which, we believe, this approach to scientifically sound farmer-centric agronomic research, with simple field trials and robust statistics, gives good chances of answering.

Abbreviations

AAN	Additionally Available Nitrogen
AN	Ammonium nitrate
CND	Crop Nitrogen Demand
CV	Coefficient of Variation
DM	Dry matter
FAM	Field Assessment Method
GAI	Green Area Index
GPS	Global Positioning System
K	Potassium
LEXP	Linear Plus Exponential
LSD	Least significant difference
N	Nitrogen
Nopt	Optimum amount of fertiliser nitrogen (kg/ha) or 'Nitrogen requirement'
NO_3	Nitrate
NH_4	Ammonium
OSR	Oilseed rape
P	Phosphorous
RB209	Reference Book 209 – refers to official fertiliser recommendations published by MAFF (before 2008), Defra (from 2008 to 2017) or AHDB (from 2017)
REML	Restricted maximum likelihood
SD	Standard deviation
SDA	Surface Discontinuity Analysis
SE	Standard error of a mean
SMN	Soil Mineral Nitrogen
SNS	Soil Nitrogen Supply
SOM	Soil Organic Matter
UAN	Urea Ammonium Nitrate liquid fertiliser
WW	Winter Wheat

2. Introduction

Applying optimal rates of Nitrogen (N) fertiliser to UK crops is important, both to farming businesses to maximise returns, and the environment, to minimise pollution. Research to optimise N use has a long history, starting in the mid-19th century and seeing the first comprehensive national recommendations published in 1967. Fifty years on, the sum of current understanding, guided by recent empirical evidence of appropriate N rates, is represented by the 'Nutrient Management Guide (RB209)' (AHDB, 2017); this invokes information on crop species and type, previous cropping, soil type and over-winter rainfall to predict optimal N use. Recent AHDB (& AHDB) work (e.g. Reports 438 (2008) and 490 (2012)) has shown recommendations in the previous version of RB209 (Defra, 2010) to be about right on average, but to have huge uncertainty. For example, in 2008, AHDB Report 438 showed that recommendations were imprecise by more than 50 kg/ha N on 50% of fields.

Whilst recommendations are generally applied to whole fields, field by field, evidence for them generally arises from series of small trials, each of <0.5 ha and comprised of plots of ~0.005 ha. Trials composing any 'trial series' have been distributed across the main arable regions, and over several seasons. However, within each season, trial distribution has generally seen unsystematic allocation to particular farms, fields and positions within fields (e.g. Goodlass *et al.*, 2002). Thus, on top of the obvious unpredictable seasonal effects, previous research has been unable to attribute variation to region, farm, field, sub-field or other husbandry factor (like variety or sowing date) because these factors have commonly been confounded within the datasets. Only soil type and previous crop have explained significant proportions of the variation, but effects were small (Webb *et al.*, 1998).

In preparing N management 'guidelines' for winter wheat (Sylvester-Bradley, 2009) an attempt was made to re-present the empirical findings in RB209 in the form of a simple model, as follows:

$$\text{N requirement (kg/ha)} = \frac{[\text{Crop N Demand (kg/ha)} - \text{Soil N Supply (kg/ha)}]}{\text{Fertiliser N Recovery (\%)}} \qquad (1)$$

The intention of this approach was that effects of local factors such as variety, sowing date, soil organic matter, or measured soil mineral N could be accommodated according to their likely or known effects on Crop N Demand, Soil N Supply or Fertiliser N Recovery respectively. Thus an N requirement (for example) of 190 kg/ha might be derived (or adjusted) as follows:

- Crop N Demand (CND; = 194 kg/ha), considered as the product of expected grain yield (say 9 t/ha @ 85%DM) and grain N (1.9% DM) divided by N harvest index (75%),
- Soil N Supply (SNS; = 80 kg/ha), considered as the sum of crop N (10 kg/ha) and soil mineral N (60 kg/ha) in spring, plus soil mineralisable N (10 kg/ha), and

- Fertiliser N Recovery (FNR; = 0.6, or 60%), considered as the increase in final crop N uptake, expressed as a proportion of the applied N that caused it.

If earlier sowing increased crop N in spring or a new variety was known to have higher protein, their likely effects on the Fertiliser N Requirement could be more easily and logically estimated. However, the AHDB SNS Best Practice Project (PR 490) showed limited value of soil mineral N testing in reliably improving predictions of N requirements, especially in situations where soil N supply was expected to be relatively low (<100 kg/ha).

Orson (2012) contended that a single N application rate would satisfy N requirements on low-N arable soils as well as RB209 predictions (Defra, 2010) and better than using SMN testing. The conclusions of more recent AHDB work have been that the key aim of N management should be for farmers to get it right on their farm on average, then to identify and manage separately individual fields, or situations which appeared ‘odd’ (Sylvester-Bradley *et al.*, 2008; Kindred *et al.*, 2012; 2016).

In the MALNA LINK project (AHDB Report 483), where data were collected from 19 farms growing milling wheat over 3 seasons, some significant differences between farms were apparent which could be worth acknowledging in a farm’s N use strategy, but these were not obviously explicable. Despite all 19 farms growing Group 1 wheats and aiming to achieve 13% protein, some farms were on target, whilst others recorded significantly less grain protein, around 10%, without obvious differences in N fertiliser rates or grain yields (Figure 1). This suggested that some farms may consistently need more N than advised by RB209 to achieve optimal yields and market requirements for grain quality, whilst others may consistently need less, so could make savings on N fertiliser use.

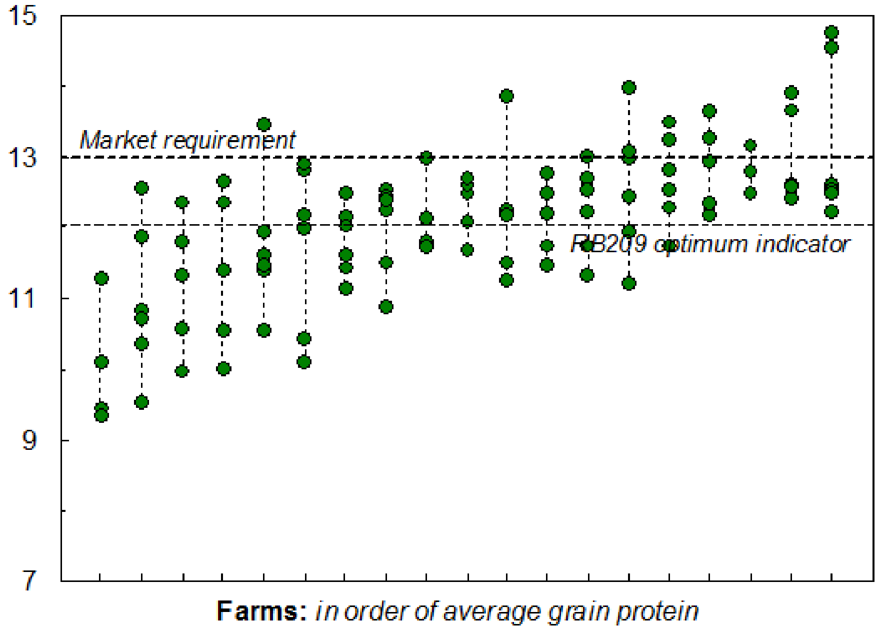


Figure 1. Grain protein content from 19 farms in the MALNA project; measured from grain samples of 2 fields per year in each of 2007, 2008 & 2009. The farm effect is highly significant (P<0.001); LSD 0.70% protein.

Also, before the start of this project, the AHDB Green Food report and the ‘Yield plateau’ report (PR 502) both suggested that insufficient N fertiliser might be limiting yields on some farms. It was thus deemed important for individual farmers to know whether their N management was about right on their farm (or on a particular block of land). If farms themselves were found to explain a substantial proportion of the variation in N optima, then there could be a real opportunity for farmers to increase yields or save N fertiliser costs by deducing the appropriate N rates for their particular farm, rather than by just using national recommendations. Thus tools and approaches were needed to enable farmers to learn by experience about whether their farm needed more, less or the same as suggested by national recommendations, and to validate their farm-specific decision making. Note that, on all but the lightest soils, lost profit from an inaccurate farm N strategy would be likely to increase year on year because N errors tend to accumulate – most medium and heavy arable soils retain N surpluses (or N deficiencies) from year to year, and N errors may have gone undetected for a long time on some farms.

Along with a site-specific approach to N Management, the HGCA N Management Guide for wheat (Sylvester-Bradley, 2009) acknowledged that N use must inevitably be associated with some uncertainty and imprecision; hence there could be value in post-mortem diagnosis of imprecisions so that over seasons these would not become cumulative. Thus the N Management Guide advocates ‘N Monitoring’ to allow estimation of inaccuracies in N use and suggests that growers should use information such as past yields, SMN, SOM%, soil N%, grain protein %, canopy colour and lodging to indicate how successful their N management had been, and then to adjust future N use accordingly.

RB209 (7th & 8th editions; 2000 & 2010) was less comprehensive but adopted grain protein (%; or N%) as a useful post-hoc gauge of the success of N management. Whilst AHDB Project Report 458 showed it is useful when used in this way with wheat and barley over fields and years, evidence from Auto-N chessboard experiments suggested this cannot be deemed sufficiently reliable to infer success within or between individual fields (AHDB PR 561). Soil organic matter or soil total N% are potentially useful indicators of soil N supply and useful monitors for N management over time (Bhogal *et al.*, 1997). However, these are likely to be monitored only once every 4-5 years.

Given the limited value of SMN testing found in AHDB PR490, other approaches for informing N management appear warranted. The only method that gives precise knowledge of N requirements is to conduct N response experiments. Whilst it is impossible to conduct conventional replicated plot experiments across every farm, the advent of precision application and yield monitoring techniques does offer the opportunity for growers to compare N rates at field scale across tramlines without enormous hassle or cost (Kindred et al., 2016a,b). By applying 60 kg N/ha more and 60 kg N/ha less on alternate tramlines considerable knowledge may be gained; visual appearance (or reflectance) and yields from these strips can now be measured quite easily with sensing and mapping techniques and, if sufficient precision can be achieved, these should indicate whether or not the farm N rate was 'right'. That is, if yields for the 3 N rates are similar (judged against repeatability of yields with normal N) then this suggests that the farm rate might be reduced in future years. Alternatively, if the high N rate yields consistently more than the farm rate by >0.3 t/ha (enough to pay for 60 kg/ha N at current prices) then N rates could be increased in future years, and yields should increase.

This project tested whether this approach could be adopted by any farm with concerns that its N rates are inaccurate. If this tramline testing approach is successful, a new set of guidelines could be developed to enable growers to interpret their results, along with more regular intelligence of field yields, SMN, SOM%, soil N%, grain protein, canopy colour and lodging.

Therefore, the aim of this project was to optimise N use on-farm more precisely by enabling individual farms to determine whether, on-average, their N use on wheat was too much, too little or about right. Additionally this project was set up to evaluate the proportions of UK farms getting N fertiliser rates about right, too high or too low.

2.1. Objectives

The specific objectives of the project were as follows:

1. To test whether there are consistent differences in N requirements of wheat between farms beyond those expected from current recommendation systems (i.e. to understand variation within and between farms, fields, seasons, rotational positions, soil types, and geographic locations).
2. To demonstrate the practicality and value of farmers using strips +/- 60* kg/ha N for indicating whether N applications are about right, too much or too little.

   * In the original proposal +/- 50 kg/ha N strips were suggested. However, after an analysis examining the balance between amounts of N likely to result in yield differences and the practicality for growers of changing their standard N rates, +/- 60 kg/ha N was chosen for the project.
3. To test, develop and demonstrate the value of other indicators of successful N management, including grain yields, grain N% (or protein%), SOM%, soil N%, SMN, 'Additionally Available N' (AAN) & canopy reflectance.
4. To evaluate the best system and indicators to use for successful N management, including cost:benefit consideration of management time & hassle involved.
5. To agree best approaches and communicate these to growers.

3. Materials and methods

3.1. Experimental methods

3.1.1. Choosing Core and Extension experimental sites

The project included two categories of sites: Core sites and Extension sites. Both categories tested the approach of comparing the farm standard N rate to 60 kg N/ha more and 60 kg N/ha less applied to alternate tramlines in winter wheat crops. The Core sites also included small (<0.1 ha) N response experiments (with small plots, ~12 x 3 m) in each experimental field to provide a structured dataset and validate the tramline approach. Each farm tested the approach on three fields per season over the duration of the project (harvest years 2014 – 2017), although not all Extension sites participated in all seasons.

Following an initial project stakeholder meeting, growers interested in participating in the project were invited to apply. Growers supplied information such as location, soil type, grass/manure history, fertiliser application method, typical rotation and yield measurement capability. In total, 55 farms were considered and were grouped so that the sites within each group were of the same RB209 classification in terms of soil type and over-winter rainfall. Sites with a history of significant manure use were avoided.

The following sites were chosen:
<u>Core sites:</u> Six farms across East Anglia, all with medium to heavy soils.

<u>Extension sites:</u> A total of 12 sites were chosen, grouped as follows:

1. Three sites in East Anglia with silty soils
2. Three sites in the North of England/Scotland (higher over-winter rainfall)
3. Three sites on shallow soils
4. Three sites in the midlands with heavy soils.

Each site was designated a Supporter from one of the consortium organisations (or a local agronomist for 2 sites) who helped the grower with site set up, sampling and advice on combining procedures.

3.1.2. Choosing fields and experimental areas

Once the sites were chosen, Supporters worked with the growers to choose fields to use throughout the project. Criteria for choosing fields were:

1. Those that had a similar soil type, such that they would be would be deemed to have the same N fertiliser requirements by RB209. Fields that were suspected to have different N requirements (e.g. due to experience with lodging, yields or grain N%) on similar underlying

soil type could be included. Each field could be in a different rotational or management block on the farm. Neighbouring fields could be used.

2. Those that were large enough to accommodate the tramline experiments and, for the Core sites, small plot trials. A run of at least ~200m was required per tramline so that good harvest data could be collected.
3. Those that were uniform enough to make meaningful comparisons between tramlines. It was recommended that previous yield or soil maps be consulted and knowledge of past field boundaries be applied. Some variation was expected and acceptable as long as the variation was reasonably consistent between tramlines.

Where possible, fields were tested more than once in the project, although if they were repeated in two seasons in succession, a different area of the field was used for the +/- 60 kg N/ha treatments. Wheats that were feed or breadmaking varieties and 1st or 2nd cereals in the rotation were included.

Background information for each field was collected from the growers, including:

- Grid reference
- Soil type
- Wheat variety
- Previous cropping (5 years) and Cropping/rotation plan (4 years)
- Any soil, canopy sensing, yield and grain protein data and maps
- Details of any variable rate N applications
- Which fertiliser type will be used and how it will be applied
- The ‘Standard’ N rate that will be used
- Details of maintenance applications, cultivations and establishment methods, any soil or tissue test results from the duration of the trial

3.1.3. Small plot N response experiments

In each experimental field an N response experiment was set up in the established crop. A randomised block design was used with 3 replicates of 6 N rate treatments, giving 18 plots in total per experiment. Plot lengths were half a tramline width e.g. for a 24m tramline, plot length was 12m. To avoid edge effects between neighbouring high and low N rate plots, plot widths were 3 m of which the central ~2m was harvested.

Before any treatments were applied, soil samples were taken from the top 15 cm to test for P, K, Mg and pH if the farmer had not tested the soil over the last 3 years. For all fields, soil samples were taken to 90 cm depth and tested for soil mineral N, mineralisable N and organic matter (top 30 cm only) by Hill Court Farm Research. At the ADAS and NIAB managed sites, crop N content was also estimated at the same time, either visually using plant density or crop cover (as described in RB209) or by uploading a photo of ~1 m^2 of crop and uploading it to the BASF CAT (Canopy Assessment Tool) to get an estimate of GAI.

The soil and crop N contents were used to determine the likely optimum N rate for that field according to RB209 (version current for that cropping season) in consultation with the farmer. This N rate was taken as the ‘Standard’ rate in the tramline trial and this rate was included in the small plot experiment to allow comparison of approaches. The N rates for the N response experiments were as per Table 1. All N fertiliser for the small plot experiments was applied by hand at the following timings as per RB209:

- N treatments 1 and 2: one timing at the start of stem extension.
- N treatments 3 – 6: three timings – 40 kg N/ha at late February or early March with the remainder split equally between applications at the start of stem extension and two weeks later.

Table 1 N treatments applied to the Core site small plot trials in each season (2014-17).

Nitrogen treatment no.	**Total Nitrogen rate (kg N/ha)**
1	0
2	½ of N level 3
3	Estimated optimum N rate -60 kg N/ha
4	Estimated optimum N rate (tramline trial ‘Standard’)
5	Estimated optimum N rate + 60 kg N/ha
6	360

Sulphur was applied as Kieserite or similar unless a non-N containing Sulphur application had been made to the whole field. All maintenance applications were applied by the host farmer for a high yielding crop and to minimise weeds, pests and diseases. It included a robust PGR programme to minimise lodging.

All plots were assessed for lodging pre-harvest. The plots were combine harvested, the grain weighed and moisture content measured and grain yield calculated as t/ha at 85% dry matter. A 0.5 kg representative grain sample was taken from each plot and sent to NIAB for protein concentration determination.

3.1.4. Tramline trials

The tramline trials used the farmers’ own equipment to treat and harvest the trials. The treatments applied within each field were as follows:

1. Standard rate: The amount the farmer would plan to apply to the crop under normal circumstances i.e. the amount that is applied to the rest of the field. This treatment was replicated giving at least two Standard rate treatment tramlines.
2. Standard rate +60 kg N/ha: The standard rate plus an extra 60 kg N/ha.
3. Standard rate -60 kg N/ha: The standard rate reduced by 60 kg N/ha.

The amount of fertiliser was increased or reduced at the main application timing only (late March/early April at early stem extension). Farmers had the option of applying +/- 30 kg N/ha across two application dates if the main application was split over two occasions.

If the farmer applied fertiliser using a sprayer or a pneumatic system, one tramline was used per treatment. If they applied solid fertiliser with a spinning disc spreader, two tramlines per treatment were required. The treatment tramlines were laid out as follows:

2014 season:

Standard + 60 kg N/ha Standard -60 kg N/ha Standard

2015-17 seasons:

Standard + 60 kg N/ha -60 kg N/ha Standard

In February of each season, and before any N was applied, the supporter of each farmer organised for soil samples to be taken for Soil Mineral N analysis down to 90 cm. The results of these analyses were shared with the farmer to help determine the Standard N rate.

As well as the N treatments, all maintenance applications were applied by the host farmer for a high yielding crop and to minimise weeds, pests and diseases. The dates, products and rates of all fertiliser applications were recorded. There were no restrictions on the type of fertiliser a farmer could use.

Farmers were encouraged to discuss their combining strategy with their supporter to make the comparisons as fair as possible. At the majority of sites, a combine with yield mapping capability was used, but in several cases yields were measured by combining each treatment tramline separately and weighing the resulting grain using a weighbridge. Where yield mapping was available, raw data (as .csv, .aft or .shp files) were sent to ADAS for analysis.

3.2. Data analyses

3.2.1. Small plot trials

Data from the 72 N response trials carried out on the Core sites over the duration of the project (2014-2017) were collated, examined and analysed. Data from four sites were excluded due to significant issues with the trials e.g. severe blackgrass infestation. Statistical analyses were carried out using Genstat (VSN International Ltd.)

The response of yield to N was estimated for each experiment individually 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.

$y = a + b.r N + c.N$

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:

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

where k is the breakeven price ratio between fertiliser N (£/kg) and grain (£/tonne). The breakeven ratio used in this study was 0.005 (tonnes grain per kg N) so that direct comparisons could be made with RB209 (both 8th and 9th editions). Standard errors (se) of each Nopt estimate were determined. Where the se of the Nopt was large, that individual experiment’s data were examined and judged as to whether the Nopt was sensible. The standard errors of the Nopt were used as a covariate in later analyses to reduce the weighting of the data from experiments with a large se for Nopt. If the calculated Nopt was greater than the maximum N rate applied, the data from that experiment were examined further to determine whether Nopt should be taken as the maximum N rate applied or whether the shape of the curve meant it was reasonable that the Nopt was greater than the maximum N rate.

A grain N (%) response curve (Normal Type curve with Depletion) was then fitted to the data from each experiment and grain N% estimates were derived for each Nopt estimate. The function for the normal with depletion curve is:-

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

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

A broken stick (or split-line) regression analysis was conducted in Genstat on the total N uptake data in each experiment. The slope of the second line was restricted to zero so that the Y breakpoint could be used as an estimate of crop N demand and the slope an estimate of fertiliser recovery.

REML and regression analyses were conducted using Genstat v19 and Excel 2013.

3.2.2. Tramline trial data

Alongside the LearN project ADAS ran the Agronomics project from 2013 to 2016, which developed protocols, data processes, statistics and software to deal with yield maps and other spatial datasets in tramline trials (Kindred *et al.*, 2016; 2017). Yield data were obtained from farmers as raw data files (e.g. .aft) or where possible via manufacturers' online Telematics platforms. The steps below were performed using a combination of ArcGIS scripts within ADAS Agronomics geo-database web portal and processes coded in R accessed via a graphical user interface (GUI) using Shiny (Rudolph *et al.*, 2016):

Agronomics process:

1. Identify field & create boundary
2. Digitise treatment areas (accounting for past spatial variation when setting up)
3. Obtain data from farm in raw format
4. Convert raw data into standardised csv datafile, with standard nomenclature & filename
5. Provide orthogonal co-ordinate system (e.g. British National Grid)
6. Calculate combine direction and segment combine runs
7. Set a baseline perpendicular to combine runs and calculate distance from this
8. Edit (join or break) combine runs and label west to east.
9. Create buffer around headland and label data points
10. Label data points with treatments, editing area to appropriately include combine runs
11. Import data into GUI for cleaning. Remove data at start & end of combine runs
12. Remove anomalous and incomplete combine runs
13. Remove obvious outliers (e.g. <2 and >18 t/ha). Remove statistical outliers (e.g. >2.5 SED)
14. Calculate variogram and consider removing local outliers
15. Calculate offset from combine lag apparent from direction of travel, consider correction.
16. Perform surface discontinuity analysis (SDA; Rudolph *et al.*, 2016) to estimate treatment effects
17. Export data, calculating means by combine run, tramline, treatment area & treatment

18. Display final map with standard symbology, bar symbol of header width & treatments
19. Report levels of certainty

The full surface discontinuity analysis (SDA) was not conducted on all LearN trials, but example analyses are presented and discussed here. The approach was first described by Rudolph *et al.* (2016) and has been detailed in a recently submitted paper by Marchant *et al.* (2018). The complex patterns of variation observed within yield monitor datasets lead to challenges when attempting to perform formal statistical analyses of these data. Standard statistical approaches would assume that in the absence of treatment differences the yield measurements would vary randomly. In fact there is a high degree of spatial correlation amongst yield data i.e. yields recorded at adjacent locations are more likely to be similar than those made a long distance apart. Some of this reflects genuine spatial patterns in crop performance caused by variations in environmental factors such as soil characteristics, elevation or slope. Other sources of spatial correlation in the data might not reflect variation in crop performance. For example, the yield monitor might perform differently when the combine is moving up a slope compared to the reverse direction. The presence of wheelings or a reduced header width commonly leads to lower yield measurements for particular harvester passes and variation in the time taken for cut grain to travel from the header to the yield monitor can lead to averaging or smoothing of successive measurements.

This spatial correlation must be accounted for when performing the statistical analysis and it is modelled by means of a variogram. A variogram shows how the expected differences in recorded yields (in the absence of treatment differences) varied with the distance between the yield measurements. A standard variogram model would require the assumption that the degree of spatial correlation was identical in each direction. Many of the artefacts introduced by the yield monitor lead to anisotropy – the yield measurements are more similar within a swath than they are between adjacent swaths. Therefore, within the SDA protocol anisotropic variograms were estimated for the yield data from each trial. Such a model accommodates the potentially greater similarity between measurements from the same swath. Then we estimate the treatment differences and the uncertainty of these differences using a regression model that accounts for the modelled spatial correlations.

The yields from each treatment tramline were averaged to give the overall final yield. Surface Discontinuity Analysis was carried out on a sub-set of experiments, enabling testing of the significance of between treatment comparisons.

For experiments where only weighbridge data were available, the yields submitted by the grower were taken as the yields for that treatment tramline.

3.3. Knowledge exchange

An initial stakeholder meeting was carried out in January 2014 to outline the aims of the project and the opportunities for participation. This was attended by growers, agronomists, and industry representatives with an interest in nutrition. Following on from this meeting and an article in the Farmers Weekly and on the AHDB website, interested growers applied to participate and then attended a meeting in February 2014 to hear more details about what was required e.g. field size, rotation, etc. During the experimental phase of the project, grower meetings were held each February to share results between growers and their supporters as well as to clarify and improve the process of carrying out the trials based on experience. Questions and discussions at each meeting were recorded and circulated to any growers who could not attend.

4. Results

4.1. Core site experiments

4.1.1. Weather

The weather experienced by the core sites (interpolated using the Metmake function in Irriguide) over the four harvest seasons (2014 – 2017) of the trials are shown in Figure 2 and compared to the long term average (LTA). This shows that the 2014 harvest season was warmer than average with a dry spring (March, April) following a wet winter, then a dull, wet May. The crops in the 2015 season experienced high radiation receipts in April and June but a dull wet July. In contrast to all the other seasons, 2016 was wetter than average in March and April, with a mild winter and a particularly dull, wet June. A dull, wet grain filling period was a feature of 2017, which was also a warmer than average season.

