Supporting and analysing on-farm Nitrogen tramline trials so farmers, industry, agronomists and scientists can LearN together

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Abstract. *Nitrogen fertilizer decisions are considered important for the agronomic, economic and environmental performance of cereal crop production. Despite good recommendation systems large unpredicted variation exists in measured N requirements. There may be fields and farms that are consistently receiving too much or too little N fertilizer, therefore losing substantial profit from wasted fertilizer or lost yield. Precision farming technologies can enable farmers (& researchers) to test appropriate N rates, through tramline comparisons and analysis of yield maps. We report findings from the LearN initiative in the UK to help enable farmers to test N rates on their farm, to learn whether the N rates they are using are about right, too high or too low. A group of 18 farmers were supported to conduct simple tramline trials with single replicates of 60kgN/ha more and less fertilizer in alternate tramlines, on 3 fields per year from 2014-2017.*

We found strong engagement from farmers in conducting tramline trials, which are in principle easy to set-up, manage & harvest. However, there are many challenges that are not always fully appreciated; ensuring comparable treatment areas; precise recording of tramline wheelings and treatment boundaries; non-linear application by spinning disc spreaders; protocols for combine harvest; transfer, processing & cleaning of data; data analysis & statistics to achieve robust conclusions in the face of confounding variation and appropriate interpretation.

Overall yields were 11.43, 11.07 and 11.74 t/ha for farm-standard, +60kgN/ha and -60kgN/ha respectively, giving differences in margin of -£8.75/ha and +£0.51/ha. Differences in yield between two 'farm standard' tramlines was used to give a crude measure of error and infer confidence. 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 nitrogen effect. A few fields and farms were found with sub-optimal N rates, but lost profits were modest. We conclude that nitrogen is not the major cause of variation in yield within & between fields and farms. Tramline trials are useful for understanding variation in yields; for maximum impact they should be networked and employ spatial analysis.

Keywords. *Nitrogen, yield, on-farm experiment, tramline trials, protein, wheat, map, agronomics, strip trials*

Introduction

Nitrogen fertilizer is often cited as a key decision point for the agronomic, economic and environmental performance of cereal crop production in the temperate environment of N Europe (Brentrup et al., 2004). Principles of N fertilizer management are well established, and substantial empirical plot research provides sound recommendations for N rates across a range of soil types, previous crops, rainfall levels and yield levels (Sylvester-Bradley, 2009). In the UK advice is provided by The Nutrient Management Guide RB209 (AHDB, 2017) to achieve the most profitable yields. However, there is large variation in measured N requirements at field level, which are not predictable from current recommendation systems (Sylvester-Bradley et al., 2008; Kindred et al., 2012; Roques et al., 2016). There may be fields and farms that are consistently receiving too much or too little N fertilizer, therefore losing substantial profit from wasted fertilizer or lost yield. It has been suggested that N fertilizer rates could be limiting yields on some UK farms, contributing to the wheat yield plateau (Knight et al., 2012). Consistent farm level variation in grain protein content suggests that farms may differ in their N requirements beyond that prescribed by the recommendation system (Weightman et al., 2011).

We demonstrated the power of spatial experimentation using chequerboard trials that showed large variation in N requirements within fields, questioning the relevance of small-plot trials in extrapolating to large areas (Kindred et al., 2017). However, despite the large variation in N optima within fields, benefits to productivity, fertiliser savings, gross margins and environmental performance of perfectly matching N requirements across fields (compared to a uniform flat rate at the average optimum) were surprisingly modest; accurately predicting the average N optimum for a field is more important than matching intra-field variation. Also, optimising N fertiliser rates did not substantially reduce variability in yield, implying that the major causes of yield variation were not related to N.

We deduced that farmers would value being able to test themselves whether or not they are getting their N management right, and established the LearN project in 2013 to evaluate this idea. Whilst most evidence for national N recommendations arises from multi-site small-plot trials, the LearN project demonstrated & tested a ‘strip trial’ approach whereby the farmers themselves compared their standard N rate with 60 kg/ha more and 60 kg/ha less N applied to alternate tramlines. Our objectives were to (i) understand and prioritise the important scales of variation in N requirement (ie within field, between fields, between farms & between years); (ii) evaluate the value, ease & usefulness of simple tramline comparisons to aid N management on-farm; (iii) assess the proportion of farms where nitrogen rates are too low and yield is being lost, or rates too high and fertilizer being wasted.

Methods

In 2013 farmers in the UK were invited to participate in the LearN project, committing to test N rates in tramline comparisons on three fields per year for four years. Farms were selected who had yield mapping combines and who represented the target situation of a long-term arable system on deep heavy soils in the East of England. Six farms tested three fields each over four years with tramline trials adjacent to conventional small-plot trials, providing a structured core dataset for validation against. An associated network of 10 farms used the tramline approach to provide wider evaluation, to gauge variability in field-average N requirements, and to determine the feasibility of farmers testing their N management decisions more routinely. Each farmer was supported by a support agency and additional measures were made of soil mineral N, mineralisable N, soil organic matter, soil N% and soil texture. Grain samples were taken from each treatment and grain protein content measured. Information on previous crops, manure history, cultivation system, N fertilizer products used and application timings were collated. Canopy reflectance measures by satellite were available on a limited number of fields.

Tramline trials

We deliberately kept the trials protocol for farmers as simple as possible, to maximize its scalability to farmers operating without support. Whilst some of the farmers were seasoned precision farming enthusiasts, most were not. We used approaches that could be adopted by any farmer, without the need for GPS and pre-defined application maps on the fertilizer spreader: the rate could simply be adjusted up or down manually at the start of the tramline. Whilst we recognized strong advantages of full yield mapping on the combine, the approach is equally relevant to use with a simple yield monitor.

Every farmer had an industry supporter to help facilitate placement of trials, taking of soil measures, harvest procedure and capture of field records and yield map data. Fields were selected that were consistent and representative of the farm, with the same fields used in each year where rotation permitted.

A simple trial layout was used comparing +60kg/ha and -60kg/ha side by side, with standard rates on either side (Fig 1). In the first year an additional standard treatment was used in the middle, however this created a gradient across the field that could not necessarily be distinguished from an underlying spatial trend. Spinning disc fertilizer spreaders do not provide a linear boundary, as they work with a double overlap. For this reason we require double tramlines for each treatment where spinning discs are used (vast majority of applications in the UK). Where liquid or pneumatic applications were made, one tramline of each N rate was acceptable. The tramlines selected were to be representative of the field and as comparable as possible, treatment tramlines were agreed with supporters and marked by canes.

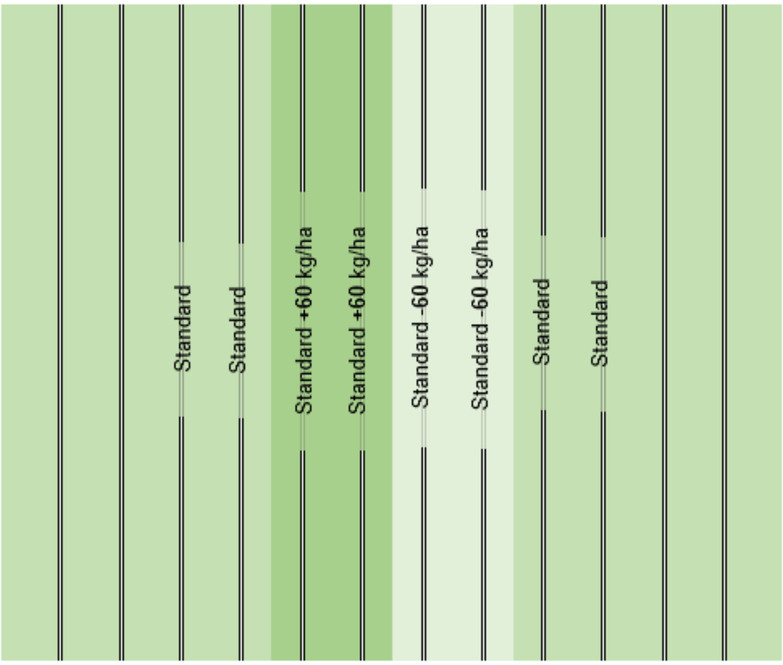


Fig 1. Trial layout for LearN tramline trials.