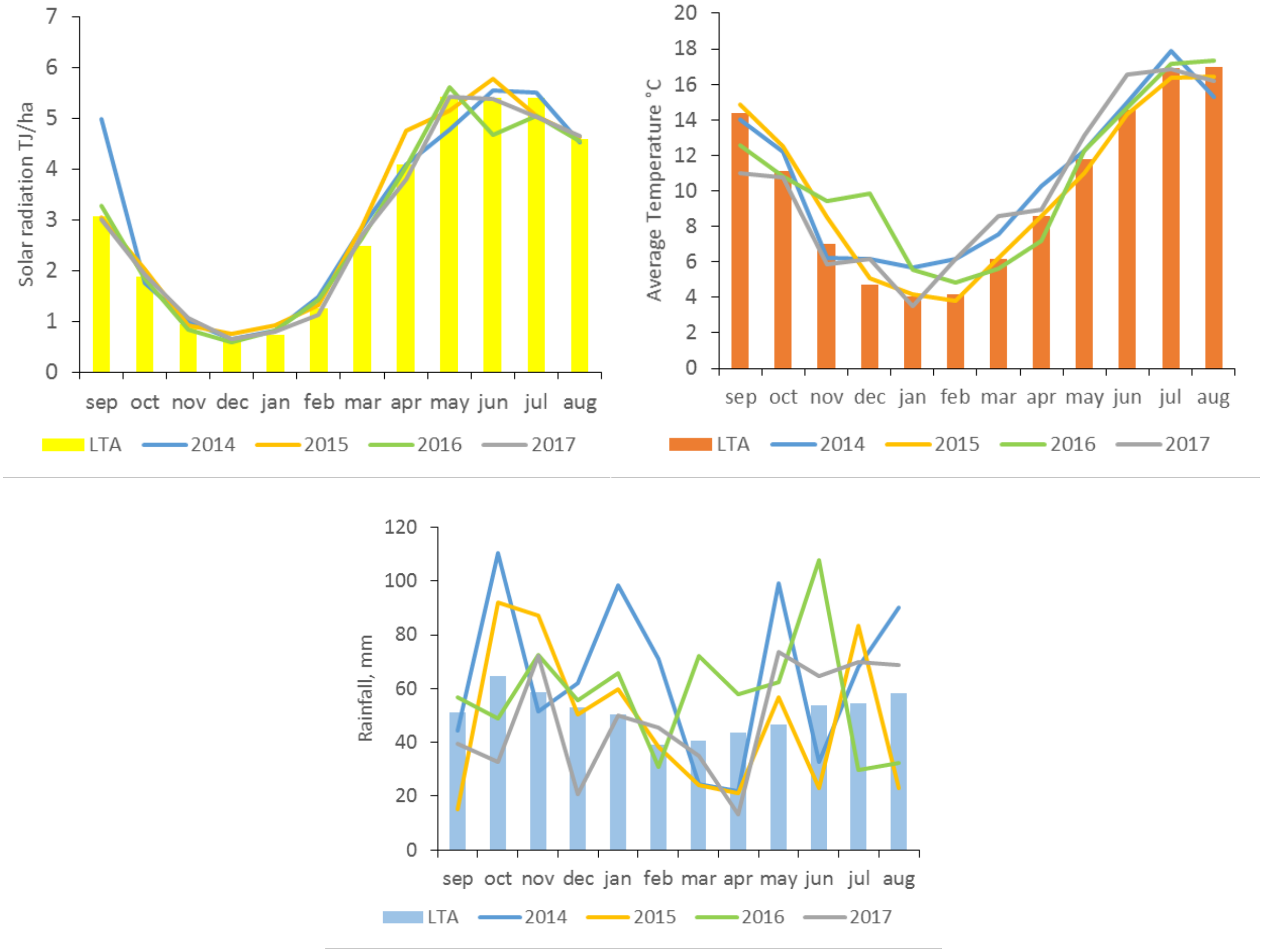


Figure 2. Monthly total solar radiation (TJ/ha), average temperature (^{o}C) and total rainfall (mm) of harvest seasons 2014 – 2017 for East Anglia, representative of the core sites (Irriguide data).

4.1.2. Core site experiments

The six core sites were chosen to all be categorised as the same soil type and rainfall area when using the RB209 FAM (defra, 2010), with site details summarised in Table 2. They were all situated in East Anglia (Essex, Suffolk and Norfolk) so classed as ‘low’ in the over winter rainfall category. Most fields tested were in the ‘deep clay’ soil category with some classed as ‘medium’, although recommendations for both categories were the same.

At the start of the project each farmer was visited and a number of fields earmarked to be used over the duration of the project (2014 - 2017 seasons). Where possible, fields were tested more than once in the project, although the extent to which this was achieved was variable. Epping had the most repeated fields, only using 6 over the whole project, and Belchamp Walter the least with 11 fields used over the project (Table 2). The crops tested could be first or second wheats of any variety. Four of the six sites predominantly tested first wheats, with the remaining sites testing a similar number of first and second wheats (Table 2). At three of the sites only feed wheats were tested; the other three tested mostly milling varieties (Table 2).

There were no restrictions placed on the type of fertiliser that could be used in the experiments, and the ‘standard’ was determined by the farmer using their usual methodology (RB209 recommendations, previous experience etc.). For all sites, the farm ‘standard’ N rate was always at least 200 kg N/ha, even where RB209 recommendations would have been lower, and the range smaller than the range of RB209 recommendations (Table 2). The highest ‘standard’ N rates (240 – 260 kg N/ha) were applied at Peldon where all but one crop tested was a milling wheat (Table 2).

Table 2. Background information about each of the six LearN Core sites

Site	Supporter	Location	Principal soil texture	Principal RB209 texture class	Manure History (0=none, 3=recent)	No. different fields used	No. 1st wheats (/12)	No. feed varieties (/12)	Principal fertiliser type	Range 'standard' N rates (kg N/ha)	Range of RB209 SMN recommend-ation*
Epping	ADAS	Epping, Essex	Silty Clay	Deep clay	2	6	6	2	Urea	200-260	150-250
Clavering	ADAS	Saffron Walden, Essex	Silty Clay	Deep clay	0	8	5	12	Ammonium sulphate	200-240	160-220
Thurlow	Agrii	Haverhill, Suffolk	Silty Clay	Deep clay	0	7	9	3	Urea	220-240	220-250
Belchamp Walter	Agrii	Dunmow, Essex	Sandy clay loam	Deep clay	1	11	12	12	Liquid N + S	220-254	220-250
Morley	NIAB	Wymondham, Norfolk	Sandy clay	Deep clay	2	8	10	12	Liquid N + S	220-240	120-250
Peldon	NIAB	Colchester, Essex	Silty clay	Deep clay	1	8	10	1	Urea Ammonium Nitrate	240-260	90-280

* RB209 recommendations based on Fertiliser Manual (defra, 2010)

Table 3. Summary of soil information for the six core sites measured in the early spring of each season and before any N was applied.

		Mean of 3 fields (range)				
Site	Year	Organic matter (%)	Soil Mineral N (kg/ha)	Estimate of Additionally Available N (kg N/ha)	Crop N estimate (kg /ha)	Total SNS (kg/ha)
Epping	2014	6.0 (1.6)	39 (45)	24 (2)	18 (5)	82 (38)
	2015	5.4 (1.2)	97 (15)	23 (11)	15 (20)	136 (8)
	2016	6.2 (2.7)	86 (28)	29 (18)	17 (10)	132 (37)
	2017	5.1 (1.2)	81 (37)	34 (45)	13 (5)	128 (16)
	Mean	*5.9*	*74*	*26*	*17*	*116*
Clavering	2014	4.6 (1.5)	26 (4)	19 (13)	17 (5)	61 (10)
	2015	4.8 (1.4)	70 (50)	26 (21)	20 (0)	117 (58)
	2016	4.1 (0.1)	50 (20)	15 (15)	18 (15)	83 (50)
	2017	4.5 (0.9)	69 (12)	22 (5)	17 (5)	108 (12)
	Mean	*4.5*	*49*	*20*	*18*	*87*
Thurlow	2014	4.2 (0.2)	42 (1)	15 (3)	13 (5)	71 (3)
	2015	3.6 (0.5)	43 (5)	99 (12)	15 *	157 (22)
	2016	4.3 (0.6)	39 (21)	21 (9)	15 *	70 (10)
	2017	3.8 (0.1)	42 (4)	19 (9)	15 *	76 (7)
	Mean	*4.0*	*41*	*45*	*	*99*
Belchamp Walter	2014	2.8 (0.3)	43 (11)	16 (7)	15 *	73 (18)
	2015	4.0 (4.0)	29 (9)	20 (7)	15 *	64 (12)
	2016	2.7 (0.7)	36 (5)	19 (2)	15 *	69 (5)
	2017	3.5 (1.4)	28 (12)	26 (10)	15 *	69 (22)
	Mean	*3.2*	*36*	*18*	*	*69*
Morley	2014	3.0 (0.5)	78 (80)	14 (23)	12 (5)	104 (60)
	2015	2.9 (0.7)	24 (4)	24 (9)	12 (3)	61 (17)
	2016	2.7 (2.2)	36 (41)	27 (17)	18 (9)	81 (54)
	2017	3.3 (1.9)	54 (38)	16 (5)	9 (8)	79 (34)
	Mean	*2.9*	*46*	*22*	*14*	*82*
Peldon	2014	3.5 (2.1)	60 (31)	17 (15)	10 (8)	87 (44)
	2015	3.1 (1.2)	44 (34)	35 (34)	12 (11)	91 (58)
	2016	4.6 (0.8)	117 (93)	17 (3)	20 (5)	147 (70)
	2017	2.5 (0.6)	75 (54)	23 (5)	8 (1)	107 (49)
	Mean	*3.8*	*74*	*23*	*13*	*109*
2014		*4.0*	*48.0*	*18*	*14*	*80*
2015		*4.0*	*51.3*	*38*	*15*	*104*
2016		*4.1*	*60.6*	*21*	*17*	*97*
2017		*3.8*	*58.3*	*23*	*13*	*94*
	Mean	*4.0*	*55*	*25*	*15*	*94*

* No estimates of crop N were available so a standard value of 15 kg N/ha was assumed

4.2. Variability in N requirements from N response experiments

Response from the 72 N response experiments across fields farms and seasons are shown in Figure 3 - Figure 9. Four trials were excluded from further analyses due to issues with N application errors, severe weed infestation and poor fitting of response curves.

The collated responses in Figure 3 shows the wide variation in responses and N optima. The N optima (triangles on each figure) ranged from 88 to 356 kg N/ha. The yields at the N optimum (Figure 3a) demonstrated that these sites were generally higher yielding that average with yields commonly between 10 and 12 t/ha, although there were a number of fields where the yield at the N optimum was 8 t/ha or below. The grain protein at N optimum varied between 9.9 and 14.0 % (at 100% DM; Figure 3b) with average proteins at N optimum 12.6 % and 11.1 % for milling and feed varieties, respectively. As with the yield and protein responses, the slopes of the grain N offtake broken sticks varied among fields (Figure 3c); grain N offtake at 0 kg N/ha ranged from 36 to 17 kg N/ha and the maximum ranged from 109 to 292 kg N/ha.

However, looking at the responses of individual fields in Figure 4, 5, 6, 7, 8 and 9, responses within farms and years seem to show some consistency, especially in some farms. For example at Morley (Figure 5), within each season the responses of yield to N were very consistent, with the exception of one field in 2015 and one in 2017. Thurlow showed a similar story (Figure 9) with similar yield responses despite differing absolute yields. At Clavering (Figure 4) responses were moderately similar within seasons but absolute yields differed between fields in 2015 and 2016. The responses to N and absolute yields at Epping (Figure 6) and Belchamp Walter (Figure 8) were more variable within seasons than most other sites.

The most striking consistencies are seen in the grain protein responses within farms within years; at all farms the protein responses of different fields in each year tend to track each other remarkably closely (Figure 4, 5, 6, 7, 8, 9), especially given the overall variability in protein responses evident in Figure 3b.

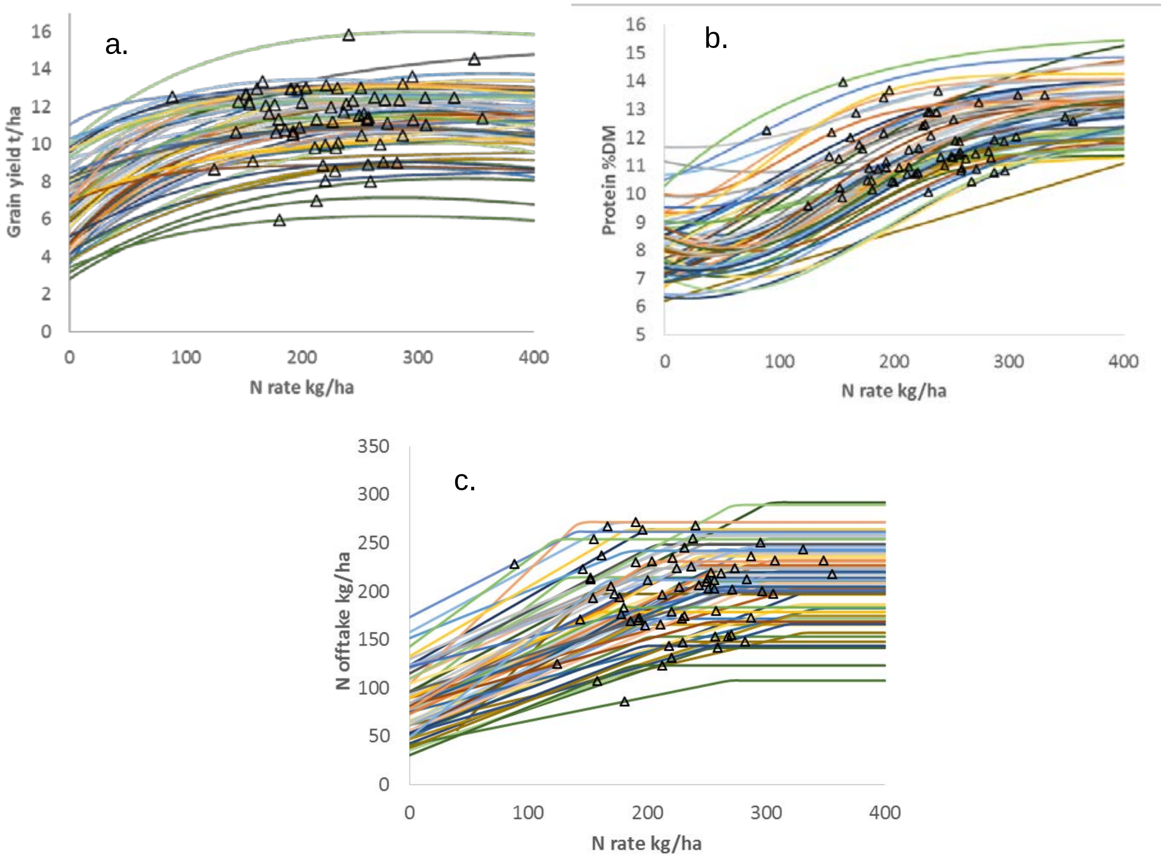


Figure 3. N responses from 72 small plot experiments conducted on the six core sites from 2014-2017. For each experiment, the open triangle gives the optimum N rate.

Figure 4. : The response of yield (t/ha), protein (% DM) and grain N offtake (kg/ha) to N at Clavering in seasons 2014 – 2017 where fields are: ●Millcroft ■ Newport Leys ♦The Downs ♦Gelding Ley ■ Kangels ●Barley Hills ■ Chimney field. Open triangles are the optimum N rate and bars are +/- SE of the Nopt.

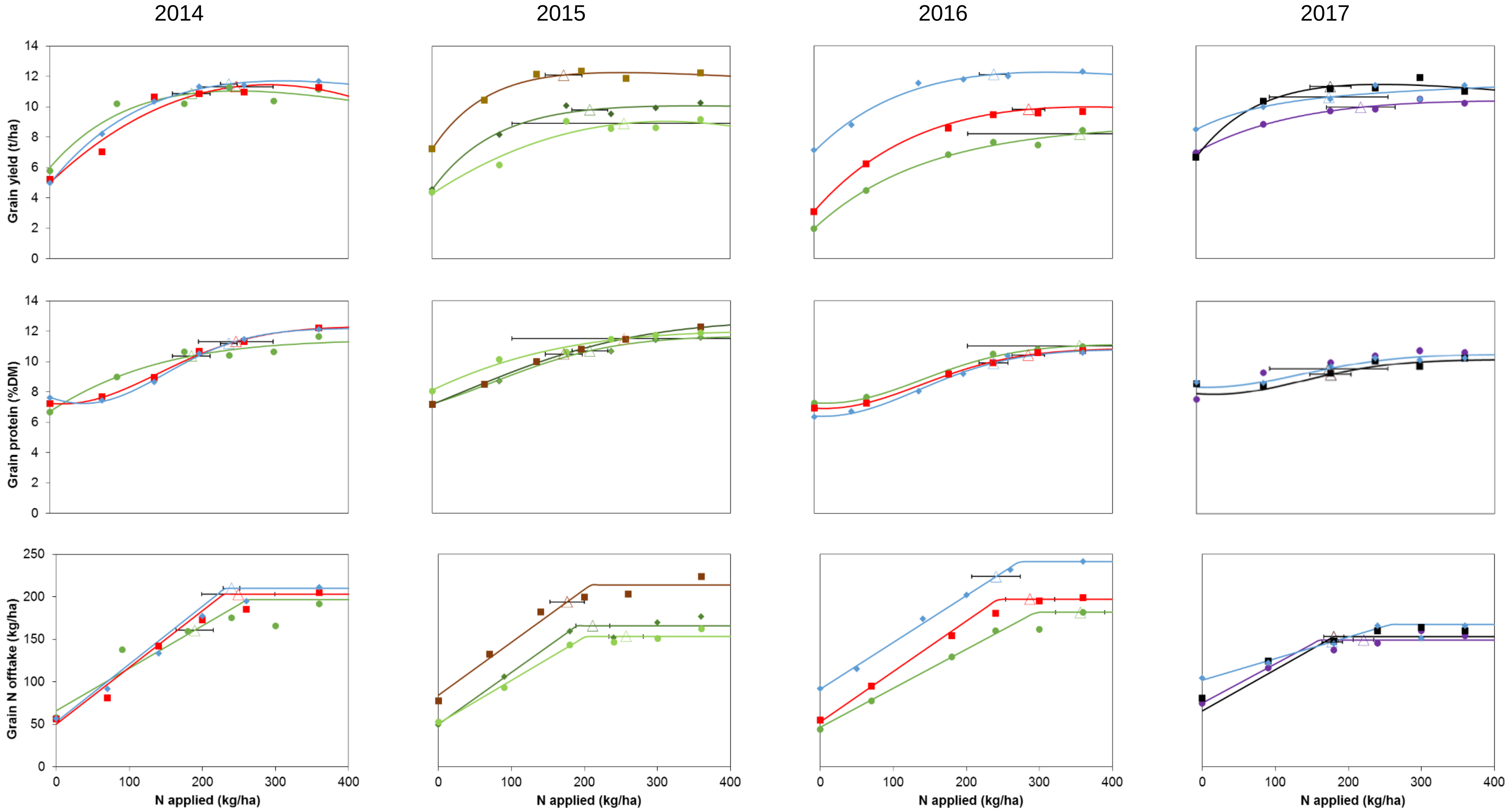


Figure 5. The response of yield (t/ha), protein (% DM) and grain N offtake (kg/ha) to N at Morley in seasons 2014 – 2017 where fields are: ● Skippers ■ Blofields ♦Hastings ● Little Gymballs ■ Manns ♦ McLeans ● Bullswood ● Angelas . Open triangles are the optimum N rate and bars are +/- SE of the Nopt.

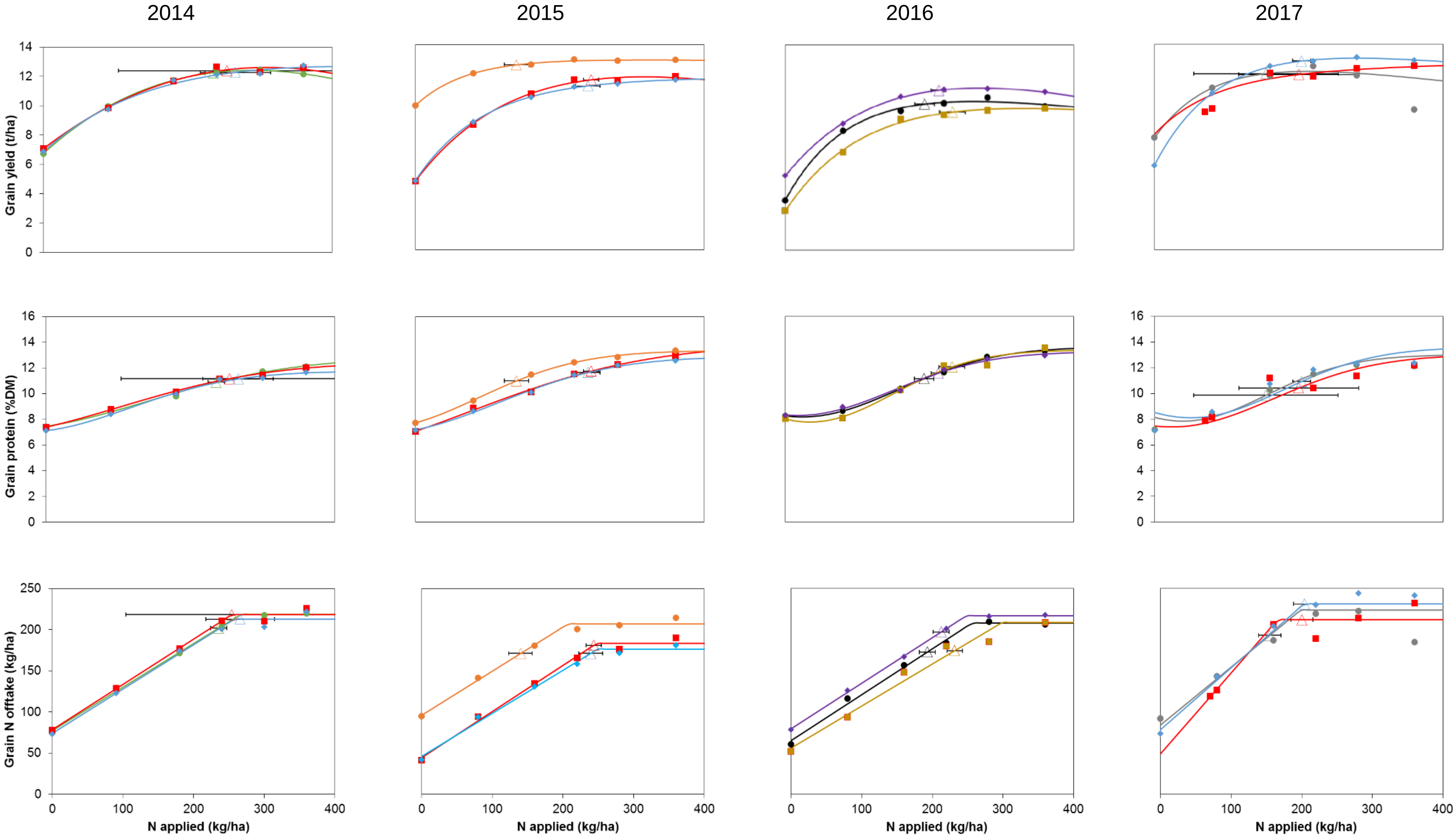


Figure 6. The response of yield (t/ha), protein (% DM) and grain N offtake (kg/ha) to N at Epping in seasons 2014 – 2017 where fields are: ●Beezons ■ Baggots ♦Grid end ■ Broadmead ♦ Browns. Open triangles are the optimum N rate and bars are +/- SE of the Nopt.