Most farms had a standard N rate of around 200 kg N/ha, applied in three or four splits. The treatment rates were imposed in one or two of the main applications, usually in April.

The harvest procedure varied by farm as optimal harvesting is dependent on how the combine header width relates to the tramline and treatment width. Key principles were to keep a full header width as far as possible and to avoid cutting across the treatment boundary.

Analysing yield map data

Alongside the LearN project ADAS led 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 was obtained from farmers as raw data files (eg .aft) or online via manufacturers Telematics platforms where possible. The below steps 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 standardized csv datafile, with standard nomenclature & filename
5. Provide orthogonal co-ordinate system (eg British National Grid)
6. Calculate combine direction and segment combine runs
7. Set a baseline perpendicular to combine runs and calculate distance from it
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 (eg <2 and >18 t/ha). Remove statistical outliers (eg >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) 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 recording at adjacent locations are more likely to be similar than those made a long distance apart. Some of this reflects genuine spatial patterns in the crop performance caused by variations in environmental factors such as soil type, 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, the presence of wheelings or a reduced header width can lead to lower yield measurements for particular combine harvester rows and variation in the time it takes 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) varies with the distance between the yield measurements. A standard variogram model would require the assumption that the degree of spatial correlation is identical in each direction. Many of the artefacts introduced by the yield monitor lead to anisotropy – the yield measurements are more similar within a row than they are perpendicular to it. Therefore, within the SDA protocol we estimate anisotropic variograms for the yield data from each trial. Such a model accommodates the potentially greater similarity between measurements from the same row. Then we estimate the treatment differences and the uncertainty of these differences using a regression model that accounts for the modelled spatial correlation.

Small plot trials

For each field on six of the farms a small plot nitrogen 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. N rates were selected to match those used in the field and in the tramline comparisons: N rate 4 of each trial was chosen as the farm's standard N rate, N rate 5 60kg N/ha more, N rate 6 360 kg N/ha, N rate 3 was 60kg less than standard, N rate 2 half of N rate 3 and N rate 1 was zero. All N treatments were applied by hand across three application dates with 40kg applied in February/March and the remainder split in equal applications at start of stem extension (April) and two weeks later (N rate 2 was applied as one application at stem extension). 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.

Yields were measured at harvest by plot combine and grain samples analysed for grain protein.

Statistical fitting of responses was conducted in Genstat (VSN International). The response of yield to N was estimated for each experiment individually using the linear plus exponential function (LEXP; equation 1) which is the standard method for quantifying N responses and N optima in the UK (George, 1984).

$$y = a + b.r\ N + c.N \tag{1}$$

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 0.9999.

Optimum N rates (Nopt) were then derived from the fitted LEXP parameters using equation 2:

$$Nopt = [\ln(k-c)-\ln(b(\ln(r)))]/\ln(r) \tag{2}$$

Where k is the breakeven ratio, or the kg grain required to pay for 1 kg nitrogen.

Grain protein responses were fitted with a Normal type curve with depletion (3) and protein calculated at the optimum N rate.

$$\text{Grain protein} = d + c.\exp(-\exp(-a.(N - b))) \tag{3}$$

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

Grain N offtake was calculated from grain yield and grain protein as in equation 4 and a broken stick (or split-line) regression analysis was conducted. 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.

$$\text{Grain N offtake} = (\text{Yield} \times 0.85) * (\text{Protein} / 5.7) \tag{4}$$

Calculation of financial margins

Financial margins of grain value over N fertilizer costs were calculated for both small plot responses and for the tramline comparisons. This allows profits foregone to be calculated. Financial margins were calculated simply as:

$$\text{Margin} = (\text{grain yield} * \text{grain price}) - (\text{N rate} * \text{N price}) \tag{5}$$

Prices used were £0.70/kg for fertilizer N and £140/t for wheat. This gives a breakeven ratio of 5:1 and means that a difference in yield of 0.3 t/ha is needed to pay for 60kg/ha difference in N.

Results

Small plot trials

Response from the 72 N response experiments across fields farms and seasons are shown in Figure 2. Issues with N application errors, severe weed infestation and poor fits resulted in 4 trials being excluded. Nitrogen optima ranged from 100 kg/ha to 350 kg/ha with the majority being around the average of 226 kg N/ha. It is 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). It is also clear that yield responses to N are generally flat beyond ~200 kg N/ha. Whilst there is very large variation in the yields achieved (from 6 t/ha to 15 t/ha) this does not relate to differences in the optima; it is not possible to achieve a higher yield on a low yielding site simply by applying more nitrogen. There are few instances where further large yield increases can be achieved from applications beyond 200 kg N/ha. Grain protein content is much more responsive to N applications, but again there is wide variability in the proteins achieved and achievable between sites. This is again reflected in the large site variation in maximum N offtake (crop N demand) and N offtake at zero N (indicative of soil N supply).

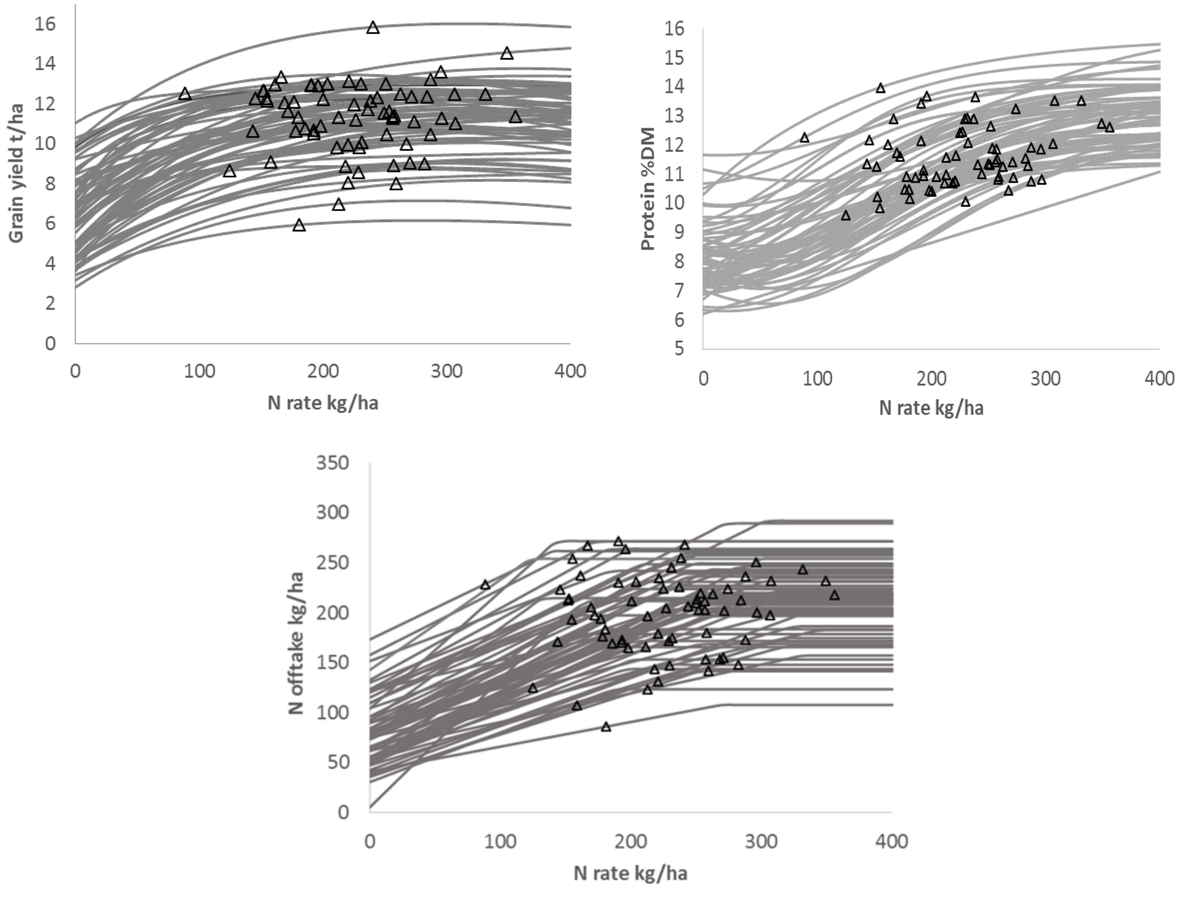


Fig 2. Nitrogen responses from 72 small plot experiments conducted on six farms from 2014-2017 for (a) grain yield (b) grain protein content and (c) grain N offtake. Triangles denote the economic optima for yield.

Looking at variation between fields, farms and years (Fig 3), there is little evidence from the six farms here that substantial consistent variation exists between farms in N optima, though there are differences in grain yield and grain protein. This could simply reflect the greater imprecision and uncertainties in measuring the N optima, but it seems we must accept that there is substantial variability in N optima between fields and seasons within farms. Within some individual fields striking consistency was observed in N responses across years (data not shown).