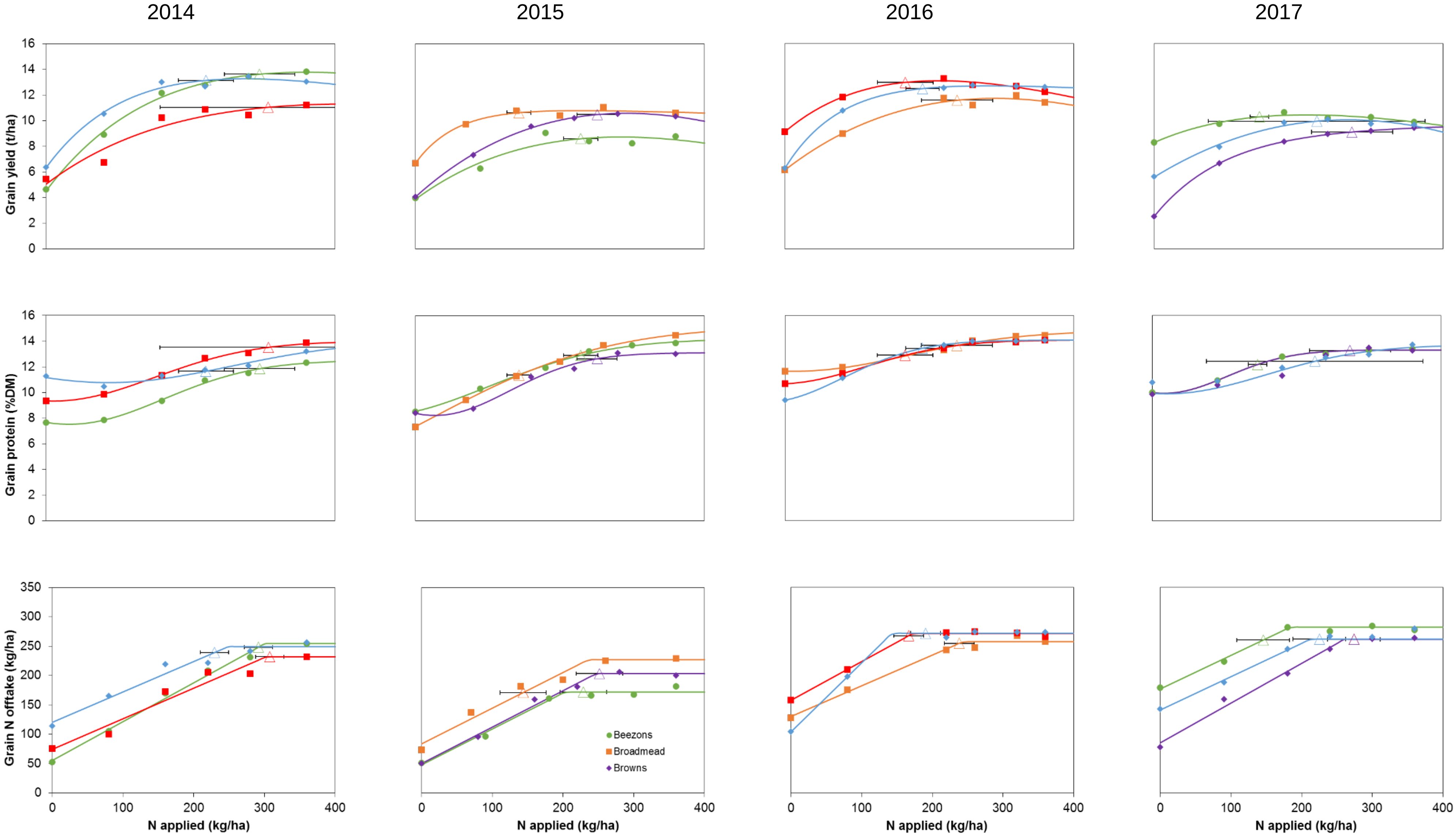


Figure 7. The response of yield (t/ha), protein (% DM) and grain N offtake (kg/ha) to N at Peldon in seasons 2014 – 2017 where fields are: ● Salters ■ Woodhall South ♦Big field ● Holts ■ 30 acres ♦ 40 acres . Open triangles are the optimum N rate and bars are +/- SE of the Nopt.

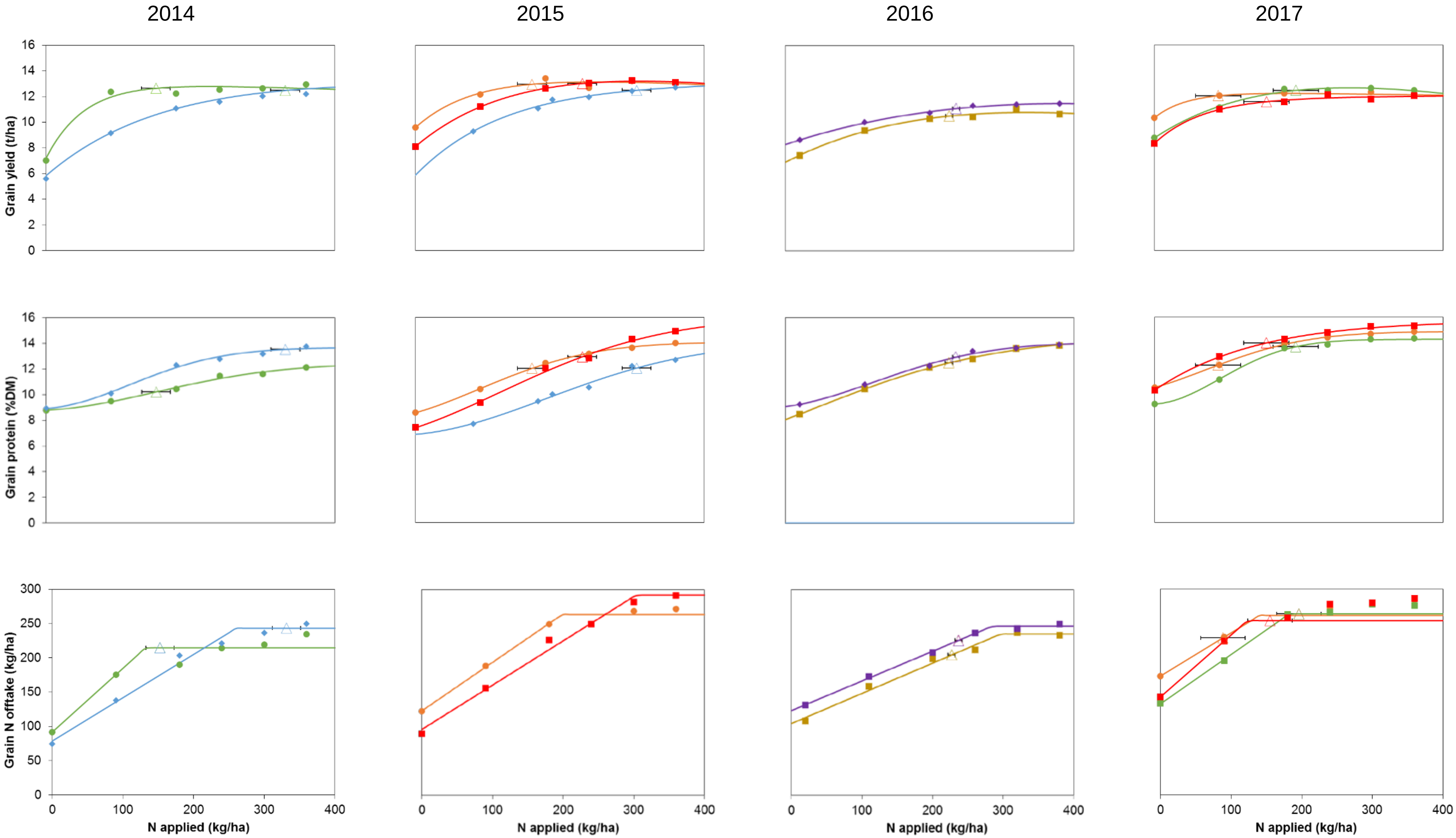


Figure 8. The response of yield (t/ha), protein (% DM) and grain N offtake (kg/ha) to N at Belchamp Walter in seasons 2014 – 2017 where fields are: ●7 Forms ■ Sudbury road ◆Top of crows farm :● 40 acre corner ■ Newbon ♦ Top of Clarks ● Otten road ■ T junction ♦ Caravan ■ School field. Open triangles are the optimum N rate and bars are +/- SE of the Nopt.

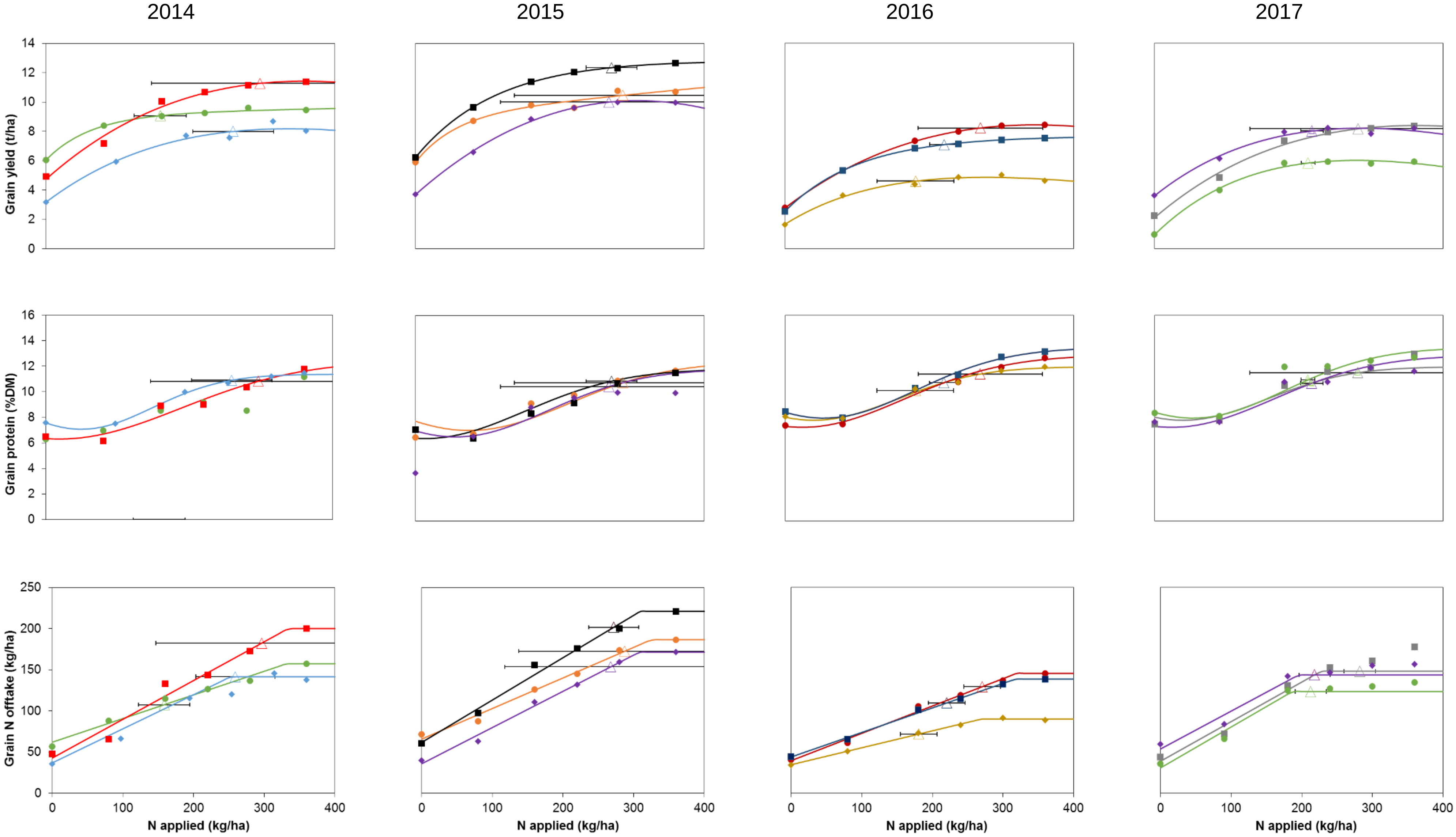
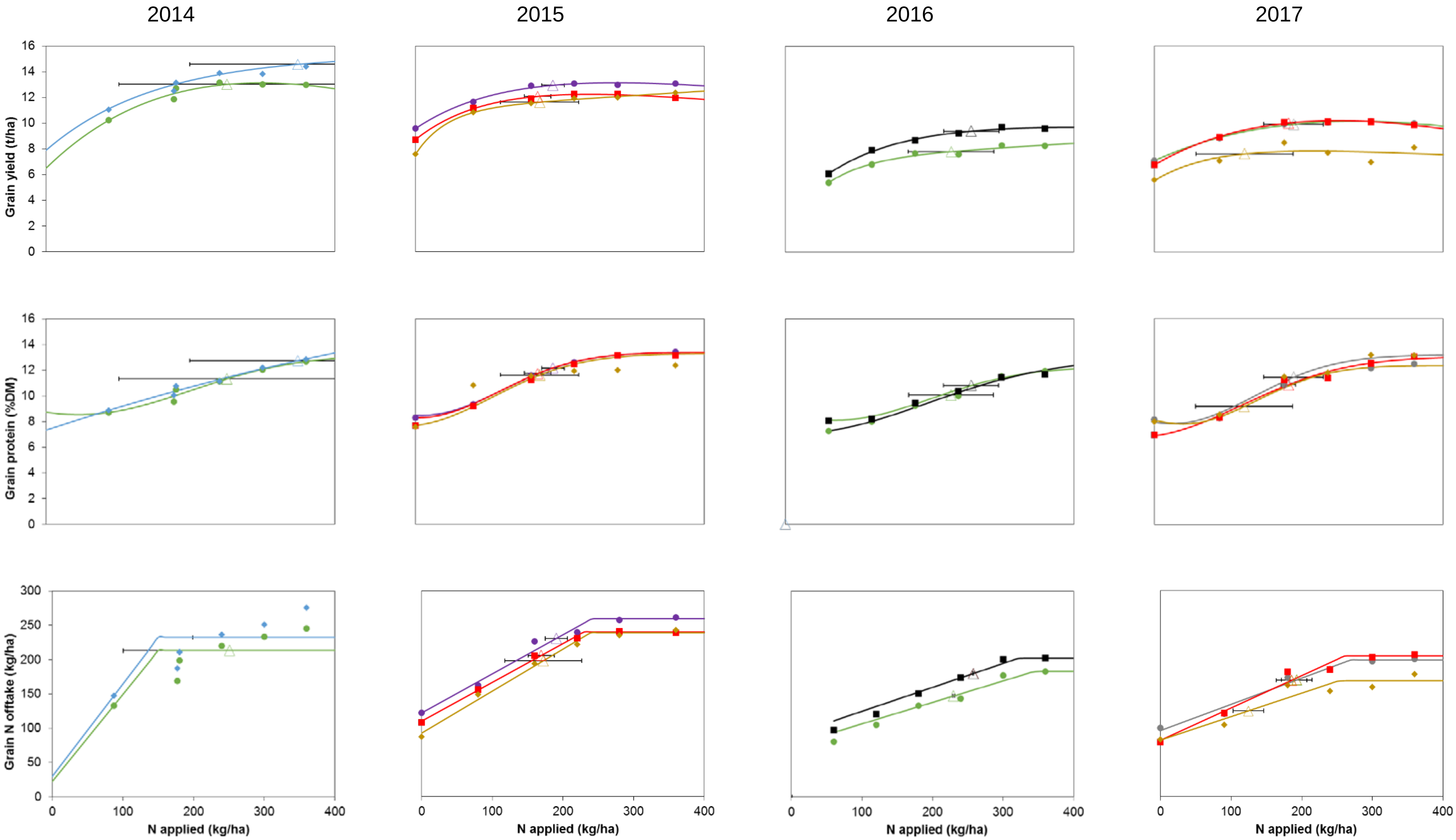


Figure 9. The response of yield (t/ha), protein (% DM) and grain N offtake (kg/ha) to N at Thurlow in seasons 2014 – 2017 where fields are: ● W063 ■ M420 ♦ W059 ● M463 ■ W065 ♦ M431 ● M432. Open triangles are the optimum N rate and bars are +/- SE of the Nopt.



N optimum for yield varied from 88 kg N/ha to 356 kg N/ha, with a mean of 225 kg N/ha, whereas the N rates used by farmers varied from 200 to 300 kg N/ha, with an average rate of 238 kg N/ha. Yields at the N optima varied from 5.9 to 15.8 t/ha, with a mean yield of 11.3 t/ha, which is the same as that achieved with the farm standard N rates. Protein contents at the optima varied from 9.9 to 14.0 %DM, with a mean of 11.7 %DM. At the farm standard N rate proteins varied from 9 to 14.8% DM, with a mean of 11.7 %DM.

When converted to total N uptake by assuming a N harvest index of 80%, the fitted N offtake curves provide estimation of the three components of N requirement; crop N demand (plateau), soil N supply (intercept) and fertiliser recovery (slope). Estimated harvested SNS varied from 38 to 217 kg N/ha, with 102 kg/ha mean. Crop N demand varied from 135 to 365 kg N/ha, with 266 kg N/ha mean. Fertiliser recovery ranged from 31% to 123%, with a mean of 70%.

4.2.1. Assessing variation in N requirement between fields, farms & years

This project was set up to assess at what levels the major variability in N requirement resides. Table 4 and Figure 10 summarise variation in N requirements between farms and fields, showing that there seemed to be similar levels of variation in N requirement within farms with little evidence of large consistent differences between farms. Contrastingly, the variation in yields and protein indicate substantial variation between farms (Figure 11).

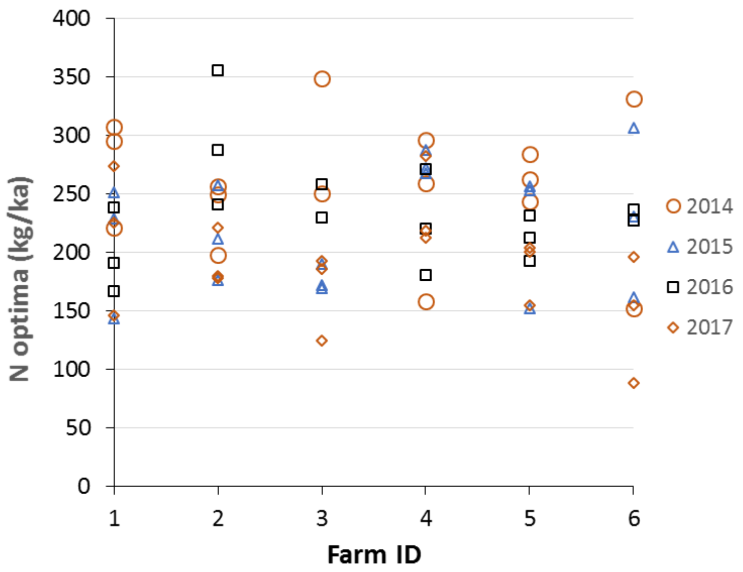


Figure 10. Variation in optimum N rate (N optima) for yield between seasons and sites, where Farm ID 1 = Epping, 2 = Clavering, 3 = Thurlow, 4 = Belchamp Walter, 5 = Morley and 6 = Peldon.

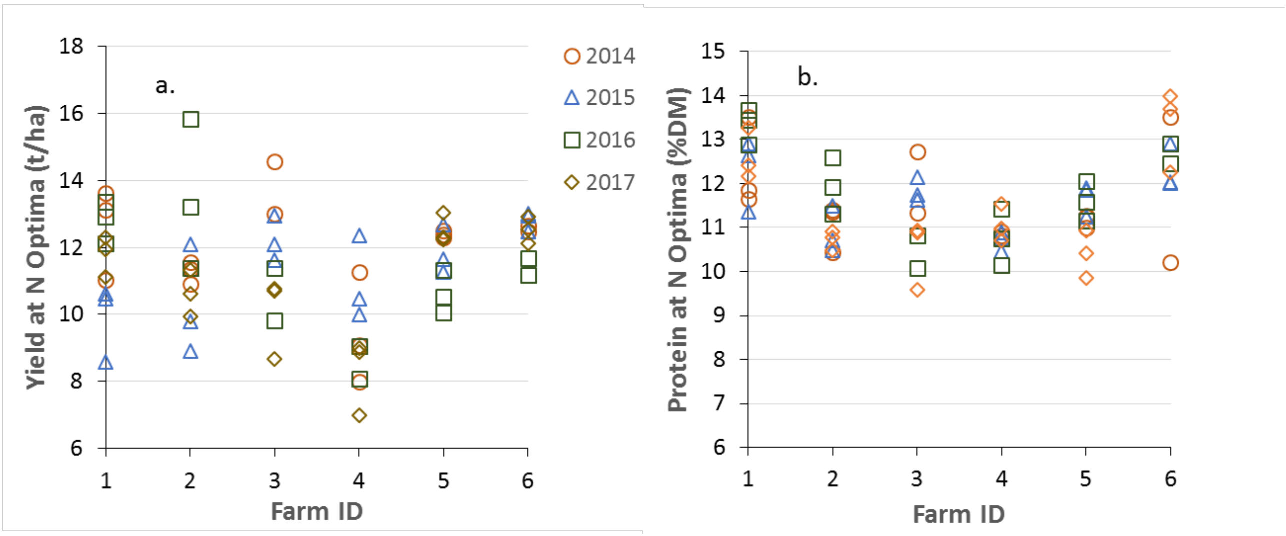


Figure 11. Variation in: a) Yield (t/ha at 85% DM), and b) Protein (% at 100% DM) at optimum N rate (N optima) for yield between seasons and sites, where Farm ID 1 = Epping, 2 = Clavering, 3 = Thurlow, 4 = Belchamp Walter, 5 = Morley and 6 = Peldon.

N optima were found to be higher in 2014 and lower in 2017. The causes of these seasonal differences seem to be explicable in terms of soil N supply and yield; in 2014 season there was lower SNS (both measured in spring (80kg N/ha) and harvested SNS (86 kg N/ha)) and higher yields (11.9 t/ha); 2017 had higher harvested SNS (117 kg N/ha), though spring soil measures (94 kg N/ha) were not higher than 2015 or 2016 (104 & 107 kg N/ha respectively), and marginally lower yields (11.0 t/ha in 2017 vs 11.3 and 11.1 t/ha in 2015 & 2016 respectively). There was substantial rainfall over the autumn/winter of 2013/2014 (Figure 2) that would have resulted in more leaching. This explains the lower SNS in this year and the resulting higher N requirements. In 2017 there was a prolonged dry period in spring (April) that was held to have restricted N uptake and tillering, followed by a wet May and summer. This could have resulted in late mineralisation of N giving substantial late N uptake, as evidenced by the higher harvested SNS and high protein contents at the standard N level (12.3% DM in 2017 vs 11.1, 11.6 and 12.0 in 2014, 2015 and 2016 respectively).

Table 4. Results of N response trials (6 N rates from 0 to 360 kg N/ha) carried out at six core sites over four seasons. Yields are t/ha at 15% moisture content.

		Mean of 3 fields (range)					
Site	Year	Optimum N rate (kg N/ha)	Yield at Nopt (t/ha)	Grain protein at Nopt (%)	Total N offtake at 0 kg N/ha (kg/ha)	Max. total N offtake (kg/ha)	Farm standard N rate (kg/ha)
Epping	2014	275 (86)	12.6 (2.6)	12.3 (2.1)	84 (52)	245 (22)	220-240
	2015	208 (108)	9.9 (2.0)	12.3 (2.0)	58 (23)	201 (55)	200-240
	2016	198 (72)	12.8 (1.3)	13.3 (1.3)	130 (54)	267 (14)	260
	2017	215 (118)	11.8 (1.2)	12.6 (1.2)	114 (87)	230 (18)	240
Mean		*224*	*11.8*	*12.6*	*98*	*236*	*238*
Claverin	2014	235 (58)	11.3 (0.7)	11.1 (1.0)	56 (2)	203 (13)	200-240
	2015	215 (81)	10.3 (3.2)	10.9 (1.0)	59 (29)	177 (61)	200-240
	2016	295 (115)	13.5 (4.4)	11.9 (1.3)	76 (44)	248 (71)	240
	2017	193 (43)	10.6 (1.3)	10.7 (0.4)	104 (36)	188 (18)	240
Mean		*234*	*11.4*	*11.2*	*73*	*104*	*230*
Thurlow	2014*	300 (98)	13.3 (1.6)	11.4 (1.4)	146 (14)	248 (19)	240
	2015	177 (21)	12.2 (1.3)	11.8 (0.6)	106 (35)	246 (20)	220
	2016*	244 (28)	10.8 (0.6)	10.9 (0.7)	87(16)	194 (19)	240
	2017	168 (68)	10.0 (1.9)	10.5 (1.3)	87 (14)	191 (36)	280
Mean		*212*	*11.6*	*11.5*	*92*	*212*	*246*
Belchamp Walter	2014	238 (138)	9.4 (3.3)	10.9* (0.1)	47 (21)	166 (58)	220-254
	2015	276 (19)	10.9 (2.3)	10.7 (0.4)	57 (32)	193 (50)	330
	2016	224 (90)	7.7 (3.1)	10.8 (1.3)	48 (12)	150 (67)	240
	2017	238 (69)	8.3 (2.0)	11.1 (1.3)	46 (23)	138 (25)	240
Mean		*244*	*9.1*	*10.9*	*47*	*162*	*233*
Morley	2014	263 (40)	12.4 (0.2)	11.2 (0.3)	75 (5)	217 (6)	220
	2015	221 (104)	11.9 (1.4)	11.7 (0.6)	71 (65)	227 (36)	220
	2016	212 (39)	10.6 (1.2)	11.6 (1.0)	64 (27)	211 (9)	220
	2017	179 (61)	12.1 (2.0)	10.2 (1.4)	95 (45)	222 (19)	215
Mean		*221*	*11.9*	*11.2*	*72*	*219*	*219*
Peldon	2014*	242 (179)	12.6 (0.1)	11.9 (3.3)	83 (17)	229 (28)	259-300
	2015	233 (145)	12.8 (0.5)	12.3 (0.9)	107 (32)	251 (95)	240
	2016*	232 (10)	11.4 (0.5)	12.7 (0.4)	120 (24)	241 (11)	259-297
	2017	146 (108)	12.5 (0.8)	13.3 (1.7)	150 (39)	260 (10)	289-299
Mean		*208*	*12.4*	*12.6*	*118*	*244*	*269*
2014		*257*	*11.9*	*11.6*	*70*	*214*	*232*
2015		*222*	*11.3*	*11.6*	*76*	*216*	*224*
2016		*234*	*11.1*	*11.8*	*87*	*217*	*245*
2017		*191*	*11.0*	*11.6*	*93*	*205*	*252*
	Mean	*225*	*11.3*	*11.7*	*82*	*213*	*238*

* Results are mean of 2 fields as one was excluded from the analysis or in the case of the protein at optimum N rate, curve fitting would not optimise

A formal analysis of the variation in N requirement using REML (Figure 12) reveals that none of the variation was associated with different farms, although 32% of variation was associated with fields within farms. There were differences between year in N optima, associated with 22% of the variability. Contrastingly, there was a strong farm effect on the yields (28%) and protein (47%) achieved, with the effect of 'year' being less important.