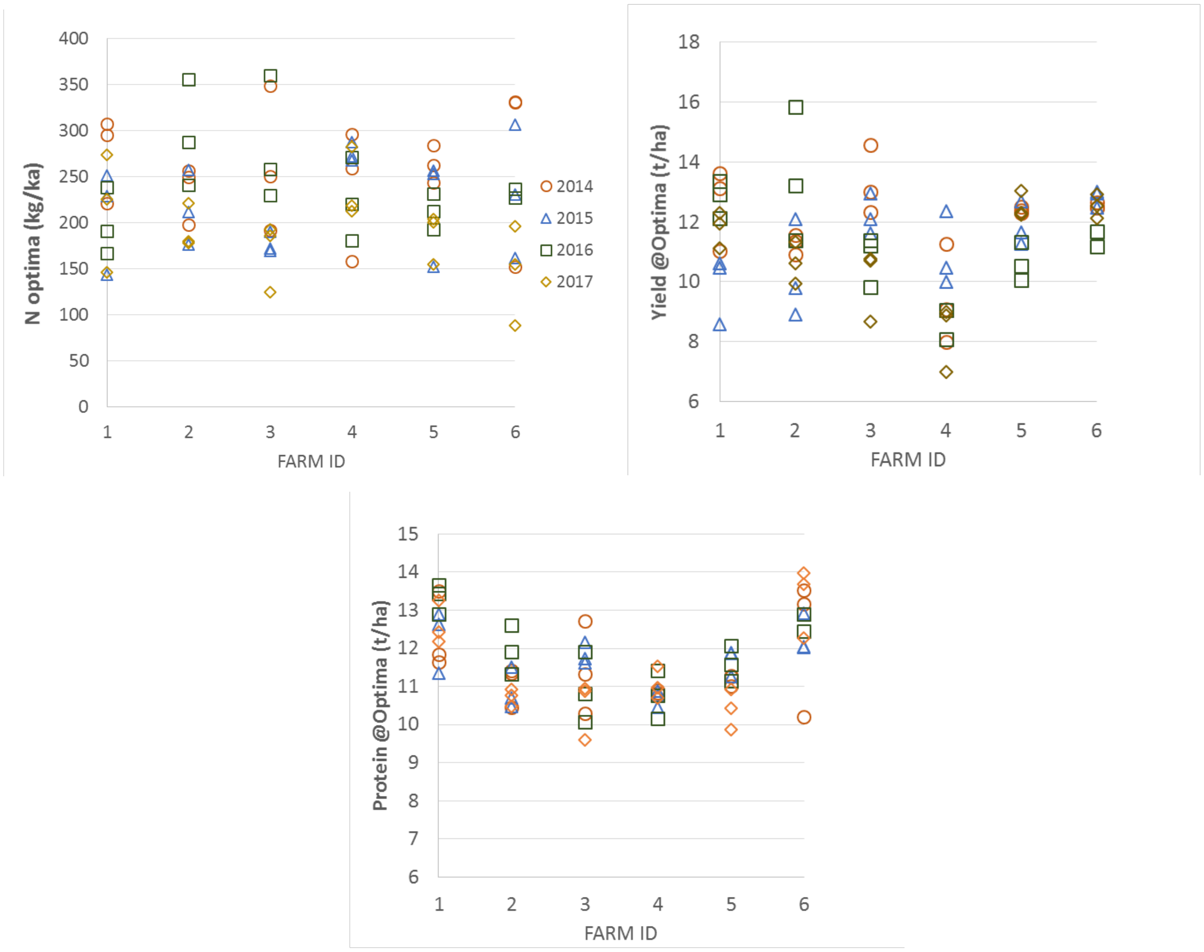


Fig 3. Nitrogen optima (a), grain yields (b) and grain protein (c) from 72 small plot experiments conducted on six farms from 2014-2017, with three fields on each farm in each year

To assess the potential impact of perfecting N management on every field we compare the financial margins over N costs at the applied N rates with those achievable at the measured N optima (Fig 4). On these farms fine tuning N rates would give only modest improvements in profitability; the average margin improves from £1409/ha to £1426/ha.

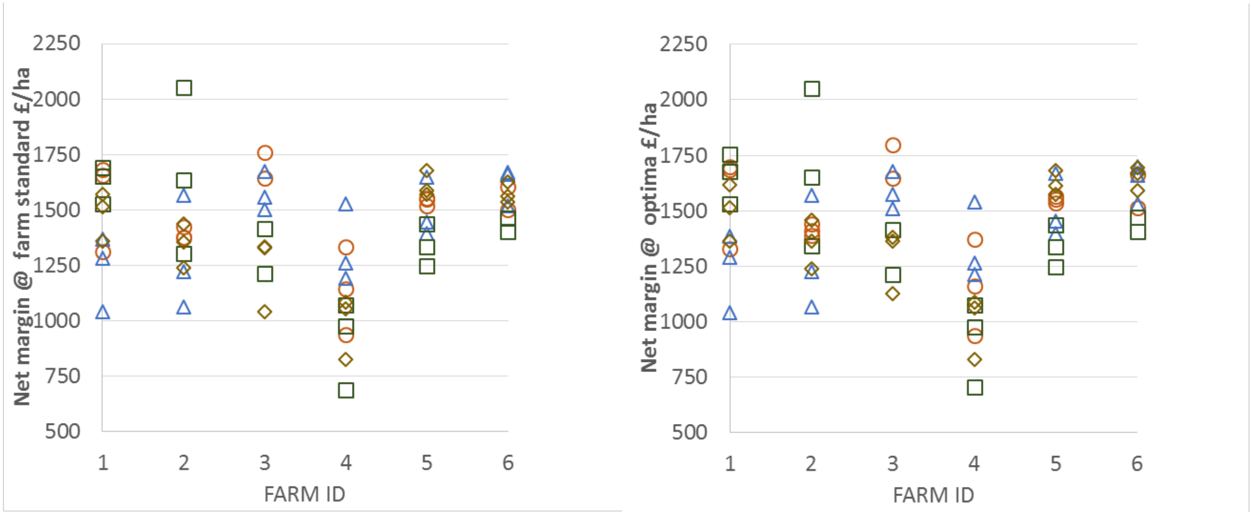


Fig 4. Financial margins over N costs with farm applied N rates (a) and measured N rates (b) from 72 small plot experiments conducted on six farms from 2014-2017, with three fields on each farm in each year

Tramline trials

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

A total of 174 tramline comparisons were established by farmers, from which we received useable data from 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.