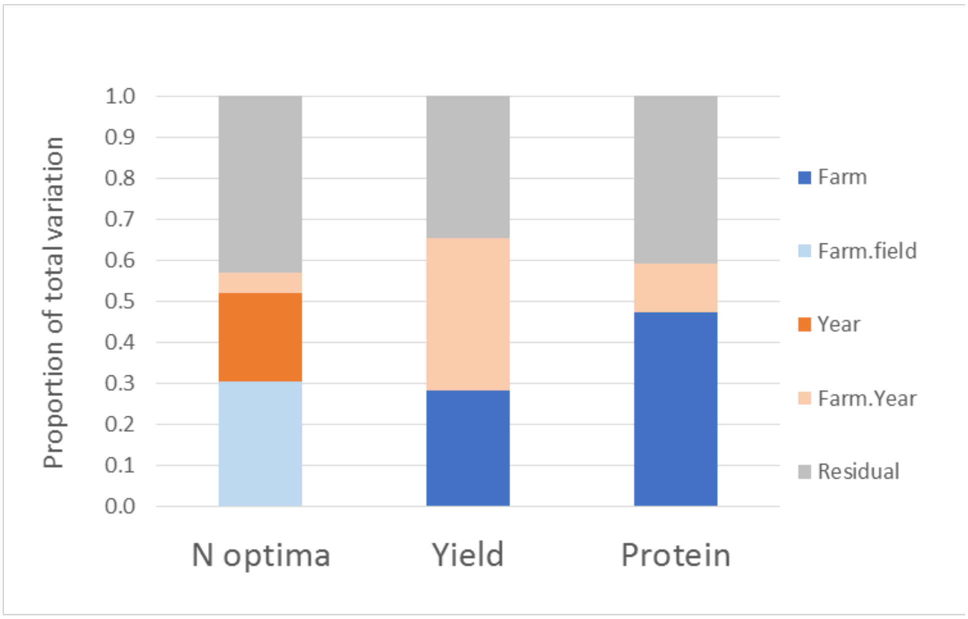


Figure 12. Partitioning variation between farms, fields & years using REML

The importance of other factors in explaining N requirement was also assessed by REML analysis. This showed the largest effect to be SNS index by RB209, with an effect of -39 kg/ha on N optimum between Index 1 and Index 2. This was also shown by an effect of rotational position with second wheats needing 25 kg/ha more than first wheats. There was no effect of SNS by measurement, milling vs feed variety, manure history, fertiliser type, soil texture or yield. Grain protein had an interesting association with N optimum; grain protein achieved at standard N rate was negatively associated with N optimum by 10 kg/ha per %DM, indicating protein can be a useful indicator of N optimum. However, the protein level at the optimum was positively associated with the optimum; the optimum increasing by 32 kg/ha for each 1% increase in protein. Given that protein level at the optimum and N optimum is mathematically linked (protein response is invariably positive around the optimum so increasing an N optimum will always increase grain protein) caution is needed in interpretation of this, but it does seem possible that varying 'protein demands' could be driving some of the variation in N optimum.

Assessing yield by REML showed significant associations with rotational position/SNS Index (1st wheat yielding 1 t/ha more than 2nd wheat) and a negative association with protein content (0.5 t/ha reduction in yield for each 1% increase in protein). No significant effects were seen of soil texture, SOM%, manure history, or milling vs feed variety. As regards grain protein at the N optimum, the biggest factor was milling vs feed variety, with soil texture (clay<loams) and yield level (-0.12%DM per t) giving small effects.

4.2.2. Explaining and predicting variation in N optimum

Figure 13 shows the variability in the components of yield (Crop N Demand, harvested SNS and fertiliser recovery) between farms, fields and years. Some farms have consistently lower SNS than others (e.g. Belchamp Walter) which is broadly reflected in the lower measured SNS. There are large differences in soil organic matter between farms with relatively little variation between fields within farms.

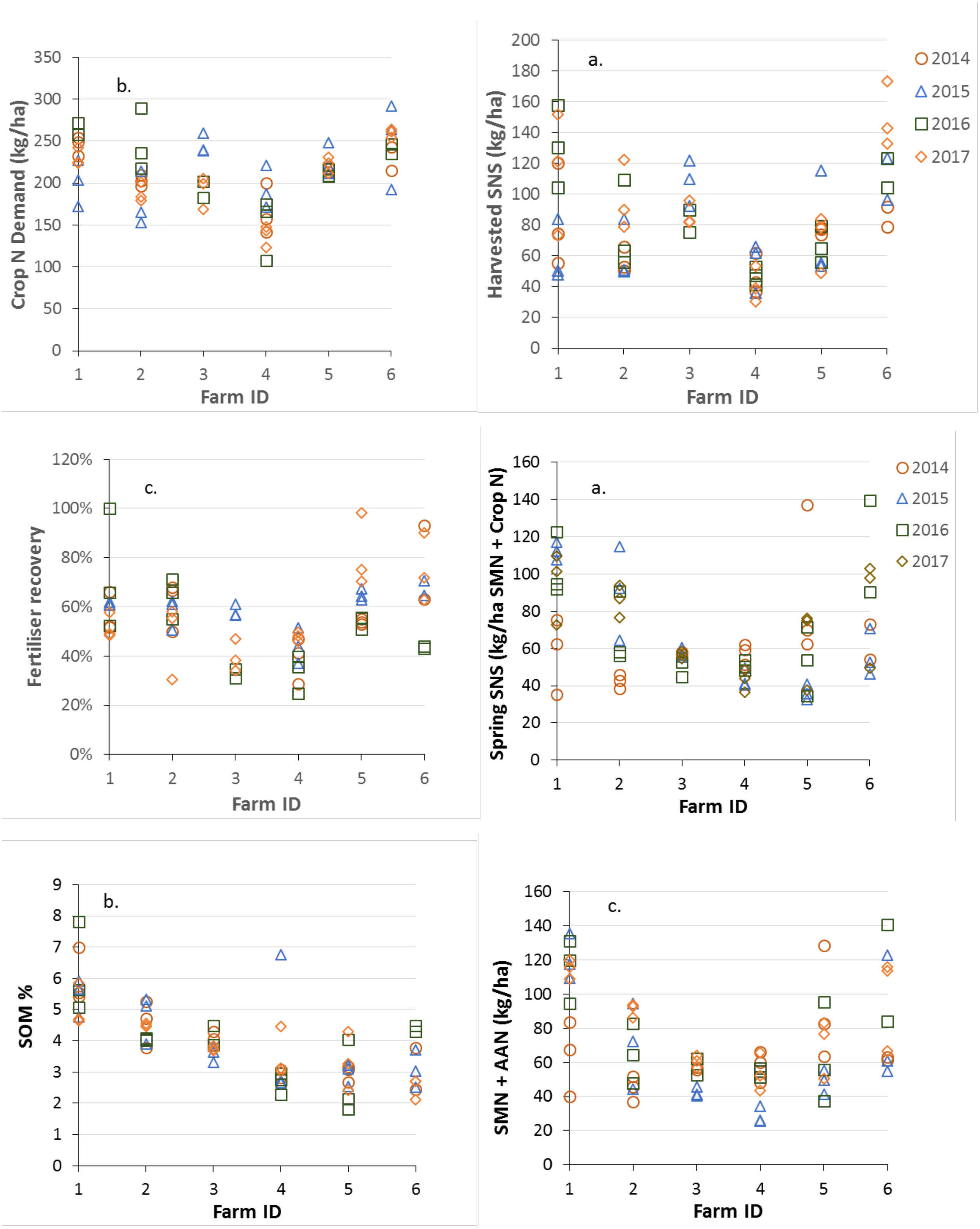


Figure 13. Variation in: a) Harvested SNS (kg/ha), b) Crop N demand (kg/ha) and c) Fertiliser recovery d) Spring SNS (kg N/ha measured in soil and crop), e) SOM (%) and f) SMN plus estimated AAN (kg N/ha) between seasons and sites, where Farm ID 1 = Epping, 2 = Clavering, 3 = Thurlow, 4 = Belchamp Walter, 5 = Morley and 6 = Peldon.

Looking at which components explain the variation in N requirement Figure 14 shows soil N supply to be the most important. Grain yield does not relate directly to N optimum in these data, though does relate to an adjusted estimate of available N accounting for harvested SNS.

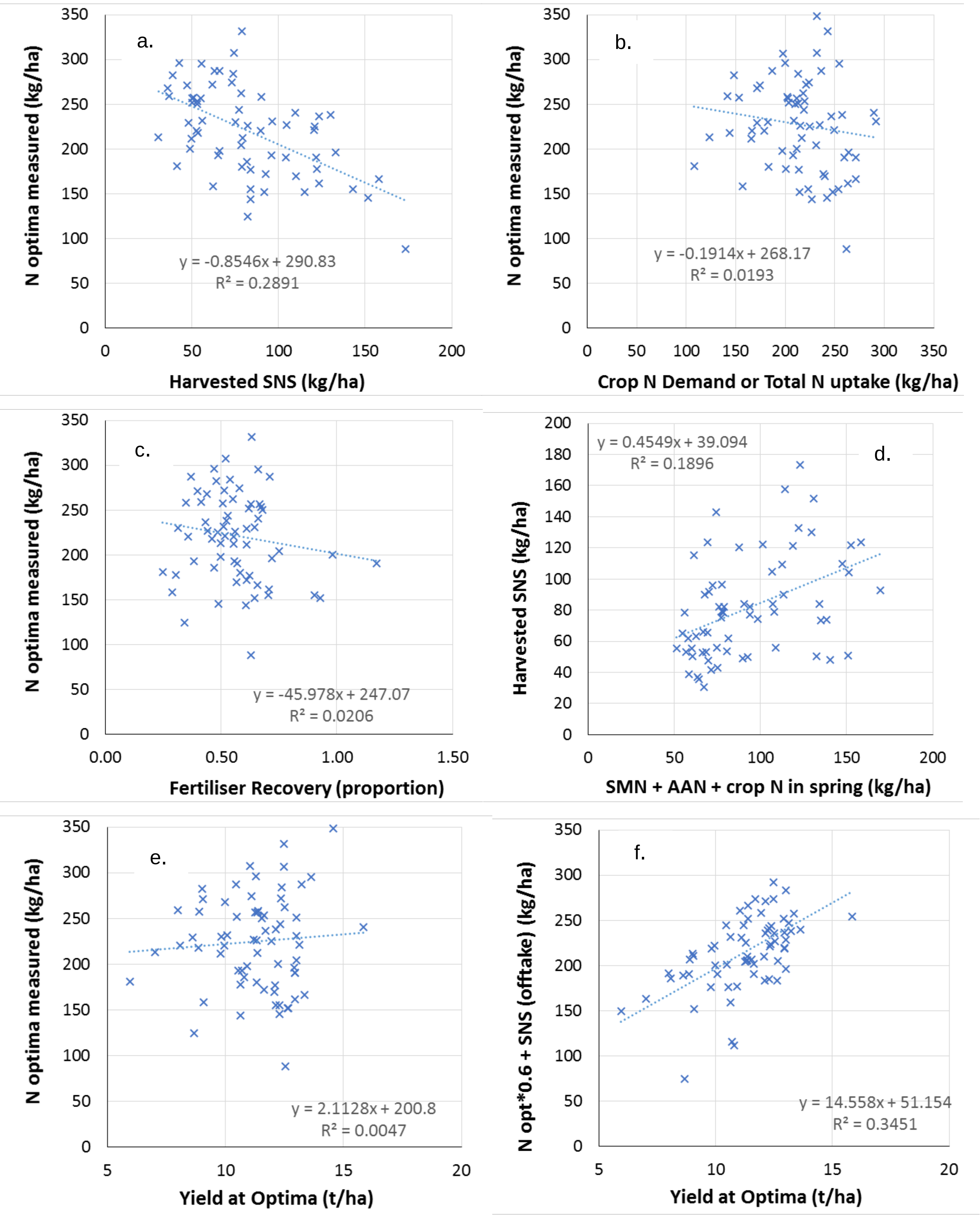


Figure 14. Understanding and predicting variation in N requirement through examination of relationships between: a) Harvested SNS (kg/ha) and N optimum calculated from small plot N response trials ((kg/ha); b) Crop N demand (or total N uptake (kg/ha) and N optimum calculated from small plot N response trials (kg/ha); c) fertiliser recovery (proportion; slope of the first line of the total N uptake broken stick regression) and N optimum calculated from small plot N response trials (kg/ha); d) SMN + AAN + crop N content measured in the spring (kg/ha) and harvested SNS (kg/ha); e) yield at the N optimum and N optimum calculated from small plot N response trials

(kg/ha); and f) yield at the N optimum and N offtake (N optimum x 0.6 (assumed fertiliser recovery) + SNS (kg/ha).

Looking at different approaches to estimate N requirements in Figure 15 it is difficult to do better than RB209 field assessment method (adjusted to 10 t/ha; Figure 15b). In general the standard N rates used by farmers were found to be about right, with the relationships in Figure 15d skewed by higher farm N rates but lower optimum observed at Peldon in 2017.

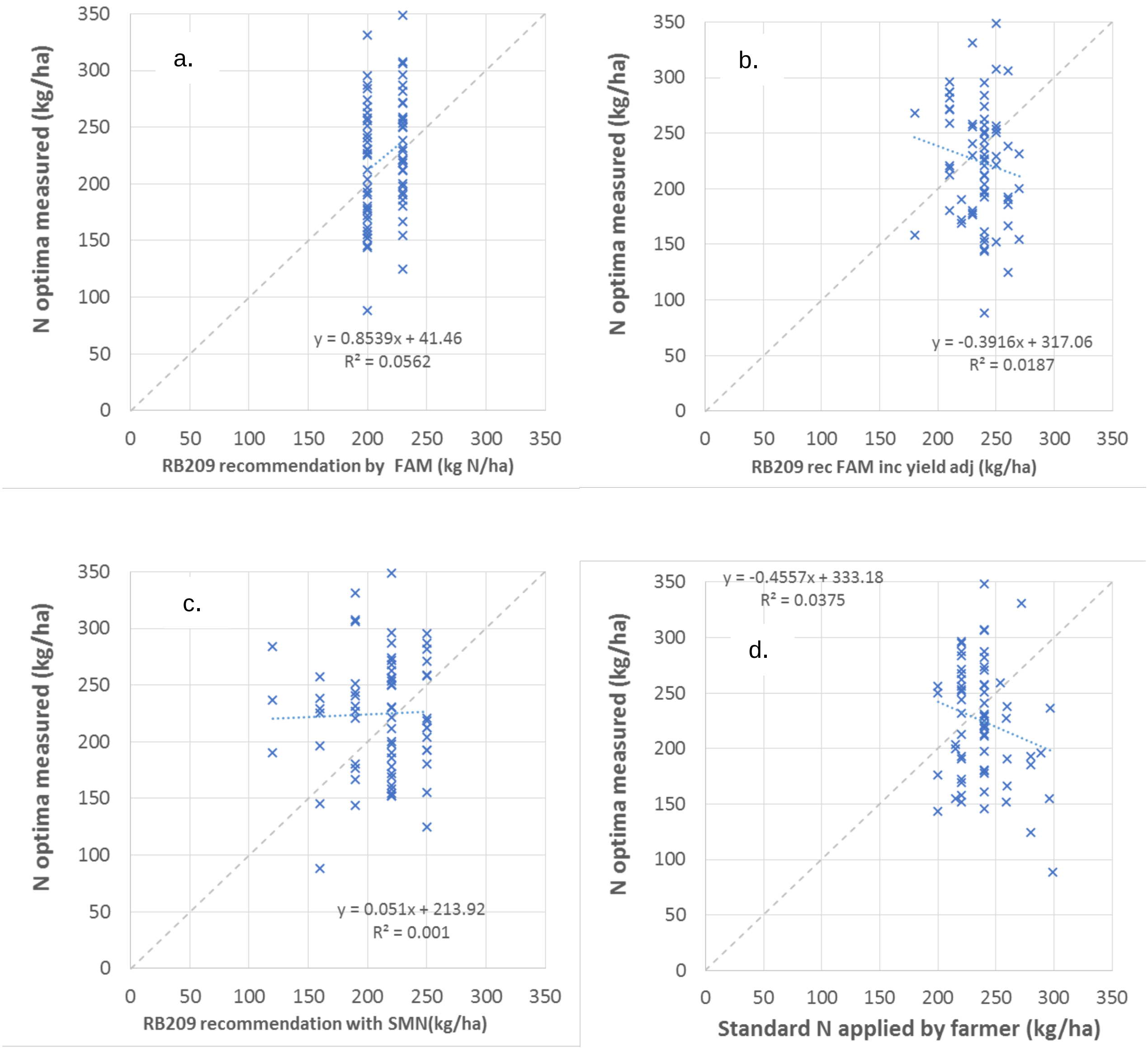


Figure 15. Estimating N requirements through examination of relationships between: a) RB209 recommendation by FAM (kg/ha); b) RB209 recommendation by FAM including an adjustment for yield (kg/ha); c) RB209 recommendation with SMN (kg/ha); d) standard N rate applied by the farmer (kg/ha) and N optimum calculated from small plot N response trials (kg/ha).

There is substantial variation in the grain protein content at the N optimum, and in achieved protein contents at the farm standard N rate, that relate weakly to N optimum (Figure 16). The optimal protein content is positively related to N optimum, suggesting that there may be a 'protein demand' influence on protein content (higher protein varieties having a higher protein 'demand', hence higher N optima; although in this dataset the average N optima for milling crops is lower than for feed crops). The protein at the standard N rate is slightly negatively related to the N optimum, suggesting that high protein contents can be indicative of the farm rate being super-optimal, and vice versa.

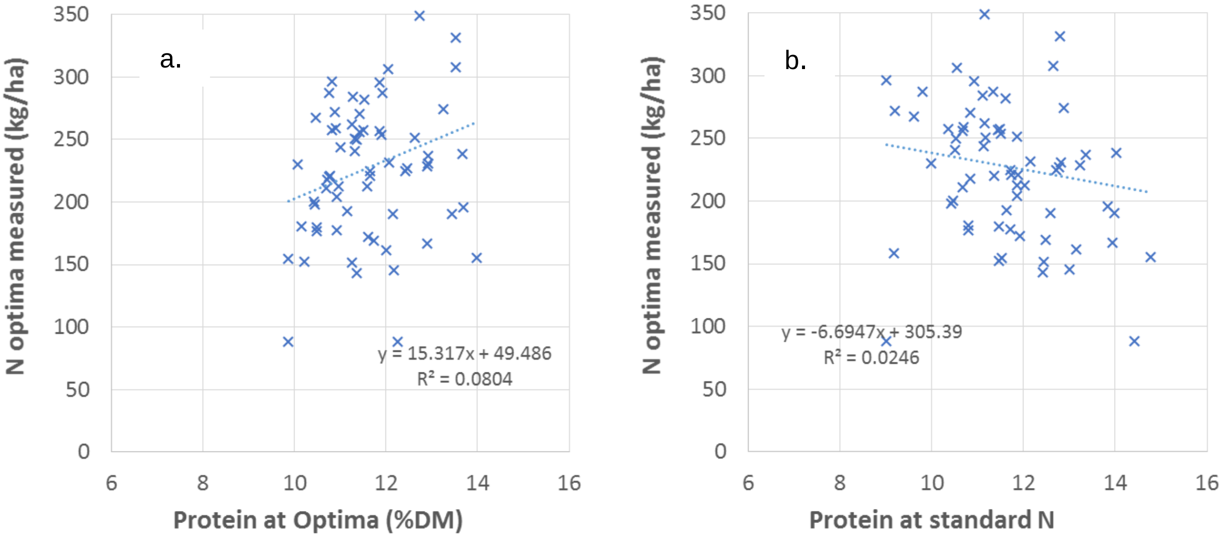


Figure 16. Relationships between grain protein (% at 100% DM) at: a) the N optimum; b) the farmers' standard N rate and the N optimum calculated from the small plot N response trials.

4.2.3. Considering economics of variation in N

The potential benefit of perfecting N management on every field can be judged by comparing the financial margins over N costs at the farm-applied N rates with those achievable at the measured N optimum (Figure 17). It is obvious from Figure 17 that any improvement in profitability possible from fine tuning rates is very modest in relation to the overall variation in net margins. Overall, the margin could be improved from £1,406/ha to £1,424/ha by perfecting N management across this population of fields, but overall financial margins vary from <£750/ha to >£2000/ha.

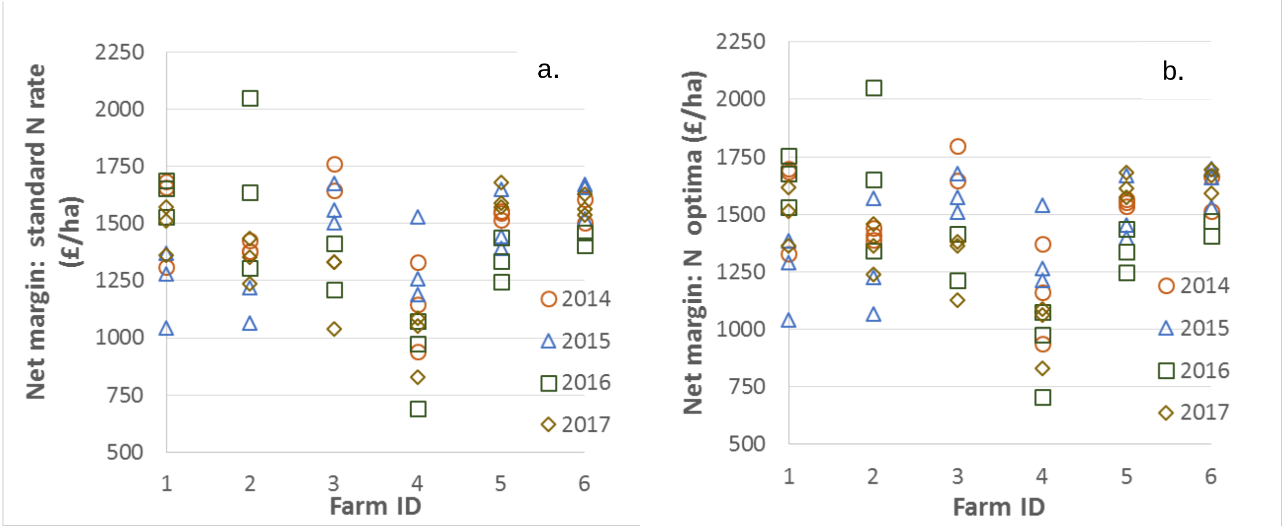


Figure 17. Variation in: net margin (£/ha) when fertiliser applied at a) the farm standard N rate treatment and b) the calculated optimum N rate, between seasons and sites, where Farm ID 1 = Epping, 2 = Clavering, 3 = Thurlow, 4 = Belchamp Walter, 5 = Morley and 6 = Peldon.

Table 5 and Figure 18 show the 'lost profit' from inaccuracies in N recommendations using a range of approaches. Overall, lost profits from using farm standard N rates (238 kg N/ha) average £18 /ha; standard N rates averaged 13 kg N/ha more than optimal N rates and yielded 0.06 t/ha less. If simple RB209 N recommendations (adjusted to a standard 10 t/ha) were used by all farms then lost profit would have been reduced to £14.50 /ha; 10 kg/ha less N would have been applied than optimal and yields would have been 0.15 t/ha less. Adjusting RB209 recommendations to 11 t/ha with 20 kg/ha more, would increase yield by 0.11 t/ha and profits by £1/ha. If yield expectations by farm were used to adjust RB209 recommendations then lost profit would increase to £17 /ha, adjusting by actual achieved yields increases lost profit to £27 /ha. The best financial performance actually comes from applying a common N rate across the board.

Table 5. Comparison of different approaches to deciding N fertiliser rates

Approach	Average N applied kg/ha	Average Yield t/ha	Average Margin over N £/ha	Average Lost profit £/ha
Optimal N	225	11.31	£1424	-
Farm Standard	239	11.24	£1406	£17.82
RB209 (8 t/ha)	175	10.83	£1394	£30.41
RB209 (10 t/ha)	215	11.14	£1410	£14.49
RB209 (11 t/ha)	235	11.25	£1411	£13.46
RB209 farm adjusted yield	236	11.23	£1407	£17.16
RB209 actual yield	241	11.19	£1397	£26.71
Standard N rate 225	225	11.20	£1411	£13.23
Standard N rate 240	240	11.27	£1410	£13.68

Adjustments to N rates make very modest differences to profitability. In refining approaches to N recommendations it seems to be much easier to make the average financial performance worse than it is to make it better.