For the majority of the trials, the difference in N rate was not immediately visually obvious from yield maps; spatial variation was generally greater than the treatment effect (Fig 4). There was also great variability in the quality of the yield maps, data resolution, data provided & harvest procedures.

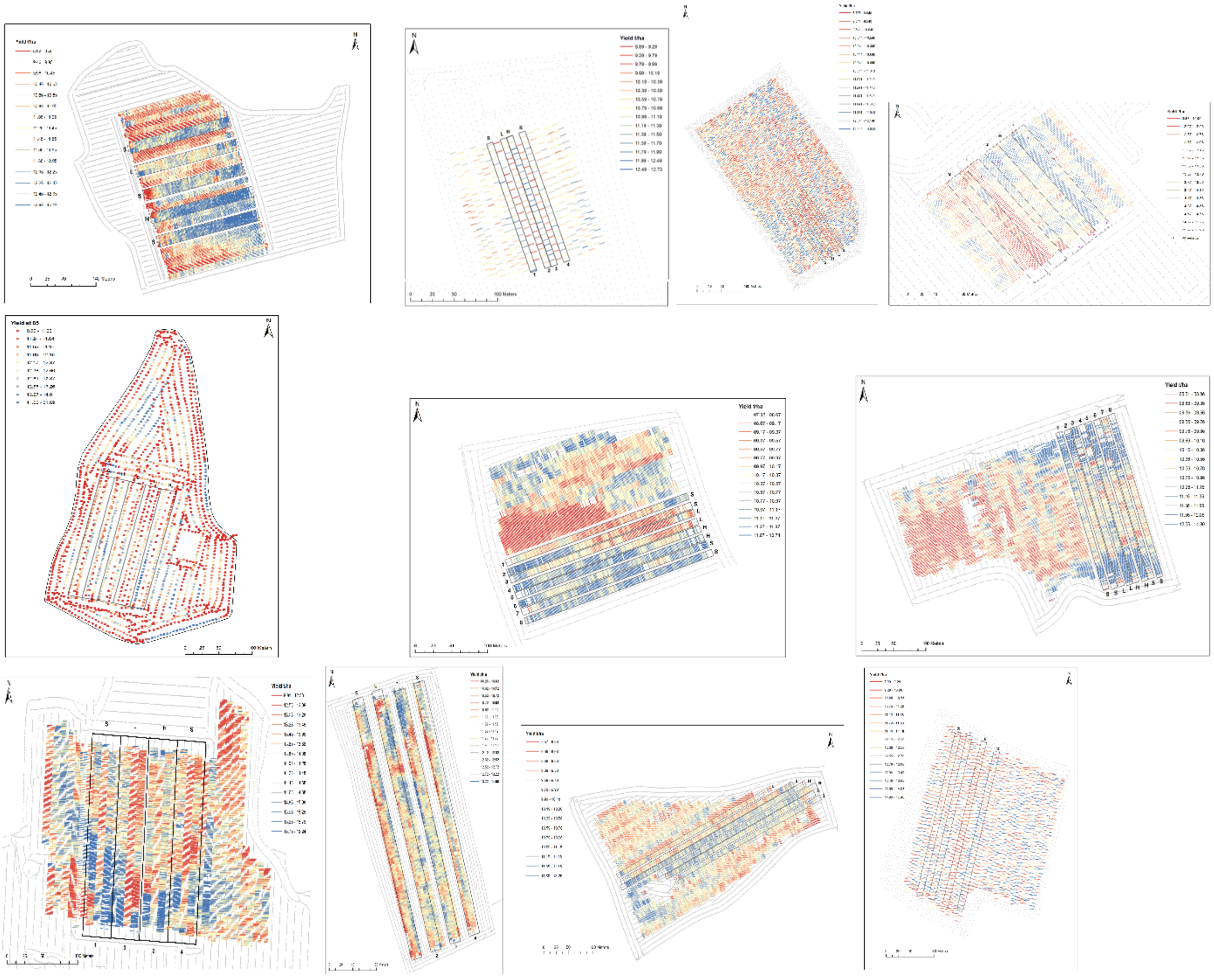


Fig 5. A selection of good and bad tramline comparisons on farmers fields

Figure 6 compares yields from small plot trials to mean yields from the tramlines at the same N rates. Whilst there is reasonable broad agreement in yields (tramline yields being ~0.5 t/ha higher than plot yields) the variability is perhaps not surprising given the levels of spatial variation that we know exist, and that plot yields represent an area of <100 m^2.