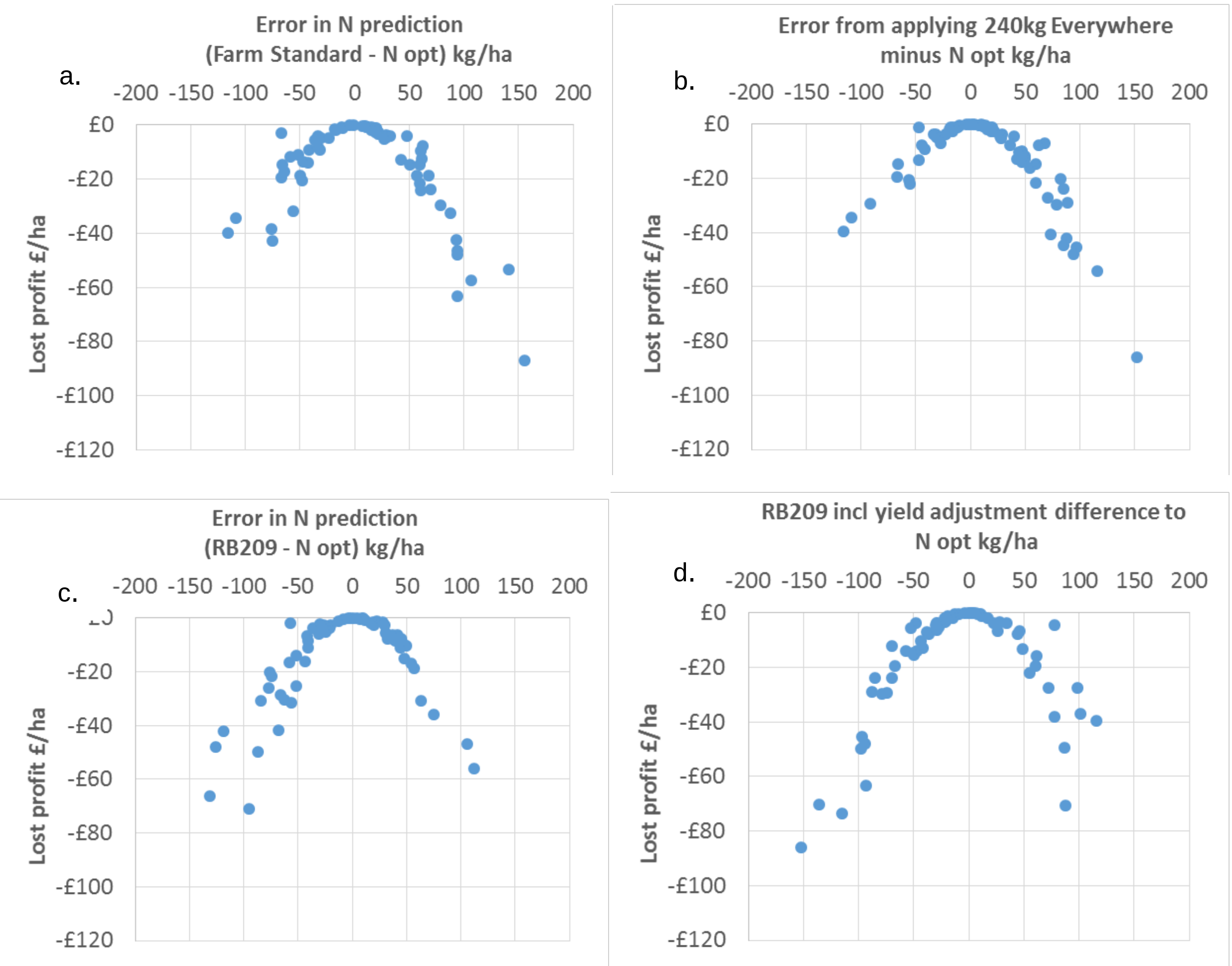


Figure 18. Lost profit (£/ha) from inaccuracies in N recommendations by using: a) Farm standard N rate; b) 240 kg N/ha on all fields; c) RB209 recommendations (adjusted to 10 t/ha); and d) RB209 recommendations using actual achieved yields as the basis for yield adjustment.

4.3. Tramline trial comparisons

Engagement and enthusiasm from growers was strong, and most farmers supported the project until the end. However, a few farmers did drop out through the project, for various reasons including field sizes being too small, insufficient support, ill health, farm management changes (e.g. harvesting being contracted out, farm staff changing), and having learnt the lessons after two or three years so not seeing the value in continuing (see Section 4.4.1 & Table 5).

A total of 174 tramline comparisons were established by farmers, from which useable data were received for 143 fields. Data from 12 fields was not forthcoming from farmers, for 19 fields data was not collected or lost at harvest or issues with data exchange meant it could not be retrieved despite best efforts.

An example output is shown below, with raw yields straight from the combine and after cleaning using the ADAS Agronomics process (Figure 19).

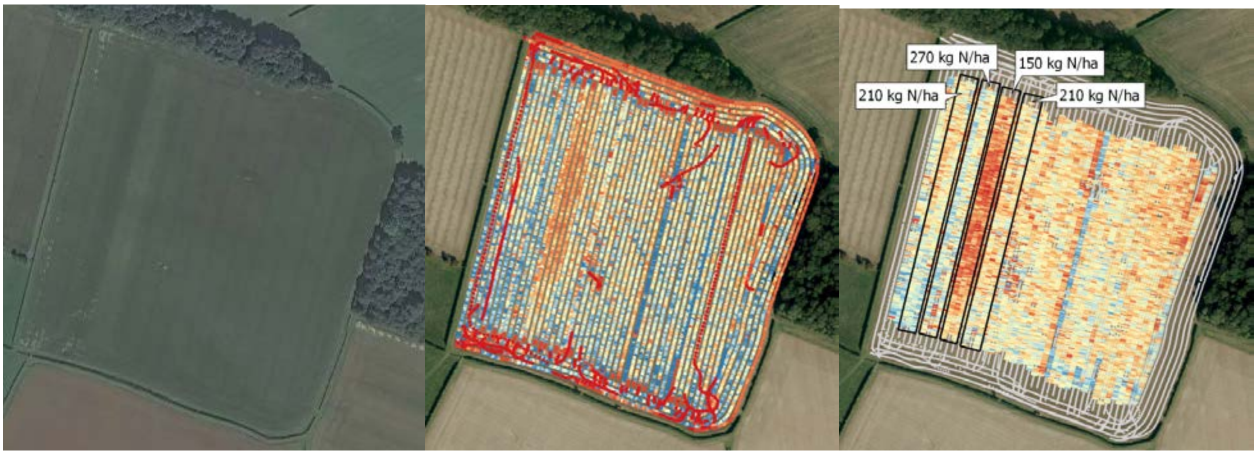


Figure 19. Example tramline comparison (Normanton, White Hut Field, 2016) showing clearly visible N rate effect in aerial imagery (a), in the uncleaned yield map (b) and in the final processed yield map (c).

Further example outputs from the processing, analysis and reporting of tramline trial yield maps are shown in Figure 20. A selection of yield maps from the tramline comparisons in the project. The example above where treatment differences are clear and evident is by far the exception rather than the rule, with only a handful of fields giving such striking and conclusive effects of N treatment. For the majority of the trials, the difference in N rate was not visually obvious from yield maps with spatial variation generally being much greater than any treatment effects (Figure 20). There was also great variability in the harvest procedures, quality of the yield maps, data resolution and data provided. This is discussed further in Section 5.2.

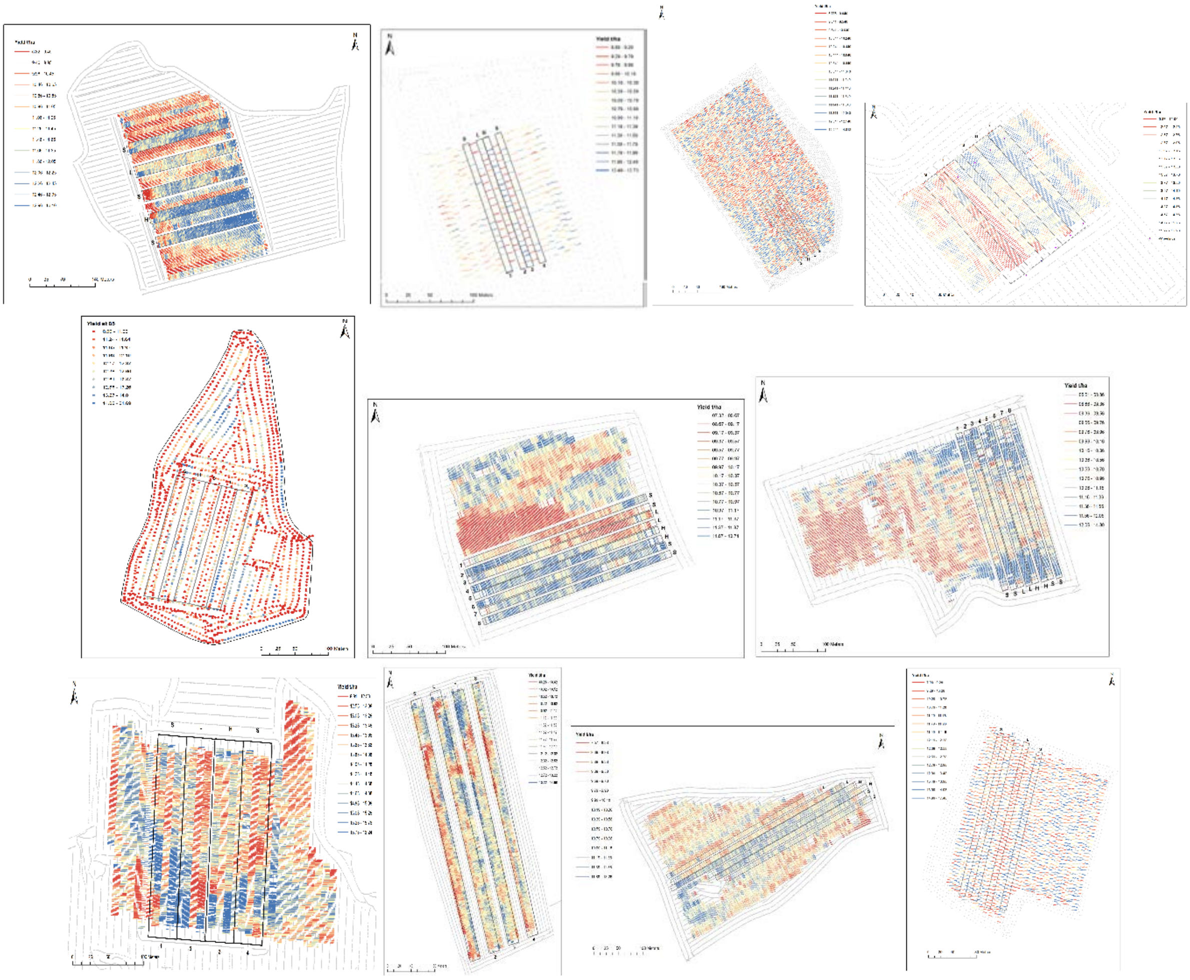


Figure 20. A selection of yield maps from the tramline comparisons in the project.

Table 6. Number of tramline trials carried out at extension sites throughout the course of the project and reasons for unsuccessful trials or growers withdrawing from the project.

Season	No. growers planning to run trials	No. trials successfully established	No. taken to harvest	No. trials yield data submitted	Reasons for unsuccessful trials / grower withdrawal from project
Pre-trials					Not enough fields available for testing Not enough tramlines per field
2014	12	11 sites 33 trials	11 sites 33 trials	11 sites 33 trials	Not enough tramlines per field Contractor lost yield mapping data. Weighbridge data used.
2015	11	9 sites 27 trials	8 sites 24 trials	8 sites 22 trials	Contractor couldn't provide yield mapping combine. Difficult to accurately measure harvested area to calculate yields using weighbridge. Change of farm management Difficulties retrieving data from combine Harvest pressures meant trial not combined correctly
2016	10	9 sites 27 trials	6 sites 18 trials	6 sites 18 trials	Grower ill health Grower not getting enough local support to be confident of running trials Harvest pressures meant trial not combined correctly Yield mapping data corrupted Yield mapping data couldn't be retrieved from online system Yield data available but GPS co-ordinates of treatment tramlines lost
2017	7	5 sites 15 trials	5 sites 15 trials	5 sites 13 trials	Yield mapping data couldn't be retrieved from online system Grower felt they wouldn't learn anything more so moved on to different projects Harvest pressures meant trial not combined correctly Yield mapping data lost

The N responses of yield and protein to applying three N rates (farm standard -60 kg N/ha, farm standard and farm standard + 60 kg N/ha) in all tramline trials are shown in Figure 21. Again it can be seen that yield differences between N rates were generally small, though there were very large differences in yield and protein between fields. Grain protein showed much more responsiveness to N than did yield.

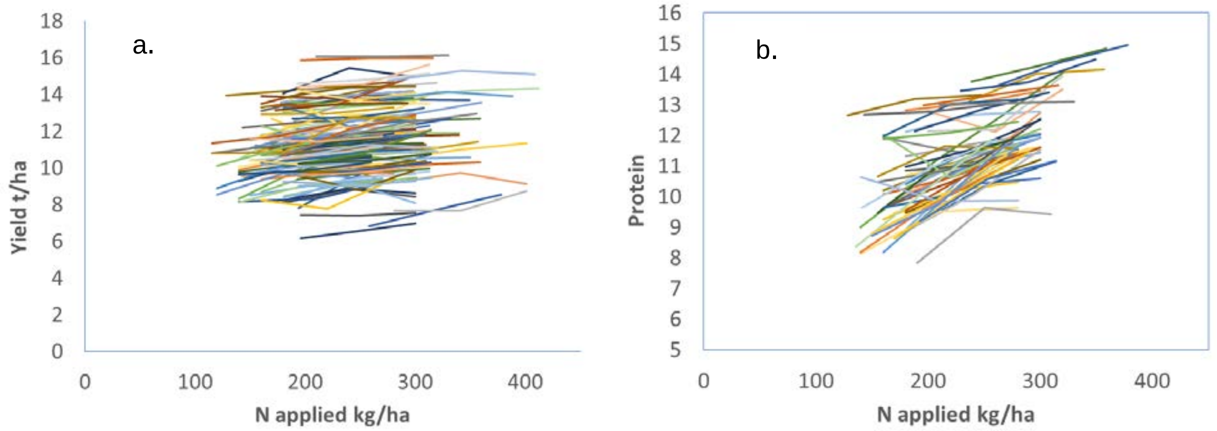


Figure 21. Responses of grain yield (a) and grain protein (b) to applying three N rates (farm standard -60 kg N/ha, farm standard and farm standard + 60 kg N/ha) in tramline comparisons across ~143 fields from 2014 to 2017.

At a grain price of £140/t and N price of £0.7/kg (Break-Even Ratio = 5:1 kg/kg) a yield difference of 0.3 t/ha is required to pay for the £42/ha cost of 60 kg/ha of N. Therefore if the addition of 60 kg N/ha gives a yield response of more than 0.3 t/ha this indicates that farm N rates are sub-optimal. Conversely, if reducing N rates by 60 kg N/ha doesn’t reduce yields by more than 0.3 t/ha, super-optimal farm N rates are indicated. If yields at standard rate are >0.3 t/ha greater than the low N treatment, and <0.3 t/ha lower than the high N treatment, the farm N rate can be taken to be near optimal. It is worth calculating the net margin over N cost for each comparison ((Yield x grain price) – (N rate x N price)), to more easily judge in £/ha which N rate gave the highest profitability, and to judge the scale of the effects.

Using this approach at face value across all the fields suggested that 30% of fields had N management close to optimum, 26% had N rates that were too high and 24% too low. For 21% of fields the net margin over N cost was less in the standard N treatment than in both the higher N treatment and in the lower N treatment, precluding conclusions being easily drawn. This highlights a very important issue in the interpretation of tramline trials: inherent spatial variation is such that any two areas of a field can never be expected to give the same yield, so random spatial variation will almost always affect results assigned to treatments. Where a difference in yields of two treatments was small, this at least indicated that the benefit from additional N was unlikely to be greater than the spatial variation (differences between tramlines treated the same), but it couldn’t indicate whether the rate is super-optimal.

If tramline yields from yield maps were not affected by N treatments, and if the inherent tramline differences were small, the low N rate tramlines would be expected to give higher profitability, as £42/ha is saved on fertiliser costs, whereas high N rate tramlines would have £42/ha higher costs. Running a dummy analysis on yields from tramlines in uniformly treated fields showed that, with random allocations of tramlines to treatments, the above approach would find 69% fields to be above optimum, 4% at optimum, 13% below optimum, and 14% unknown (i.e. margin at standard N lower than with both low & high N). That the results above are different to this indicates that real yield effects of N rates are being observed in the experiments here.

4.3.1. Dealing with uncertainties in tramline trials

Good estimates of the underlying spatial variability would require multiple replication of all treatments; however, most fields did not have sufficient tramlines to allow this, especially where spinning discs were used (so requiring two tramline widths per treatment). However, in nearly all fields it was possible to get yields from two standard N treatment areas, on either side of the +/-60kg N/ha comparison. The simple approach was taken of using the difference between the two standard N treatments that surrounded the +/-60kg comparison to indicate the spatial variation. It was recognised that this very crude approach could be misleading, because actual underlying variation could be much higher than was estimated from a sample of just 2 areas; however at least this approach was doable by a farmer and was better than simply comparing means, with no thought about spatial effects.

Using this approach to gauge whether the differences between the tramline yields could be considered due to the N treatments, rather than due to inherent spatial variation, the proportion of fields where conclusions were ‘unknown’ rose to 54%, with 22% found to be super-optimal, 11% about right, and 13% sub-optimal. To some extent, more information could be gleaned from the ‘unknowns’ where the yield differences between the two ‘standard N’ tramlines were small or modest: such results suggested that N rates used were unlikely to be very sub-optimal. However, it could not be concluded whether N applications were super-optimal or even highly super-optimal.

Running a dummy analysis of the above approach using data from a range of uniformly treated fields, with dummy treatments randomly allocated to tramlines, showed that 55% of fields would be found super-optimal, 3% optimal, 2% sub-optimal, and 40% unknown (i.e. error between two standards larger than treatment differences, or standard N giving a lower margin than both low N or high N treatments). Again, that the observed proportions were very different to this gave confidence that ‘real’ effects of N rate were being shown.

In interpreting results of the tramline trials it also proved very important to inspect the spatial variation within the yield map (and in any other sources of spatial intelligence such as satellite or UAV imagery, or data from crop sensors), hence to judge whether spatial trends or differences were unduly affecting treatments within the comparison. By visually assessing the yield maps from each field together with mean values for each treatment area, a manual subjective conclusion was drawn for each yield. On this basis 32% of fields were judged to be super-optimal, 44% optimal, 25% sub-optimal and 4% had variation which was too great for any conclusion to be drawn.

4.3.2. Agronōmics analysis

The full Surface Discontinuity Analysis (SDA; Rudolph *et al.*, 2016; Marchant *et al.*,2018) was not conducted on all LearN trials, but three example analyses are presented and discussed here. In each case coordinates have been rotated such that swaths are presented as running north-south to make it simpler to distinguish between along-row and between-row variation.

Taking the simple approach of comparing mean yields from each tramline (Table 6; A), Boroughbridge4 was inconclusive, Epping4 was optimal (but with considerable uncertainty), and Normanton9 was just sub-optimal, and with greater certainty because Std1 and Std2 treatments gave similar yields (the yield increase of +0.34 t/ha from Standard to High N was sufficient to pay for an extra 60 kg N/ha). In comparing these conclusions with those from using the more sophisticated SDA approach (Table 6; B), several observations can be made:

- Estimates of grain yield with Standard N from each approach appear surprisingly different. The differences arise because the SDA process removes yield outliers and removes any linear trends detected in the data before estimating average yields.
- The standard errors estimated by SDA tend to reflect the degree of similarity between the two Standard yields in the simple approach. This is reassuring.
- Interpretations of two trials out of the three trials were different, with SDA indicating that Boroughbridge4 (Table 6; Figure 22) was sub-optimal rather than inconclusive, Epping4 (Table 6; Figure 23) was inconclusive rather than optimal, and Normanton9 (Table 6; Figure 23) was still sub-optimal. Given that the SDA approach incorporates a much more thorough recognition of spatial variation, the SDA approach almost certainly gives the more reliable conclusions, and the differences with using the simple approach raise further concerns about farmers drawing conclusions from their own trials.

Table 7. Results of geostatistical analyses of three LearN experiments comparing grain yields with low, standard (Std) and high N rates (numbers in brackets are standard errors, t/ha).

	A: Raw mean grain yields from each tramline	B. Processed mean grain yield from each tramline	C: Mean 'standard' grain yield & N treatment effects estimated using SDA (t/ha)
Boroughbridge4			
Standard	8.47	9.24	8.79 (±0.37)
Low	9.37	9.55	-1.18 (±0.21)
High	9.63	10.29	+1.46 (±0.23)
Standard	10.24	10.54	
Epping4			
Standard	8.69	9.81	7.57 (±0.85)
Low	7.50	8.39	-0.72 (±0.45)
High	8.05	8.09	-0.95 (±0.44)
Standard	8.21	8.74	
Normanton9			
Standard	10.36	9.16	10.80 (±0.05)
Low	9.27	8.49	-0.77 (±0.14)
High	10.42	9.43	+0.31 (±0.14)
Standard	10.11	8.99	

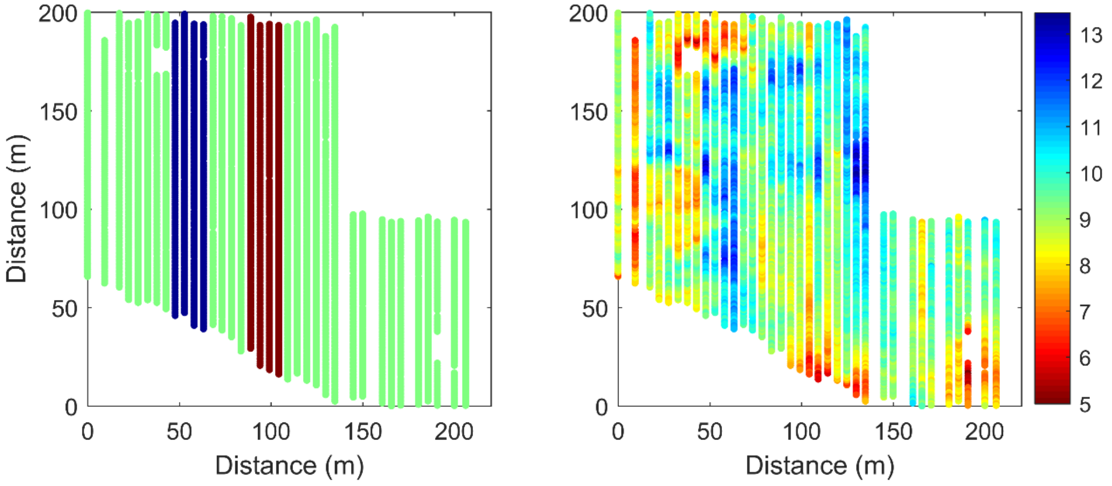


Figure 22: LearN treatments for Boroughbridge4 field (left). Green points signify standard treatment, red points low treatment and blue points high treatment. Recorded yields for Boroughbridge4 field after pre-processing (right).

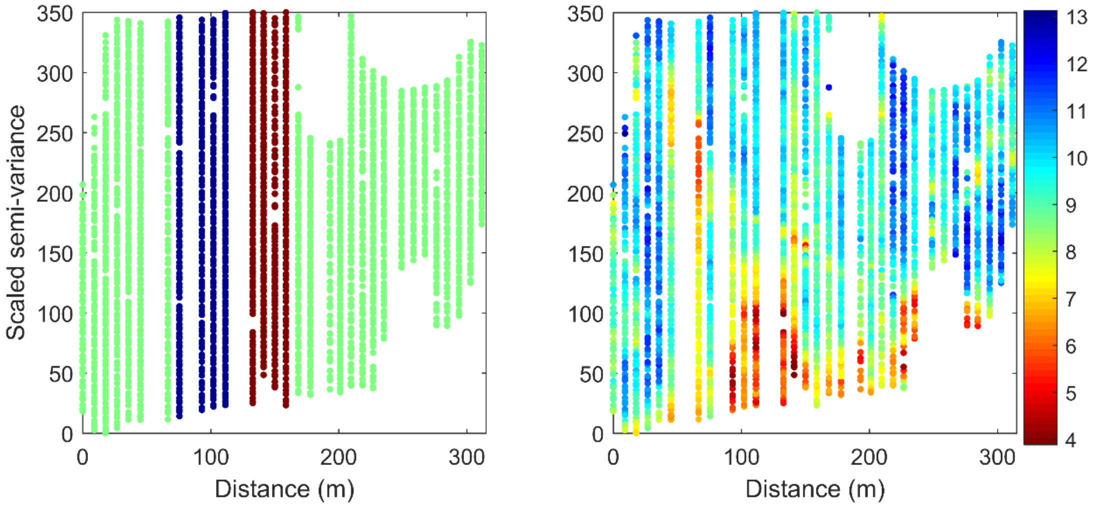


Figure 23: LearN treatments for Epping4 field (left). Green points signify standard treatment, red points low treatment and blue points high treatment. Recorded yields for Epping4 field after pre-processing (right).

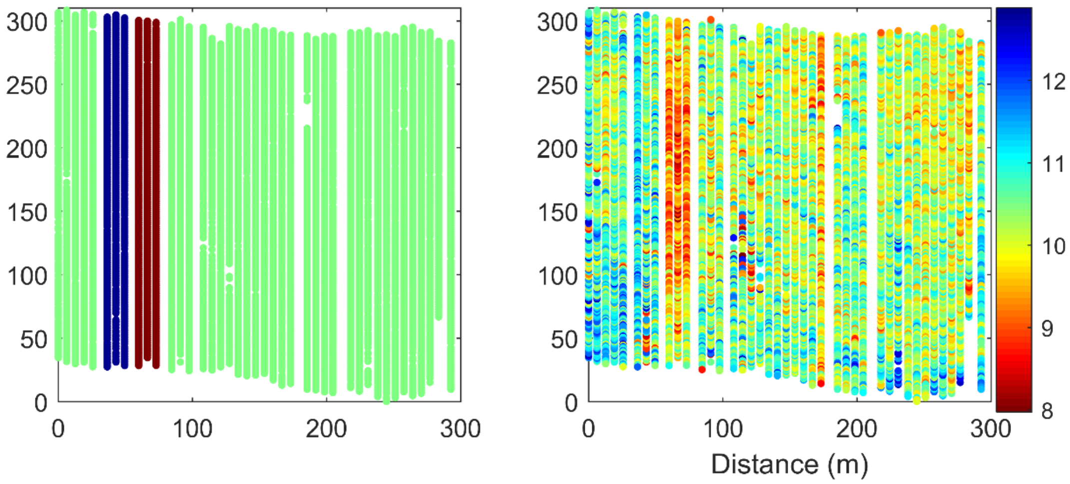


Figure 24. LearN treatments for Normanton9 field (left). Green points signify standard treatment, red points low treatment and blue points high treatment. Recorded yields for Normanton9 field after pre-processing (right).

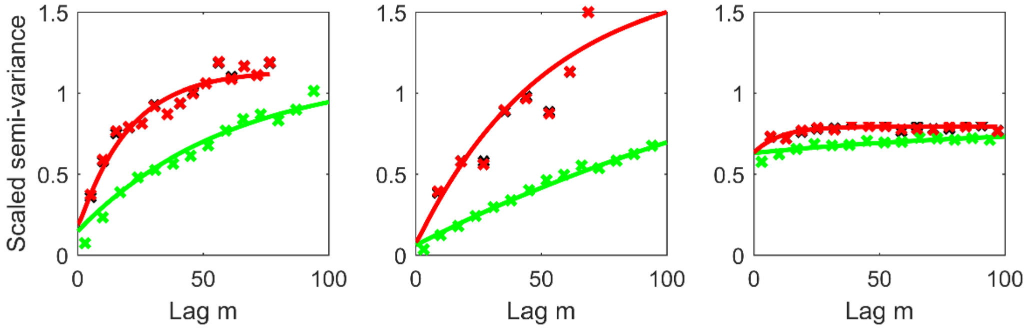


Figure 25: Estimated anisotropic variograms for Boroughbridge4 (left), Epping4 (centre) and Normanton4 (right) LearN experiments. Green curves and crosses indicate within-row variogram. Black curves and crosses indicate variation perpendicular to direction of travel. Red curves and crosses indicate variation between yield observations from adjacent swaths. Red and black responses were almost the same.

Further discussion of the experiences and learnings from the tramline trials is given in section 5.2 . Note that the learnings about how best to conduct tramline comparisons, informed by our experience in this project, have been compiled into a 'Guide for Farmers' Crop Trials' (ADAS 2018).

4.3.3. Tramline trial results at core sites

The yields and proteins from the small plot trials are compared to the yields from the tramline comparisons in the same fields in Figure 26. Whilst this shows broad agreement overall there is very substantial variation in yields at some sites, and there is not strong agreement between yield differences from different N rates seen between the response experiments and the tramline trials. Results for grain protein show much greater correlation. Given the variability in yield and N requirement we know to exist within fields (Kindred *et al.*, 2016) and the impossibility of locating small plot trials in exactly the same location as tramline comparisons, such differences are perhaps not that surprising. It seems clear that spatial variation in grain protein is much lower than it is for yield.

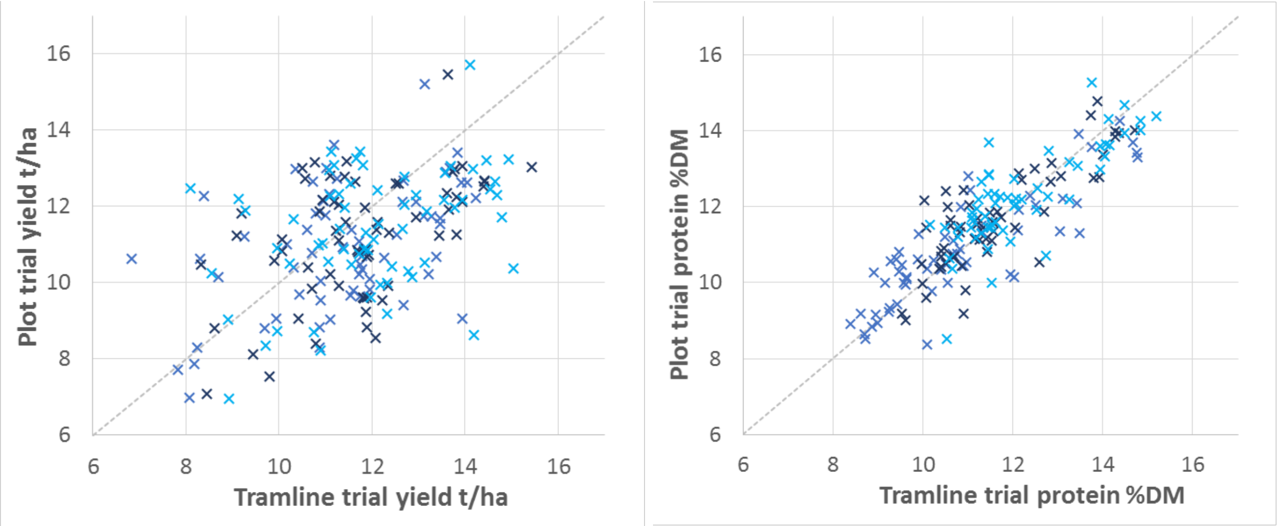


Figure 26. Comparison of yields (a) and proteins (b) from plots and tramlines in the same field, across fields. Colours represent the three N levels standard (dark blue), +60 (mid blue) & -60 kg N/ha (light blue).

Given the lack of significant differences in N requirements found between the six core farmers, and given the relatively poor correlation between yields from plot trials and tramline yields, it is difficult to use the plot trials to 'validate' the tramline trials fairly, as the extent to which a plot trial can represent the whole field is questionable. However, in Table 7 we compare the success of the N rate used by the core farmers across all fields as judged from (i) the plot trials, (ii) the tramline comparisons and (iii) grain protein levels, within each season. Conclusions were not always consistent across these three criteria, but they were rarely contradictory. In the instances where the N rates used were a long way from N optima measured in the plot trials (e.g. Peldon in 2017) the conclusions were usually the same.

Table 8 Summary data from small plot trials at all core sites in each season along with tramline trial yields and margins (over N cost) averaged over all fields included in each season's results (3 per site, apart from 4 occasions where data from 1 field were excluded), and a comparison of conclusions on the optimality of the farmers' standard (Std) N rate using three criteria (i) small plot trails, (ii) tramline trials, & (iii) grain protein levels. ↑↑ much too low; ↑ too low; ~ about right; ✓ right;↓ too high; ↓↓ much too high. Farm ID: 1 = Epping, 2 = Clavering, 3 = Thurlow, 4 = Belchamp Walter, 5 = Morley and 6 = Peldon.

Fm.	Year	N opt	Farm N	Protein	Tramline yields, t/ha			Margins over N cost, £/ha			Conclusions from:		
ID		kg/ha	kg/ha	%DM	Low	Std	High	Low	Std	High	(i) Small plot trial	(ii) Tram-line trial	(iii) Grain protein
1	2014	**275**	233	11.7	11.2	11.6	11.8	1,451	1,457	1,442	↑	✓	↑
1	2015	**208**	220	10.5	10.5	10.8	11.0	1,359	1,363	1,338	~	✓	↑
1	2016	**198**	260	14.5	10.0	10.5	10.4	1,257	1,284	1,226	↓↓	✓	↓↓
1	2017	**215**	240	12.3	10.7	10.9	11.1	1,376	1,362	1,344	↓	↓↓	~
2	2014	**235**	213	11.0	11.1	12.1	12.8	1,447	1,543	1,608	↑	↑↑	~
2	2015	**215**	227	11.0	13.0	12.1	13.2	1,696	1,609	1,645	~	↓	~
2	2016	**295**	240	10.5	12.0	12.2	12.8	1,547	1,543	1,578	↑↑	↑	↑
2	2017	**193**	240	11.7	10.4	10.6	10.4	1,341	1,320	1,240	↓	↓	↓
3	2014	**300**	240	11.2							↑↑		~
3	2015	**177**	220		13.5	13.8	14.0	1,781	1,776	1,760	↓↓	↓	
3	2016	**244**	240	10.18	12.5	12.6	13.8	1,617	1,600	1,721	~	↓	↑
3	2017	**168**	280		11.8	11.8	11.9	1,498	1,454	1,423	↓↓	↓	
4	2014	**238**	231	9.9	9.9	11.2	11.6	1,272	1,404	1,418	~	↑	↑
4	2015	**276**	220	10.6	11.3	11.7	11.8	1,476	1,478	1,453	↑↑	~	~
4	2016	**224**	240	11.6	9.5	10.7	11.0	1,208	1,326	1,332	~	✓	~
4	2017	**237**	240	11.0	8.7	9.2	9.3	1,088	1,114	1,087	~	✓	✓
5	2014	**263**	220	11.4	13.3	14.1	14.4	1,749	1,815	1,819	↑	↑	~
5	2015	**221**	220	10.5	12.2	12.2	12.5	1,591	1,549	1,557	~	↓↓	↑
5	2016	**212**	220	10.7	10.2	11.2	11.4	1,320	1,407	1,396	~	✓	~
5	2017	**186**	215	11.2	11.1	10.8	10.8	1,444	1,354	1,316	↓	↓↓	~
6	2014	**242**	266	13.0	12.8	13.3	13.7	1,672	1,669	1,685	↓	↑	↓
6	2015	**233**	240	12.8	13.0	13.9	13.8	1,688	1,778	1,727	~	✓	↓
6	2016	**232**	278	13.9	10.4	10.5	10.9	1,302	1,271	1,284	↓↓	~	↓↓
6	2017	**146**	295	14.0	13.0	12.9	13.1	1,656	1,605	1,587	↓↓	↓↓	↓↓

Looking at individual fields, where low N optima were measured in the small plot trials (13 fields less than 180 kg N/ha), tramline trials using a simple comparison indicated that N rate was super-optimal in 8 fields, optimal in 3 and unknown in 2 fields. Accounting for uncertainty (based on the difference between standard N rates) gave 7 as super-optimal, 1 as optimal and 5 as unknown. However looking at the 9 fields where N optima were measured as greater than 280 kg N/ha the tramline comparisons only gave a firm conclusion that N was sub-optimal in one field, with 4 being optimal and 2 unknown. However, the yields from the plot responses (as means rather than fitted yields) gave a very similar result, indicating that extra uncertainties may arise in the fitting of N optima based on small plot yields rather than to higher margins being achievable at higher N rates. This should perhaps lead us to be somewhat sceptical of results where N optimum is measured as high, or where highest yields are achieved in the highest N rate tramline, as this could be achieved by chance.

4.3.4. Findings from tramline comparisons across wider sites

Across all 143 tramline comparisons the average farm standard N was 239 kg N/ha, overall yields at farm standard N were 11.43 t/ha, rising to 11.74 t/ha with 60 kg/ha more N and falling to 11.07 t/ha with 60kg/ha less N. Average financial margin was £1,434/ha for both standard and +60 kg N/ha; with 60kg/ha less N the margin was £1,425/ha. This supports that overall farmers' N rates are not super-optimal, whilst in some cases modest increases may be warranted, financial gains are likely to be modest. Figure 27 shows that variation in net margin achieved across the 18 farms and 143 fields in this project was very large, but variation field to field was much more important than the influence of N rates used within the fields. The evidence shows that profitability is most often fairly flat across the 120kg N/ha difference in N rate tested by farmers, with as many instances of profitability being greater with less N as instances where increasing N rates could increase financial margins through higher yields.

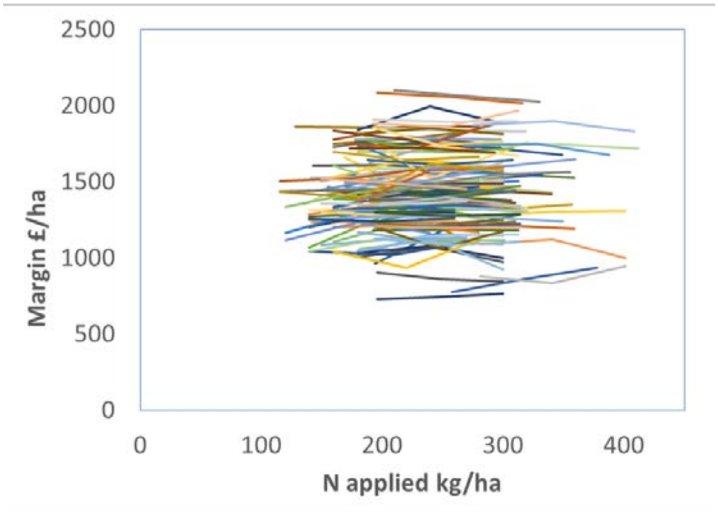
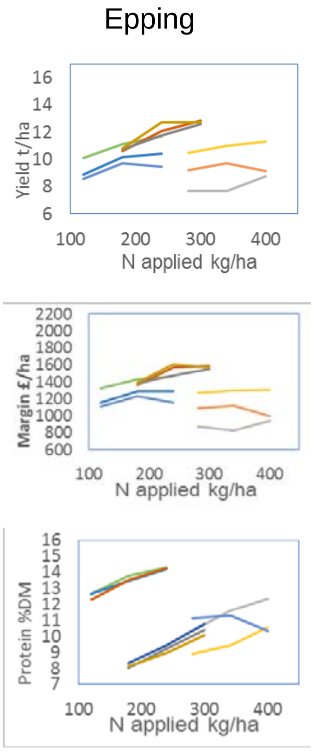


Figure 27. Financial margin over N fertiliser costs for 143 tramline comparisons.

Looking at individual fields (Figure 28) revealed that there was generally as much variation within farms as between farms. There were no farms with convincingly consistent evidence that raising or lowering their N rates would markedly increase profitability. Where there were seemingly large responses to yield or margin in individual fields some care was needed to consider whether these were due to 'real' effects of N or underlying spatial variation. Across all the trials tested in this project there were surprisingly few fields where the farmers' N rate was conclusively sub-optimal (e.g. Figure 19).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Yield t/ha
16
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12
10
8
6
100
200
300
400
N applied kg/ha
Margin £/ha
2200
2000
1800
1600
1400
1200
1000
800
600
100
200
300
400
N applied kg/ha
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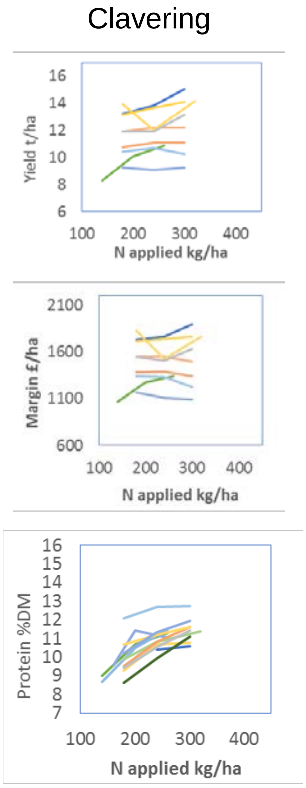
N applied kg/ha


Clavering
Yield t/ha
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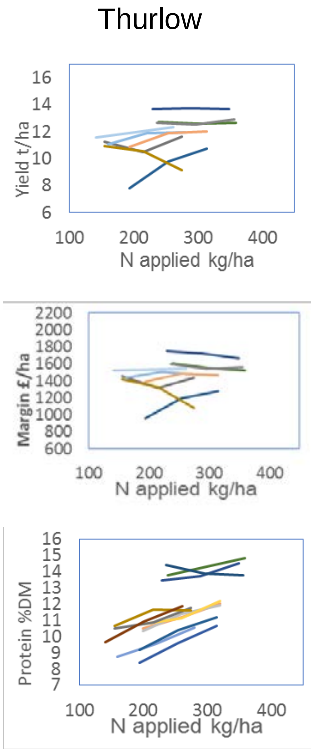
N applied kg/ha


Thurlow
Yield t/ha
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N applied kg/ha
Margin £/ha
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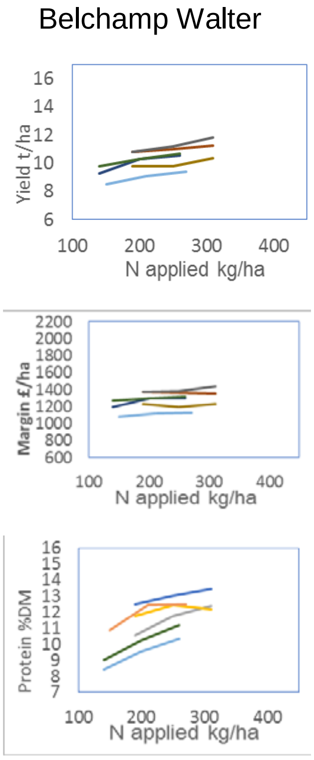
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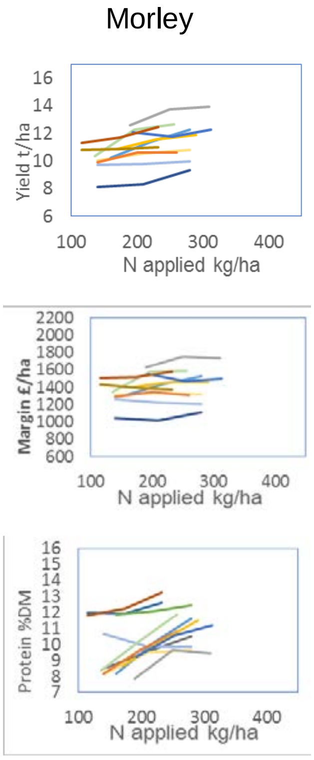
Morley
Yield t/ha
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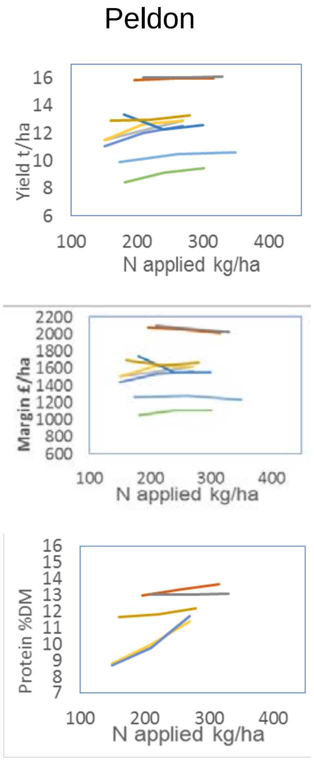
Peldon
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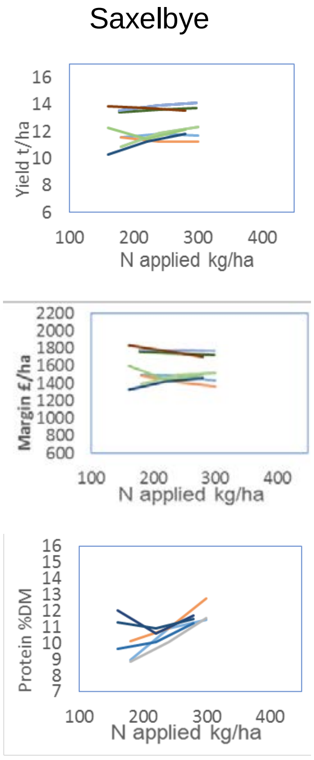
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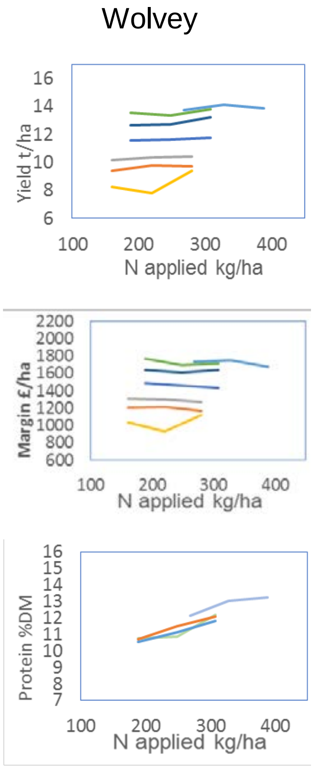
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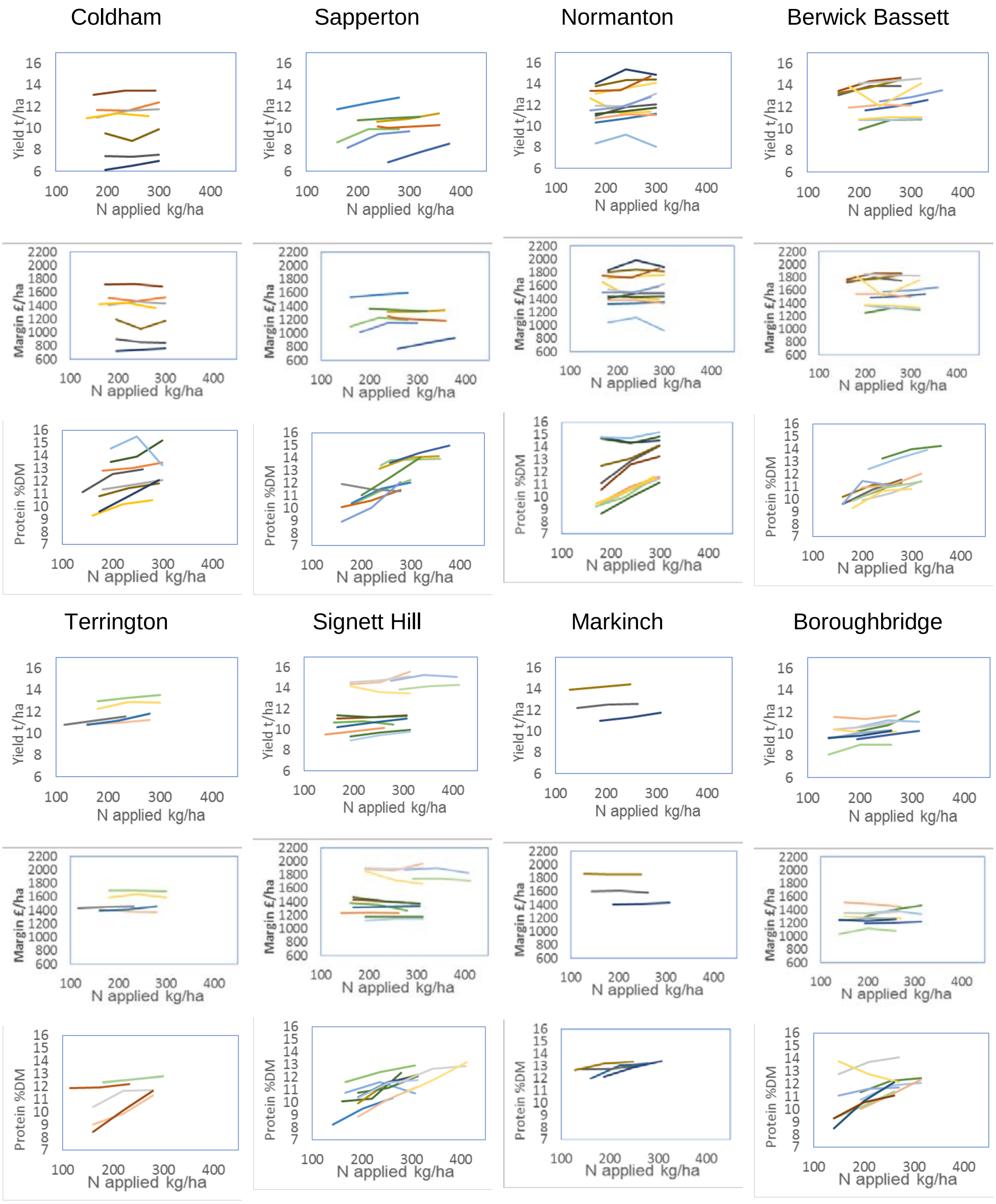

Figure 28. Responses in the tramline trials to increasing N rates of grain yield, margin over N cost and grain protein from each field of each farm in each year.

Averaging the financial margins for the tramline comparisons across all years within each farm (Table 8) suggested that four farms were over-fertilising on average (Thurlow, Peldon, Wolvey and Sapperton) and two might have been under-fertilising (Normanton and Signett Hill). However, if individual years were considered, no farm was consistently super- or sub-optimal across all years.

Table 9. Averaged responses to applied N over four seasons (harvests 2014-2017) in grain yield, margin over N cost and grain protein from tramline comparisons on 16 LearN farms. Maximum margins are shown in **bold**.

	Yields, t/ha			Margins, £/ha			Proteins, DM		
	Low	Standard	High	Low	Standard	High	Low	Standard	High
Epping	10.6	11.0	11.0	1353	**1364**	1332	12.3	12.6	13.3
Clavering	11.5	11.7	12.2	1489	1480	**1503**	9.7	10.9	11.4
Thurlow	12.6	12.5	12.9	**1634**	1582	1599	10.0	10.7	11.8
Belchamp Walter	9.8	10.6	10.7	1247	**1310**	1292	9.7	10.7	11.7
Morley	12.0	12.4	12.7	1526	**1541**	1536	12.7	13.4	14.0
Peldon	11.8	12.0	12.3	**1544**	1532	1522	10.3	10.8	11.6
Saxelbye	13.8	14.0	14.2	**1799**	1798	1774	12.0	12.5	12.8
Wolvey	11.0	11.1	11.5	**1413**	1396	1404	10.6	11.4	12.1
Coldham	10.8	11.0	11.4	**1424**	1413	1420	12.0	12.4	12.7
Sapperton	10.1	10.3	10.7	**1306**	1286	1287	10.3	11.0	11.1
Normanton	9.4	10.2	10.5	1215	1275	**1279**	9.1	10.5	11.5
Berwick Bassett	11.9	12.2	12.5	**1519**	1515	1517	9.8	10.9	11.4
South Wootton	11.2	11.3	11.6	**1460**	1427	1422	11.9	12.6	12.8
Terrington	13.3	13.6	13.7	1704	**1712**	1681	12.0	12.7	13.2
Signett Hill	8.8	9.2	9.6	1126	1135	**1150**	13.1	14.0	14.2
Boroughbridge	10.8	11.0	11.4	**1376**	1370	1379	11.0	11.8	12.4

Given the uncertainties in quantifying yield effects without SDA and hence judging optimal N requirements from these simple tramline comparisons, robust conclusions on the value of grain protein levels in diagnosing the accuracy of farm N requirements cannot be made for the wider sites. However, farm average grain protein levels did not correlate obviously with the conclusions about farm standard N levels made from tramline margins over N cost.

4.4. Grower's experience with the LearN project

4.4.1. Grower experience

The six core farms (N response and tramline trials) were identified early in the project and participated in all seasons of the experiments. They were supported by ADAS, NIAB and Agrii who established small plot trials in each field and helped to execute the tramline trials. Because of this level of interaction, the experience of these growers is less relevant when thinking about how practical and straightforward tramline trials are for growers themselves to execute in the future. Therefore these sites are excluded from considerations in this section.

At the beginning of the project when an appeal went out for growers to participate, there was a lot of interest. In total, 55 growers applied to provide extension sites with tramline trials. Twelve growers were chosen to participate due to their location, soil type etc. (see Materials and Methods section). Here we explore their experiences rather than the quality of the trial data.

Although the participating growers were enthusiastic and interested in the subject, various issues meant that the numbers of growers reduced throughout the course of the project. Difficulties occurred throughout each trial season, but the majority of the problems occurred at or after harvest (Table 5). In some cases, despite growers having a harvest plan, bad weather meant harvest was pressurised and so particular attention could not be paid to trial fields. The most common issue was related to data retrieval; data being corrupted or lost when trying to download from the combine, or being unable to download data from an online repository (Table 5).

There was also evidence that some growers felt that a four year commitment was difficult to maintain; two growers felt that they would not learn any more from participating in the final season and one said they felt it didn’t give them enough benefit to be worth the effort required to participate. This meant the number of growers participating in the final season was reduced (Table 5).

All growers who were involved in the LearN project at any stage were invited to a final meeting to hear about the overall results and express their opinions on the project and trials process. Those growers that did participate in all seasons of the trials were positive about the process. One commented: “I think it is an important tool to have to be able to do tramline trials. It is a useful discipline to do across the farm with a number of inputs. I would encourage anyone to do it. It’s an easy thing to do when you have controlled traffic farming.”

Another participant also found the trials beneficial, saying: “I thought the benefit in participating in the project was that the trials were related to me. I had confidence in how the data were collected. I know how it was done and knew I had done a good job.” However, he did acknowledge that the trials do increase pressure on growers: “Combining is a pressurised time. Leaving little strips is not good when the season is catchy.”

A number of growers said that they gained useful insights. For example: “I found that I was conservative on N usage so could ease it up a bit. I was happy with what the project told me and reassured that what my gut told me was about right. If I do start upping N rates I will keep an eye on it. At the start I was worried we would have flat crops as we don’t use much PGR, but nothing went flat. The problems didn’t materialise. If I upped rates I would change timings slightly.”

Another said “As I increased or decreased rates I got back the cost of N generally. There were a couple of occasions when I didn’t. What I learnt overall was to chill out about N. Just go with 240.”

Overall, there was a lot of interest and enthusiasm from the growers who participated, and they put in a lot of effort to try to make the process work. However, one grower at the meeting did question whether all growers would be willing to engage in tramline trials: “Those involved in LearN were a self-selecting group of farmers. Those that are out of bounds of the norm may not want to share their practices. How do you extract data from the extremes?”

5. Discussion

This project set out to ask the following questions:

- Are there consistent differences between farms in N requirement?
- Are simple tramline comparisons useful for farmers to judge their N management
- What indicators and approaches are most useful to judge N requirements?
- Could farmers overall benefit from raising (or lowering) N rates?

We will consider these in turn.

5.1. Defining and understanding variation in N requirements

This project has provided the first opportunity to study systematically the scales of variation in N requirement across fields, farms and years. Based on previous differences seen in grain protein content achieved between farms, we predicted we would find consistent differences in N requirements between farms, beyond that expected from basic N recommendations. This has not proved to be the case, with variation in measured N optima within each farm seeming to be as great as any variation between farms. N optimum ranged from ~80 kg/ha to ~350 kg/ha but with the majority of optima being around the average of 226 kg N/ha. Around 65% of fields had measured optima within +/- 50 kg/ha of the recommended N rate, a higher proportion than seen in previous studies where only 50% of fields were found to be within 50kg/ha of the measured N optimum (Sylvester-Bradley *et al.*, 2008). It is also somewhat surprising that there were no nil responses to N; in previous studies we have usually found around 20% of trials to have N optima at or close to zero (Sylvester-Bradley *et al.*, 2008). This may reflect the similarity of farms selected in this study; we deliberately chose farms in long term arable rotations without livestock, grass or frequent additions of organic materials. Previous work has tended to seek trial sites giving a wide representative spread in geography and soil type, normally with only one field per farm per year. The farms here were also self-selecting, they engaged with us because they were interested in improving their N management, so will already have been thinking carefully about the N rates they apply. Nevertheless, we regard these farms as typical of the majority of arable land in the Eastern half of England, and we did not necessarily expect to find less variability within this group of fields than was seen in previous studies. It is worth noting that the farms here collectively achieved average yields of 11.4 t/ha where the UK average yield is around 8 t/ha (Defra, 2017), and they applied 239 kg/ha fertiliser N where the national average application to wheat crops is 192 kg N/ha (BSFP, 2017).

Both the plot trials and the tramline trials clearly showed yield responses to N to be relatively flat beyond ~200 kg N/ha. Whilst there was very large variation in the yields achieved (from 6 t/ha to 15 t/ha) this did not relate to variation in optima; thus it was not possible to achieve a higher yield on a low yielding site simply by applying more N. There were few instances where further large yield increases could be achieved from applications exceeding 200 kg N/ha. This conclusion (of considerable variation in N optima between fields, but a limited effect on achieved yields) is the same as was found previously when variation within fields was studied (Kindred *et al.*, 2016). This raises serious questions about the causes of variation in yield, and where priorities should be focussed.

It seems that variation in N requirement largely exists at the field level rather than at the farm level. However, it is intriguing that some fields on some farms e.g. at Morley (Figure 5) were very consistent in their N responses, whilst in other studies we have found a great deal of variation in N requirement even within fields (Kindred *et al.*, 2016).

This dataset is one of the very few datasets that allow us to analyse the effect of year on N optimum across the same farms. Usually farms have not been the same across years, so only exceptional years could be recognised such as 2012, when widespread negative responses to high N rates were observed. Here we found season to have a substantial effect on the N requirement, with 2014 giving higher N optima and 2017 lower. Whilst the higher N requirement of 2014 may have been predictable from the lower measured soil N (and greater over-winter rainfall), the lower optima in 2017 were more subtly determined, possibly resulting from the late mineralisation of N after dry soils in spring were re-wetted in summer, ultimately giving higher SNS and higher proteins. The responses in 2017 may also have been affected by the very dull but warm June which could have caused greater respiration of large canopies, as seen in 2012, reducing the positive effects of higher N rates. This is supported by other N response experiments by ADAS in 2017 (Sylvester-Bradley, *pers. comm.*). It doesn’t seem feasible that the low N optima of 2017 could have been predicted from any evidence at the time of the main N applications. Even with perfect weather forecasting we could not predict the extent to which late mineralisation of N would be stimulated, or greater respiratory costs from dullness and warmth in June would affect N requirements; neither of these effects has been recognised sufficiently clearly or frequently to be considered in current recommendation systems. So the differences in N optima between years cannot be considered as predictable. If year effects on N responses are strong, this degrades the value of any learnings from tramline trials testing N responses in individual fields in individual years; as we can only learn about that field in that year, we cannot be sure the same conclusions would be reached in another year.

5.1.1. Drivers of variation in N requirement

Despite the large variation in both Crop N Demand and in Fertiliser N Recovery observed in the 68 N response experiments in this project, it is clear that variation in Soil N Supply was by far the most important cause of variation in N requirements. This supports findings from previous studies (Kindred *et al.*, 2012, Kindred *et al.*, 2016). Frustratingly, our ability to measure or predict the

amount of soil-derived N likely to be taken up by the crop is far from perfect. However, both soil analysis and field assessment methods (e.g. RB209) used to predict SNS do get it right on average, and are amongst the best tools we have in judging N requirements, despite their deficiencies (Kindred *et al.*, 2012, Kindred *et al.*, 2016).
We did not find a strong link between N requirements and achieved yields in this study as was identified in the recent RB209 review (Roques *et al.*, 2016), though there is perhaps evidence of a boundary line in the relationship (Figure 14) where very high N optima (>300 kg N/ha) are only observed with yields greater than ~10 t/ha and some of the highest N optima were associated with very high yields. However, very high N applications were not a pre-requisite for achieving very high yields; half of the fields yielding >13 t/ha required less than 250 kg N/ha, the highest yielding field had an N optimum of 241 kg N/ha. This is similar to the conclusions being found in the Yield Enhancement Network, where, contrary to popular expectations, the relationship between achieved yields and applied N has been weak (Sylvester-Bradley & Kindred, *pers. comm.*).

When harvested SNS was included within the N available at the optimum (i.e. N optimum x 0.6 fertiliser recovery plus SNS) as used by Roques *et al.* (2016) there was a significant relationship with yield (Figure 14). However, given the strong relationship observed previously and here between yield and SNS (Kindred *et al.*, 2016) care must be taken in the interpretation of this, as high yields are associated with high SNS, and SNS is included in the y axis.

Higher yielding and higher protein varieties have been shown previously to have higher N requirements (Sylvester-Bradley & Clarke, 2009, Sylvester-Bradley & Kindred, 2009; Sylvester-Bradley *et al.*, 2016), but this has not shown through in this dataset. This may be because in this dataset variety choice was confounded with rotational position and SNS level, with milling crops actually achieving on average higher yields and lower N optima.

5.1.2. Considering grain protein content

There are large differences between farms in grain protein content, confirming observations in previous studies comparing protein contents achieved on-farm (Bhandari *et al.*, 2006, Weightman *et al.*, 2011, Kindred, pers comm). These differences in grain protein however are not directly related to differences in N optima. Interpreting differences in grain protein content in the context of N requirements is complicated because protein can act both as a driver of N optimum (higher protein varieties having a higher protein ‘demand’, hence higher N optima) and as an outcome / indicator of N supply (low proteins indicating under-fertilisation, high proteins indicating over-application). Substantial differences in grain protein at the optimum have been shown at the farm level here, without discernible differences in N requirements, and this reduces our confidence in the usefulness of *absolute* grain protein content as an indicator of success in N management (as opposed to relative differences which are clearly useful). We don’t yet understand the causes of the variation in protein responses to N seen across fields, farms and years here. Given that some farms seem to achieve high proteins easily whilst others struggle to reach protein specifications for milling, it seems possible that there may be soil or environment factors that determine the 'protein potential' of a field. Alternatively, it could be that grain protein content is largely affected by the timing of the supply of N, with high proteins being achieved on farms where more N is applied late or where the soils allow continued uptake (& mineralisation) later in the season.

It seems that spatial variation in grain protein content is less than that seen for grain yield; there was surprising consistency in many of the protein responses shown by single grain samples taken from the tramline trials despite the lack of replication of treatments and only minimal efforts to ensure representativeness. This supports findings from chessboard trials by Kindred *et al.* (2016) and spatial sampling by hand and by on-combine protein sensors supported by Sainsbury's with Camgrain growers (Kindred, pers. comm.) that protein levels can be quite consistent within fields.

Assessing grain protein from tramline comparisons can therefore give a useful indication of N responsiveness: if no further increase in protein is seen with additional 60 kg N/ha at the main N application timing you can be fairly confident that you are at the top of the N response curve, and have over-fertilised the crop. It is more challenging to interpret the more usual situation where large protein differences are seen with different N rates.

5.1.3. Economics of perfecting N requirements

Despite the considerable variation seen in N requirements across the 68 small-plot trials, the economic penalties from getting N rates wrong were found to be surprisingly modest (Figure 18). Around the N optimum the response of yield to N was quite flat, such that fertilising ~50kg/ha either side of the measured N optimum had little impact on financial performance; what was lost in yield was saved in fertiliser costs if N rates were too low, or what was spent on fertiliser was gained in yield if N rates were too high. On average, the 'lost profit' by LearN farmers' standard N rates (when compared to perfect N prediction) was £18/ha on an average margin over N costs of £1,406/ha. The half of the number of tested fields which were more precise made an average profit only £3/ha less than with perfect N prediction, and on average erred by +/-34 kg N/ha. Lost profits on the other half of the fields averaged £33/ha, with the difference from perfect N prediction being +/-79 kg N/ha on average. The less accurate outcomes were highly influenced by the 10% of fields which were most inaccurate, having an average lost profit of £70/ha and an N error averaging +128 kg/ha (interestingly these all occurred where N recommendations had been over-estimated). Identifying and improving recommendations for these outlier fields should clearly be a focus for improving N management overall. Unfortunately, it is not easy to find prediction systems that consistently improve outcomes for the whole population of fields; improvements to recommendations for current outliers can create outliers elsewhere (Kindred *et al.*, 2016). Overall, the lost profits can be reduced to £13.50/ha by following RB209 recommendations adjusted to a 11 t/ha yield but, with these farms, we find that any attempt to refine the recommendations by adjusting according to soil N measurements, or according to achieved yields or protein levels actually makes the average prediction error and lost profit worse rather than better. The same conclusion (of added complexity in N predictions reducing their financial performance) was also found in other recent AHDB projects (Kindred *et al.*, 2012; 2016). In fact, the best financial performance across these farms would come from applying 225 kg N/ha across all the tested fields on the core farms, giving a lost profit of £13.23/ha. Applying 240kg N/ha across all fields gave a lost profit of £13.68/ha.

Our original concern at the start of this work had been that if there were farms that either over- or under-fertilised consistently by >50kg/ha, the financial losses on lost production or wasted fertiliser would be very large and, on retentive soils, the errors could become compounded year by year. However, at least for the farms studied here, the evidence points to all farms being broadly correct with their N rates, with broadly as many fields on each farm being over-fertilised as under-fertilised.

Whilst there was substantial variation in N optima between fields, the potential gains from improving N rates were modest for the majority of fields; it was in identifying the minority of fields where N rates were most wrong that the biggest benefits would have arisen.

The flatness of payoff functions has been recognised as limiting the economic value of optimisation of agronomic inputs, once reasonable accuracy has been achieved (Pannel 2006; Pannell et al., 2018; Reader et al., 2018). This has implications for the value of variable rate applications in precision farming (Pannell et al., 2018), and also for prioritising agronomy research on developing innovative practices with the potential to deliver step changes in performance, rather than fine tuning existing well-understood systems (Pannell, 2006). Given the large & unexplained variation in yields (6-15 t/ha) and economic margins (<£750->£2000/ha) seen in this study there is a clear need for research to focus on understanding & managing the major drivers of yield to support future increases in productivity; it seems that only limited benefits are likely from more research into optimising N fertiliser rates.

5.2. The value of tramline trials

We need to consider the value of tramline trials in the LearN at two levels; firstly as a tool specifically for improving N management, and secondly as a new approach to agronomic research more generally, whereby farmers (and their support industries) can set up their own studies and generate their own data and knowledge. However, given the simple approach taken here to the conduct of tramline trials (because this project began before ADAS had developed tramline trialling protocols & its Agronomics statistical analyses approaches) and the extensive experience gained during this and other concurrent projects in how best to improve tramline trialling protocols, the specific value of future tramline trials for improving N management is best inferred here from the broader evidence (including the small plot trials), rather than from just the outcomes of these particular tramline trials.

5.2.1. What can tramline trials say about N management on-farm?

Given that the small plot N response experiments showed no evidence of consistent differences between farms, but did show significant differences between years, the potential benefits from tramline comparisons of N rates would seem to be smaller than we imagined at the outset of this project. In the case of N requirements, results from individual fields could not be taken as having broader relevance across the farm as a whole. Furthermore, we do not have evidence from the small plot trials that any farm should consider its N requirements to consistently differ from other farms or from national recommendations. Most of the variation in N requirements exists at the field or within-field level, though within farms and years some field trials responded to N in a remarkably consistent way. The potential value of tramline N trials therefore would appear to lie in judging N requirements of individual zones, fields, or blocks of fields (that are farmed together) over a number of years. Most of the variability in N requirements observed between the small plot trials was outside that which current recommendation systems or soil measurements could predict. So tramline trials appear to provide one of the few tools available to check and refine N rates.

The biggest value will come from identifying zones, fields or blocks of land where current N rates are a long way out, or where recommendations are most uncertain. However, experience with the tramline trials as conducted here is that definitive answers cannot be guaranteed, because of the high degree of spatial variation in grain yields within fields.

To measure N requirements accurately is a big challenge, even for small plot trials, because there is a need to resolve not just whether a difference in yield exists between two N levels, but the slope of that difference needs to be judged. Even knowing that slope does not give us a definitive answer on what to do about it, unless N rates are very wrong. If yields from an additional 60 kg/ha N rate are >0.3 t/ha higher, then higher N rates may well be warranted, but (because yield responses *diminish* with ever increasing N) it is likely that most of this yield increase would be achieved with a smaller increase in N (we advocated 60 kg/ha differences in the trials here to have a good chance of seeing effects, but if growers were changing N rates across whole fields then 20 or 30 kg/ha increments would be more reasonable). We need to consider the return on investment from increasing N rates e.g. what level of return would you expect from an additional investment of £20/ha? Given that the cost is certain but an increased return is far from certain a grower is likely to require substantially more than just enough extra yield to cover their costs; would *a chance of* 0.2 t/ha additional yield worth £28/ha be enough to warrant spending £20/ha on 30 kg/ha more N?

Where yields are found to be similar between N rates it can be judged that N rates were likely to have been super-optimal, but it is not possible to be definitive about how much N rates should be reduced. High precision is necessary to say with confidence that yields at the different N rates were similar. Adjusting N rates by 20 to 30 kg/ha increments, and routinely conducting tramline trials with +/- 60 kg N/ha compared to the new rate, could allow optimal N rates to be refined with more confidence over time. However, the biggest challenge comes from getting robust conclusions from tramline comparisons, given the high underlying spatial variation in grain yields.

5.2.2. Challenges with tramline trials

In the vast majority of fields here the inherent spatial variation seen in the yield maps was far greater than the effect of the 120 kg/ha difference in N fertiliser. Only in a handful of fields was the yield effect of N visually obvious within the yield map. This partly reflects the overall findings that most fields on these farms were fertilised near to their optimum, with large yield gains from higher N rates being rare, and yield differences not expected where N rates were super-optimal.

However, we should not downplay the difficulties in getting meaningful results from tramline trials and yield maps. Spatial variability within fields is such that any two areas will always give different yields, and yield maps contain much noise and many artefacts that need to be processed appropriately. Through the course of the LearN project we have learnt an enormous amount from working with farmers to conduct, analyse and report their tramline trials. However, we were probably rather naïve when we set out with regard to the ease with which robust conclusions could be drawn from individual tramline trials conducted by unpractised and lightly-supervised farmers. Experience in the project shows that, to make fair comparisons requires careful selection of comparable areas within the field, accurate recording of treatment locations and effective data cleaning, selection and analysis. We now appreciate that it is crucial to collect enough yield data from the field to provide an estimate of its inherent spatial variation. This can then enable estimation of the confidence level with which it can be concluded that the apparent difference in yield between treatment areas was really due to the treatment imposed. This type of statistical analysis has become possible during the project but is not yet achievable with the tools commonly available to most farmers.

5.2.3. Conducting tramline trials to reach robust conclusions

Farmers have different standards of proof to scientists, and it can be challenging to communicate the importance of accounting for underlying spatial variability, where farmers can dismiss this as ‘just statistics’ rather than recognizing the real risks and costs of drawing false conclusions from inappropriately accepting simple differences as real effects.

During the life of this project ADAS has developed protocols, processes, software and statistics to support the conduct, analysis and interpretation of tramline trials, and has formed its ‘Agronomics’ service for clients, for which the experience from LearN has contributed greatly. Advice for conducting farmer-led trials has been collated and summarised in a Guide to Farmers’ Crop Trials (ADAS, 2018). The major learnings from this are given below.

It is important to give consideration to how trials are set out in the field, ensuring that treatment areas selected are as comparable as possible, and are without major confounded differences e.g. such as where a treatment boundary coincided with an old field boundary. Ideally past yield maps should be consulted, but we find it surprisingly rare that farmers can quickly and easily supply previous yield maps for a field. Historic aerial imagery accessible from Google Earth is invaluable, and Sentinel satellite imagery is becoming increasingly useful and easy to obtain freely online. Despite some support, we saw wide variation in how appropriately treatment areas were placed within fields in LearN.

In setting out trials it is invaluable to place standard treatments on either side of the treatment areas, not compromised by headlands, so that two sets of comparisons can be made. We have found it best to put the +60 and -60 treatments next to each other to give the best chance of seeing an effect across the treatment boundary (i.e. a 120kg N/ha difference). Where in the first year treatments were placed -60, standard, +60 across the field it could be difficult to distinguish treatment effects from an underlying trend in the field.

Ideally all treatments would be replicated, as this substantially improves confidence in results. However, we frequently found that fields were not large enough to replicate treatments in comparable areas, especially where double tramlines were required, due to fertiliser applications made with spinning discs. At the very least it proved necessary for the difference between the two standard areas to be available to gauge underlying spatial variability. This simple but crude approach enabled at least some judgement to be made. However, using this approach alone led to forgoing firm conclusions on as many as half of the fields, so additional improvements are needed.

We saw wide variation in how trials were harvested and it proved impossible to provide a ‘one-size-fits-all’ protocol for harvesting the trials; optimal harvesting procedures depended on the width of the combine header relative to the tramline or treatment width, as well as the attitudes of the farmer and the harvesting team. Best results were often achieved where combine position was pre-defined, for example with controlled traffic (CTF) systems (although this could cause much data to be wasted, where the header straddled treatment boundaries). Several LearN farmers used only part lengths of tramlines to set up differences, and cut out these treatment areas with the combine separately to the rest of the field. This could severely limit the confidence that could be placed in the comparison because information on spatial trends from the surrounding area was lost. This also restricted the chance of seeing whether treatment effects were effective along the full length of the field, maybe across different soil types with different yield potentials, or whether an apparent effect was just caused by background variation. Part of the motivation for limiting the length of treatments was the perceived risk of lost profits. However, losses averaged only £10/ha from reducing N rates by 60 kg/ha and there were no losses overall from increasing rates. Thus, with typical 2 ha tramlines, the cost in lost yield would only have been £20 – a small sum in relation to the value of possible learnings that could be made. There were greater concerns from farmers growing milling wheat crops, where failure to meet the protein specification was feared. However, there were in fact very few milling crops where the low N rate gave protein levels of less than 12% when the standard rate gave more than 12%. We therefore strongly advocate conducting tramline trials along the full length of the field.

Since beginning this project protocols have been strengthened around recording the precise locations of tramlines and treatments. One of the biggest uncertainties was found to be in judging whether individual combine runs were within or without a treatment area, or whether it straddled the treatment boundary. Knowing how the trial was harvested as well as the header width and the combine make and model all proved helpful when conducting the data analysis, so in future these all should be recorded.

In interpreting tramline trial results it proved invaluable to compare financial margins over N costs rather than just the yield differences, so as to set the results in their appropriate context.

The project showed that, whilst simple comparisons of tramline means were reasonably achievable by farmers, and could be useful, they were not fully satisfactory; for half the trials we were unable to draw firm conclusions about which N rate was best, and for others there was still a risk of drawing misleading conclusions. This applied however well placed the comparison areas were and however meticulously the experiment was harvested. However, on most farms, where yield mapping was enabled, simply averaging yields over a large area involved discarding a huge amount of information contained within the maps about underlying spatial variation. This information could prove invaluable in ‘correcting’ the treatment means, and in judging the confidence in any treatment differences in a much more sophisticated way than merely comparing means from two large areas with standard husbandry.

5.2.4. Agronōmics analyses

Using the bespoke spatial analysis method of SDA provided robust estimates of treatment effects as well as providing estimates of the confidence attributable to any comparison. However, software to conduct SDA is not yet widely accessible, and takes some level of training, skill and time to install and implement. SDA only became available to ADAS in 2016 and at present ADAS is providing SDA as a service to the industry, whilst seeking ways to make it more available to others, including farmers.

ADAS experience in using SDA on a few LearN tramline trials and on tramline trials for other clients is that conclusions can be drawn on comparisons with as much or better confidence than is achievable with small plot trials. Results can be improved by routine inclusion of tramline boundaries and locations of wheelings within datasets, and inclusion of prior information on spatial variation e.g. via co-variates of specified zones. ADAS is seeking further development of the agronomics process to make inclusion of wider data easier and to make its use more widely available.

5.2.5. Canopy reflectance and satellite imagery

As well as assessing final yields, setting up comparisons of high and low N allowed comparisons of effects on other measures. Any visual differences easily seen between treatments provided a powerful indication that the crop was still responsive to N, and enabled judgements to be made about a crop's N status. Often, differences were much clearer visually from the air than from on-the-ground, so images from UAVs, aeroplanes or satellites were most instructive. Measures of spectral reflectance such as NDVI were found to detect much more subtle differences in crop 'greenness' than was possible by eye, and could be collected by handheld sensors (e.g. RapidScan, Yara N tester), tractor-mounted sensors (e.g. Yara N Sensor, Greenseeker), UAV and aerial multi-spectral cameras, and satellites. Elsewhere several approaches have been developed to infer N status and N recommendations, for example sensing reflectance of N-rich or low-N strips or 'green windows'. These approaches have largely been developed to inform precision-farming, variable rate applications (Raun *et al.*, 2008; Samborksi *et al.*, 2009. Yue *et al.*, 2015) abroad and have not been widely adopted in the UK because calibrations have not been fully developed and benefits of the approach over simpler sensor systems have not been demonstrated. However, for several years commercial satellite imagery has been available at relatively low cost from companies like SOYL and AgSpace IPF, and from 2016 onwards Sentinel 2 NDVI data has been available free from websites such as Sentinel Playground, Landviewer and DataFarming.com.au. It is well worth looking at such imagery when conducting trials to help ascertain underlying variation and to assess if and when any treatment differences become visible. Satellite imagery is however inevitably affected by cloud, so there can be no guarantees on the availability of data or its temporal resolution.

Unfortunately it has not been possible to test systematically canopy sensing approaches within this project. Whilst handheld, tractor mounted, aerial and satellite sensors would undoubtedly show differences between the treatments, such data require considerable resource to acquire and interpret, and it was not clear how this information would serve to improve the assessments of N requirements from tramline trials here, beyond interpretation of the yield map data.

Given that the variation in N requirement mostly occurs between fields and years, it is possible that in-season crop sensing could provide a route to better estimating differences in N requirements between and within fields. New approaches are being developed commercially using new sensing technologies and artificial intelligence for predictive data analysis. By combining estimates of plant nutrient status and green area or crop biomass it is possible that the Nitrogen Nutrition Index approach (Justes *et al.*, 1994; Lemaire *et al.*, 2008) could be applied for the UK. However, we caution that our experience in developing and testing new approaches to estimate N requirements here and elsewhere shows that it is much easier to make N recommendations economically worse than it is to improve them (Kindred *et al.*, 2012; 2016).

5.2.6. Costs and benefits of tramline trials

We have shown that the average economic costs of tramline trials applying +/- 60kg N/ha in terms of lost yield or wasted fertiliser are small, typically losing £10/ha net from applying 60kg N/ha less to a tramline and losing nothing from applying 60kg more. Where costs in the trial are larger than this then it indicates that N management was far out, so substantial savings should be possible from future improvements. There is a perception of a higher risk and cost from milling wheat crops where there is the possibility of deductions or even rejection from lower protein wheat, though our experience is that this is unlikely.

The amount of hassle associated with tramline trials is very much dependent on the perception of the farmer, and the degree of diligence that is expended on the trial. At their simplest, these trials can be set up by simply adjusting the N rate in the tractor on two tramlines in a field, noting or marking which tramlines are used, then combining the fields as normal and checking the combine yield monitor in the field or viewing the yield map. However, this is unlikely to provide robust and conclusive evidence unless the yield differences are very large, implying the field is being very under-fertilised. There is also a high risk from this approach that false conclusions are drawn, where differences in the areas due to underlying spatial variation are wrongly ascribed to a treatment difference. By putting more effort into laying out the trial area and harvesting it carefully the chances of getting useful and conclusive results will be much improved. Additionally, the chances of making robust conclusions from a single trial will be substantially enhanced by employing SDA.

The benefits from LearN type tramline trials depend on the current accuracy of the farmer’s N management; if N rates are already about right then there will be little financial gain, just greater peace of mind. The greatest potential benefits come from the ~35% of fields where N rates differ by >50kg/ha from the optimum. If it is possible to reduce N errors of these fields by ~30kg/ha then financial performance could be improved by around £20/ha across the field, or block of fields. However, given the variation between fields and years, and given the need for incremental adjustments to N rates that then need to be checked, the full benefits from LearN trials will accrue from widespread and repeated use, which may begin to take more management effort than is really warranted by the potential rewards.

5.2.7. Wider potential for tramline trials

Over the past five years we have interacted with scores of engaged farmers who enthusiastically conduct their own on-farm trials, looking at N and a host of other issues. Although on-farm trials are able to test a limited number of treatments (up to 4) and so will not replace the need for small plot trials to look at detailed responses to an input or interactions, we see huge potential to build the knowledge-base of arable farming by connecting the learnings that are being made individually by farmers, and there are large opportunities to utilize on-farm trials to test new products or practices, and to answer more fundamental research questions, such as how soil variation affects yield variation. To enable the routine adoption of a farmer-centric approach to research will require significant investment in skills for facilitators and a digital infrastructure to support data exchange, communication and knowledge sharing.

Whilst there is an engaged community of farmers in the UK who are already conducting on-farm trials or are open to it, this by no means includes all farmers. Wider participation depends crucially on making the initiative attractive, providing useful and timely information back to growers and fostering an active network with face to face meetings that people want to be a part of. Undoubtedly there is value in farmers collaborating and cooperating because replications across farms provides greater certainty. However, experience here shows that a few farmers will always drop out due to unforeseen circumstances, and some level of data loss seems to be inevitable. If operating research projects which depend on farmers' data it is therefore important to build in an adequate level of redundancy.

5.3. Best indicators for success in N management

For the farms investigated here, self-selecting engaged farmers in long-term arable situations with high yields where N requirements were expected to be similar, it was difficult to improve on recommendations beyond RB209 (or a single average N rate). We did not find evidence that individual farms should consider their N requirements differently from other farms in the group, or from the recommendations. The quantity of N fertiliser that should be bought by a farm is an economic decision that the farmer must make each year. This decision depends on the farmers' attitude to risk and return, grain price and fertiliser price as well as empirical evidence of crop performance and wider experience. A range of tools are available that can help farmers in making this decision, but unfortunately there is no ‘silver bullet’ that can provide the definitively ‘right’ answer.

Whilst farmers must decide on average N rates to use over all fields, we’ve shown that the biggest impacts on profitability come from the few fields where actual N rates are a long way out (>50 kg N/ha). Any tool that can give an indication of the fields that are at risk here would be welcome.

We have shown that *for the farms in this project* the RB209 field assessment method needed to be adjusted to a higher than typical yield level of 11 t/ha to give the most profitable predictions of N requirements. However, fine tuning for yield at a farm or field level showed no advantage in improving N recommendations (and in fact gave a penalty), suggesting that this adjustment should be made at a broad level rather than necessarily on a field-by-field basis.

The biggest driver of variation in N requirements across the fields studied here was soil N supply. Whilst in this study measurements of soil mineral N, mineralisable-N, soil organic matter and soil total N% were found to be only weakly predictive of harvested SNS, this partly reflects the narrower range of SNS levels encountered within the farms here. However, substantial differences were observed in all these measures between farms, which should be informative of likely SNS levels and the potential for mineralisation. Some farms consistently had very low SMN levels, whilst others had much greater variability, which tended to be reflected in more variable N optima. SMN measurement also proved valuable in 2014, showing soil N levels were low after a wet winter, and subsequent N optima were higher. Other studies have advocated the use of soil measurement where soil N levels are expected to be high or uncertain (Kindred *et al.*, 2012), and this certainly can provide a useful tool. It is disappointing that we have not been able to demonstrate more definitive benefits to improve N decision making from the range of soil measurements in this study.

We were hopeful that grain protein content would prove a useful indicator of successful N management (Sylvester-Bradley & Clarke, 2012), but unfortunately we have found substantial variation in grain protein measured at the optimum, and variation between farms that we now know does not indicate consistent differences in N requirement. The variation in grain protein between farms does not necessarily relate to differences in N requirement, and protein seems to act as both a driver and an indicator of N optima. It thus appears that protein should still be considered as a tool in building evidence of appropriate N rates at farm and field scales, but grain protein content alone is not a safe direct indicator of whether N rates were optimal. Within the tramline trials the responsiveness of grain protein to N was much clearer than with grain yield, so protein can be useful in judging the extent to which the crop is still responsive to N. If no response is seen, this indicates that N levels are likely to have been super-optimal. However, the complex relationships and variability between yield response, protein response and N optimum precludes definitive advice being given at this stage, and this warrants further study.

Tramline trials can give a direct indication of whether N rates were optimal, sub-optimal or super-optimal. However, a clear conclusion cannot be guaranteed and the inferences that can be made across the farm and across years are more limited than we hoped. We therefore recommend using tramline trials on fields where N requirements are most uncertain. We also recommend using tramline comparisons when changing N strategies on the farm, to test that improvements are in the right direction. Applying an extra 40-60 kg is often easier than applying less, and potentially less costly (especially if milling premiums may be put at risk).

Given that variation in N requirements exist at the field scale between years and that current approaches do not adequately predict the differences seen, it seems that the last hope for better estimating N requirements is to judge the crop itself *in-season*. Although widely adopted abroad (e.g. Justes *et al.*, 1994) such approaches have not been widely advocated or adopted in the UK; however, sensing and plant tissue testing have received increasing interest in recent years. Calibration and validation is required to provide meaningful thresholds for sub- and super-optimal N status, which are dynamic with time, growth and development of the crop, and may differ with varieties and agronomic factors. Leaf tissue testing is available commercially, but there has not been recent independent validation of its benefits in the UK. The MALNA project demonstrated that ear N concentration at GS 71 (2%N) could help indicate whether grain protein targets would be met (Weightman *et al.*, 2011), other work has assessed using flag leaf N (Sylvester-Bradley, 1990). The Minolta SPAD or Yara N tester approach to assessing chlorophyll content of flag leaves is available commercially and is well documented (Ortuzar-Iragorri *et al.*, 2005), but are somewhat limited in terms of their ease of use. A whole range of sensing technologies and data analytics are now coming on stream that may provide affordable solutions in the near future.

It seems there is a level of variability and uncertainty in N requirements that we just have to tolerate, unless crop sensing based approaches can be developed and proven.

5.4. Are we generally getting N rates right?

The evidence from the self-selecting arable farms in this study suggests that overall N rates used on all farms were not far from optimal, and not far from RB209 recommendations. If anything there appeared to be more fields where N was over-applied rather than under-applied. There was no evidence that individual farms were consistently over- or under-applying N to all fields. There were very few fields where large increases in yields from additional applications were seen, with most responses being fairly flat.

For this group of farmers, who are typical of engaged arable farms yielding >10t/ha and applying ~240kg N/ha, we can now say with some confidence that their yields are not generally being limited substantially by availability of N. The unanswered question concerns the advice that should be given to the ‘average’ UK farmer with average yields of only 8 t/ha and N applications to wheat average at 192 kg/ha. This difference in yield between the average farm and LearN farmers (11.4 t/ha) is clearly not due to the difference in N applied, as the average yield from the lowest N rate of 179 kg N/ha in the tramline trials still yielded 11.1 t/ha.

We have found that, within the bounds of what is typically applied by high yielding farmers in the UK, the benefits from improving N recommendations, and the penalties for being wrong, are surprisingly modest. Around ~200 kg N/ha, yield responses to N are relatively flat, such that responses in yield are broadly compensated for by changes in the spend on fertiliser. With perfect prediction of N optima, margins in this study could be improved from an average of £1,403/ha for current practice to a possible £1,426/ha; a benefit of £23/ha appears insignificant when compared with the >£1,000/ha range in margin over fertiliser seen between fields in this study (Figure 27), largely driven by variations in yield which were unrelated to N fertiliser.

The modest average feasible benefits from improving N requirements have implications for precision farming technologies & services offered around variable rate N (Kindred *et al.*, 2016; Pannell et al., 2018).

5.5. Environmental implications of this study

The minor or nil modifications in N use envisaged as a result of this work clearly indicate minor or nil effects on the environmental repercussions of current N usage on UK wheat crops. The high yielding fields on the particular farms chosen for the study showed low SMN values (average 60 kg/ha) and few were high (10% exceeded 100 kg/ha; Table 3). In relation to average fertiliser N use (239 kg/ha) grain N offtake was high (average 197 kg/ha) and this would indicate that average crop N uptake was at least 246 kg/ha, assuming a high N harvest index of 0.8. Thus on average 42kg N /ha more was applied to these crops than was taken off in the grain, but in total (including straw) the crops took up more nitrogen from the soil than was applied as fertiliser. This implies that the fertiliser-soil-crop system was close to being in balance, and implies that there would typically be little nitrogen at risk of being lost. Assuming an average of 80kg N/ha was available from the soil the apparent fertiliser recovery of crops in this study was 70%, considerably higher than the 60% assumed to be normal for UK crops.

N emissions were not measured in any of these trials and limited resources have not enabled a comprehensive estimation of all components of the N balances at all these sites but it seems from crude summary data that effects of the conclusions from this work on nitrate leaching and emissions of nitrous oxide and ammonia would be insignificant.

5.6. Recommendations for further research

The following recommendations for future work are made, for the benefit of improved N management, and more broadly to achieve improved productivity.

- The most important area for future research must be to better understand the enormous variations in yield (and hence profitabilities) seen between fields and farms that we now know are not due to differences or deficiencies in N management. As an industry we must seek to find the causes and whether any agronomic, genetic, chemical, soil or engineering solutions can be used to overcome any of the shortfalls.
- We do not currently understand the variability in grain protein responses between fields, farms and years, nor its relationship to grain yield or the optimum. This may be explained in part by timing of N uptake. Further study of protein and its response to N is warranted, both to better achieve milling premiums and to understand whether protein 'demand' or 'potential' influences N optimum, and how best protein can be used as an indicator of N requirement.
- Canopy sensing offers the potential to give an absolute in season field by field and metre by metre indication of N status, but considerable work is required to develop and validate robust calibrations, and then to develop an interpretation (and associated algorithms) that will provide robust N recommendations without risks of reducing profits.
- We have provided a conclusive answer on the appropriateness of current N rates for high yielding arable farms applying ~240 kg N/ha, but we cannot be conclusive about the 'average' farm yielding 8 t/ha with 190 kg N/ha. Ideally similar trials would be conducted on these farms, though it is expected that engagement could be more difficult.
- This project has demonstrated a novel way of conducting agronomic research which, with improvements to the trials protocols and the supporting software, could become routine for all sorts of questions in arable farming. The LearN project arose as this approach was in its infancy so outcomes of all trials were by no-means perfect; however LearN has shown an approach to conducting farmer-centric research which we will believe could be transformative both for the industry and for crop science. To achieve this transformation will require investment in digital and social infrastructures to facilitate communications, data sharing, benchmarking, knowledge generation and knowledge exchange.
- There is also a need to work with combine manufacturers to improve the quality of yield maps to enable finer precision.

6. Major LearNings and Key messages

- Most variation in N requirements is seen between fields and years, rather than between farms. This means that the N requirements of each field (or similar block of fields) should be considered on their own merits in each year.
- In using ~240 kg N/ha on average, all the farms in LearN were getting their N rates broadly right. Whilst yielding 11.4 t/ha on average, there was no evidence that any farms could consistently be yielding substantially more by applying more N.
- The RB209 fertiliser recommendations are right on average after accounting for the higher than average yield of these farms (11 t/ha) compared with the UK average yield of 8 t/ha. However we saw no consistent advantage from fine tuning yield adjustments on a field-by-field basis.
- The economic costs from errors in optimising N rates are generally modest, especially in relation to the large variation in financial performance (>£1,000/ha) observed between fields.
- The biggest costs of imprecision in N use come from the small proportion of fields where optimal N rates are substantially (>50kg N/ha) higher or lower than expected. Efforts should be focussed on identifying and managing these fields where N recommendations are uncertain.
- Nitrogen is not responsible for the vast majority of variation in yields seen within and between fields, farms and years. Given the very large & unexplained variation in yield seen in this project and others (6-15 t/ha) understanding the causes of this variation must be a priority for the industry, in order to develop management solutions to raise productivity.
- There is substantial variation in grain protein content between farms that is not related to differences in N optimum. Grain protein cannot therefore be used as an entirely reliable indicator for N management. However, grain protein is much more responsive than yield in tramline trials, so can be useful for indicating a crop’s responsiveness to N.
- Measures of soil N showed differences between farms and years that were useful. However we could not demonstrate definitive improvements to N recommendations from their use, possibly because the variation in SNS between fields was skewed, with many small to moderate values and only a few large values.
- Simple tramline comparisons of +/-60 kg N ha can usefully indicate whether the N rate applied is about right, too much or too little.
- Some of the many LearNings on how best to conduct these trials were as follows:
  - Spatial variation is usually greater than any treatment effect, and visually obvious treatment differences in yield maps are rare.

    - Care is needed in locating treatment areas in fields to ensure representative and fair comparisons. Ideally past yield maps or satellite imagery should be used to gauge spatial variation.
    - Guidance on conducting tramline trials has been developed in a Farmers' Crop Trials Guide (ADAS 2018).
    - With spinning disc spreaders double tramlines of each treatment are required to give sufficient area for harvesting of the intended N rate. This becomes limiting for many fields on some farms as there are insufficient tramlines to test all rates.
    - The plus and minus 60kg N/ha treatments should be placed side by side to give maximum contrast, and should have full areas (i.e. not a headland) of standard treatments on either side. Having two standard treatments enables some gauge of spatial variability to be made.
    - Full tramline lengths should be used, to give best context of spatial variation across all soil types and other conditions within the field.
    - Location of treatment areas should be recorded accurately.
    - Care should be taken at harvest to ensure full header widths and, where possible, avoid cutting across treatment boundaries.
    - Yield data should be cleaned to remove anomalous data points and combine runs.
    - Yields within each treatment area should be averaged, and margins over N costs calculated.
    - When interpreting treatment effects:
        - Use at least two 'standard' N tramlines to indicate inherent variability; if the difference between them is greater than other treatment differences, then further conclusions are uncertain.
        - If no difference in yield between N rates = Super-optimal

          → Reduce future N rates
        - If the difference between standard & low/high is less than 0.3 t/ha = Near optima

          → Maintain N rates
        - If the high N rate gives >0.3 t/ha increase over standard = Sub-optimal

          → Increase future N rates
- Even with good set up of tramline comparisons and good harvest discipline, simple comparisons of average tramline yields, as in LearN, cannot be always be conclusive. The new SDA statistical approach adopted by ADAS's Agronōmics service can more robustly quantify differences between treatments and their certainty levels.
- Overall, tramline trials indicated that around 30% of standard N rates were close to optimum, 26% were above optimum, 24% were below optimum and 21% of trials were inconclusive.

- Tramline comparisons will be most worthwhile for fields where N rates are uncertain or when a farm is considering or implementing changes to its N management strategies.
- When changing fertiliser rates for fields change by ~20-30 kg N/ha increments, and conduct +/- 60kg N/ha tramline comparisons to monitor effects and check you are getting closer to optima.

7. Conclusions

We know that managing N fertiliser is important for yield, profitability and the environment. However, we have now shown that variability in N requirement is not responsible for the majority of variation in yield in the UK, whether within-field (as evidenced by chessboard experiments; Kindred *et al.*, 2016), or between fields and farms. It is not possible to radically improve the yield of lower performing fields or areas by applying more N. If N is not responsible for most of the variation within and between fields, between farms and between years then other factors must be. Given the very large variation seen in yields within and between fields and farms, determining the cause of these differences, and whether they can be managed and overcome, should be a primary question for the agricultural industry and agricultural research community.

It seems that we can't escape the variability and uncertainties in N requirements; the variability within farms is as great as that between farms. We still don't have any fail-safe method to predict optimal N rates, but there are several tools we can use to gather evidence and experience (over time) to steer our N management. The good news is that farms and recommendation systems are getting the optimum right on average, and the economic costs of getting it wrong are generally modest. We should be mindful of the small proportion of fields where N rates are most wrong, and should be focussing the tools available on identifying and improving these. Farmers should look out for fields that are a long way out, for example those that suffer from significant lodging.

Detecting N optima is a very subtle task, and it is a lot to expect to be able to do this with precision in tramline trials, as it is differences in the gradient of yield response between treatments that must be determined, rather than just probable yield differences. This doesn't detract from the evident value of tramline comparisons more generally, in testing yield differences between treatments. LearN tramline trials will be most useful in fields where N optima are uncertain, and in checking any changes to N management that are made across the farm.

Given the general 'flatness' in the economic outcomes between the N treatments tested here, especially relative to differences in economic performance between fields, there is a sense that we as researchers have focussed too much on chasing the economic optimum to squeeze out a few extra £/ha, rather than fully considering the bigger picture of the large variation in yield and profitability that is not related to N. Farmers should be following best practice in their N fertiliser management, utilising nutrient management planning and thinking carefully about how much nitrogen they buy and apply. However, the evidence suggests that the economic marginal returns from ever increasing fine tuning of nitrogen rates are likely to be modest at best. The effort may be better invested in considering other factors that may be driving yield differences across the farm.

This project has demonstrated, perhaps for the first time in the UK, that it is possible to work with large groups of farmers, supported by industry, to conduct field scale experiments managed and measured by farmers with precision farming technologies, to answer genuine agronomic research questions in a scientifically rigorous manner, generating and sharing new knowledge. However, it is not as simple to generate sound conclusions from farmer-led trials as we first imagined. We've seen that spatial variation almost always exceeds the variation caused by the treatments imposed, and trials where the treatment effects are visually obvious are generally rare. Expert support and bespoke data processing and statistics are needed to get the most out of farmer-led trials. Through the LearN project we have learnt 'best practice' for conducting such trials, culminating in the ADAS Guide to Farmers' Crop Trials (ADAS, 2018). We believe that working with networks of farmers using appropriate concepts, metrics and tests within the 'Agronomics' approach, as demonstrated here, will give the fastest route to progress, providing robust answers to questions that matter (Sylvester-Bradley *et al.*, 2018).

8. Acknowledgements

The authors wish to express their sincere thanks and appreciation to all the growers that participated in this research project, namely, Simon Parrish, James Balaam, Andrew Balaam, David Jones, James Faulkner, Aaron Hogsbjerg, Eric Wright, Phil Woodward, Tom Paybody, Dan Matthews, Giles Halfhead, George Renner, Edward White, Mark Means, Nick August, John Drysdale, Stephen Buckle and Bill Burt. Their hard work in setting up, running and harvesting the trials and the time taken to collect the data is fully acknowledged and much appreciated. Without their efforts, this project would not have been possible.

The contribution of CF Fertilisers is gratefully acknowledged, including provision of all the soil tests and fertiliser product throughout the project, as well as the support of participating farmers and Alli Grundy's valuable contribution to the steering committee.

We would also like to thank all the support staff from Agrii, NIAB, ADAS, CF Fertilisers and other organisations who helped the growers execute the trials. Supporters have changed over the course of the project but include: Sam Fordham, Sam Hogsbjerg, Greg Taylor, Sarah Hookway and Steve Burton from Agrii; Poppy dePass from NIAB; Alli Grundy from CF fertilisers; Damian Hatley, Dan Munro and Dom Edwards from ADAS; Eric Anderson from Scottish Agronomy; Andy Eccles from Omex; and Leigh Maclean and Robin Bolton from DARD.

The Informatics team at ADAS (Lucy Wilson, Ben Hockridge, Christopher Stocks and previously Antonio Calatayud) is acknowledged for their work processing yield mapping data and developing the ADAS Portal. Ben Marchant and Sebastian Rudolph of British Geological Survey have provided invaluable support in developing the processing and statistical analysis of yield data, through the Agronōmics project, including analyses of many LearN datasets.

We thank Sajjad Awan, James Holmes and Shamal Mohammed of AHDB for guidance and steering through the project.

The consortium appreciates the contribution of the AHDB funded summer students, Georgina Barratt and Alex Johnson, who added extra elements to the project.

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