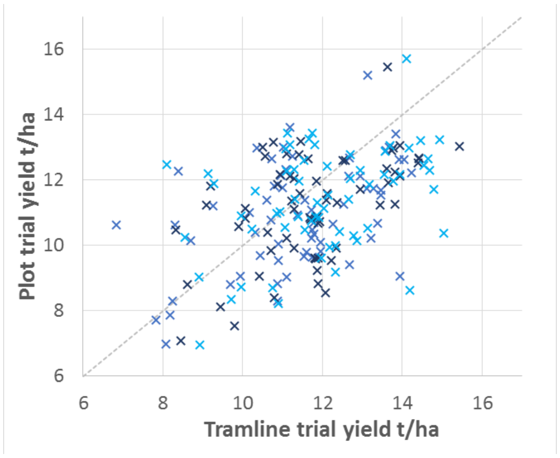


Fig 6. Comparison of yields from plots and tramlines in the same field, across fields. Colours represent the three N levels standard, +60 & -60 kg N/ha

The N responses from all tramline trials are shown in Figure 7. Again it can be seen that yield differences between N rates are generally small, though there are very large differences between fields. Grain protein shows much more responsiveness to N. 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 margins are £1434/ha for both standard and +60 kg N/ha; with 60kg/ha less N the margin is £1425/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.

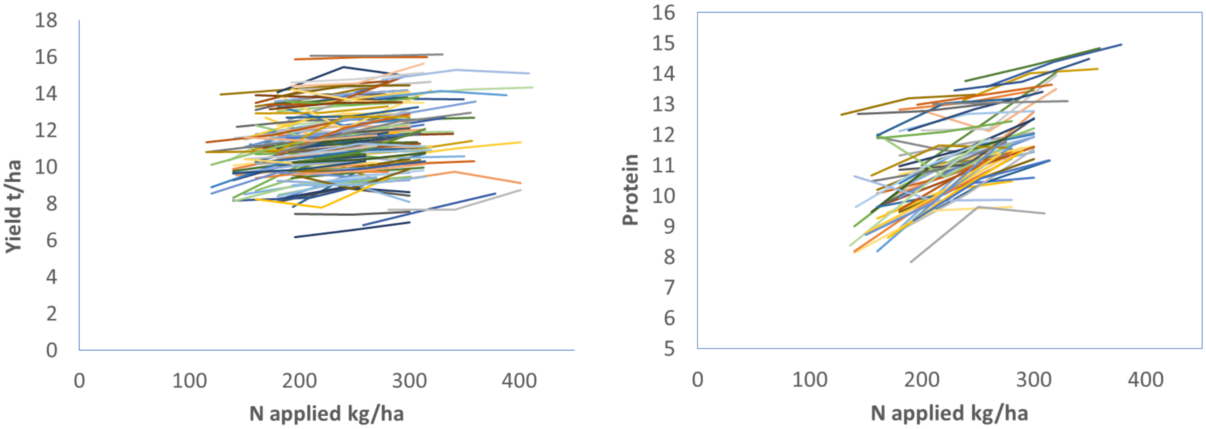


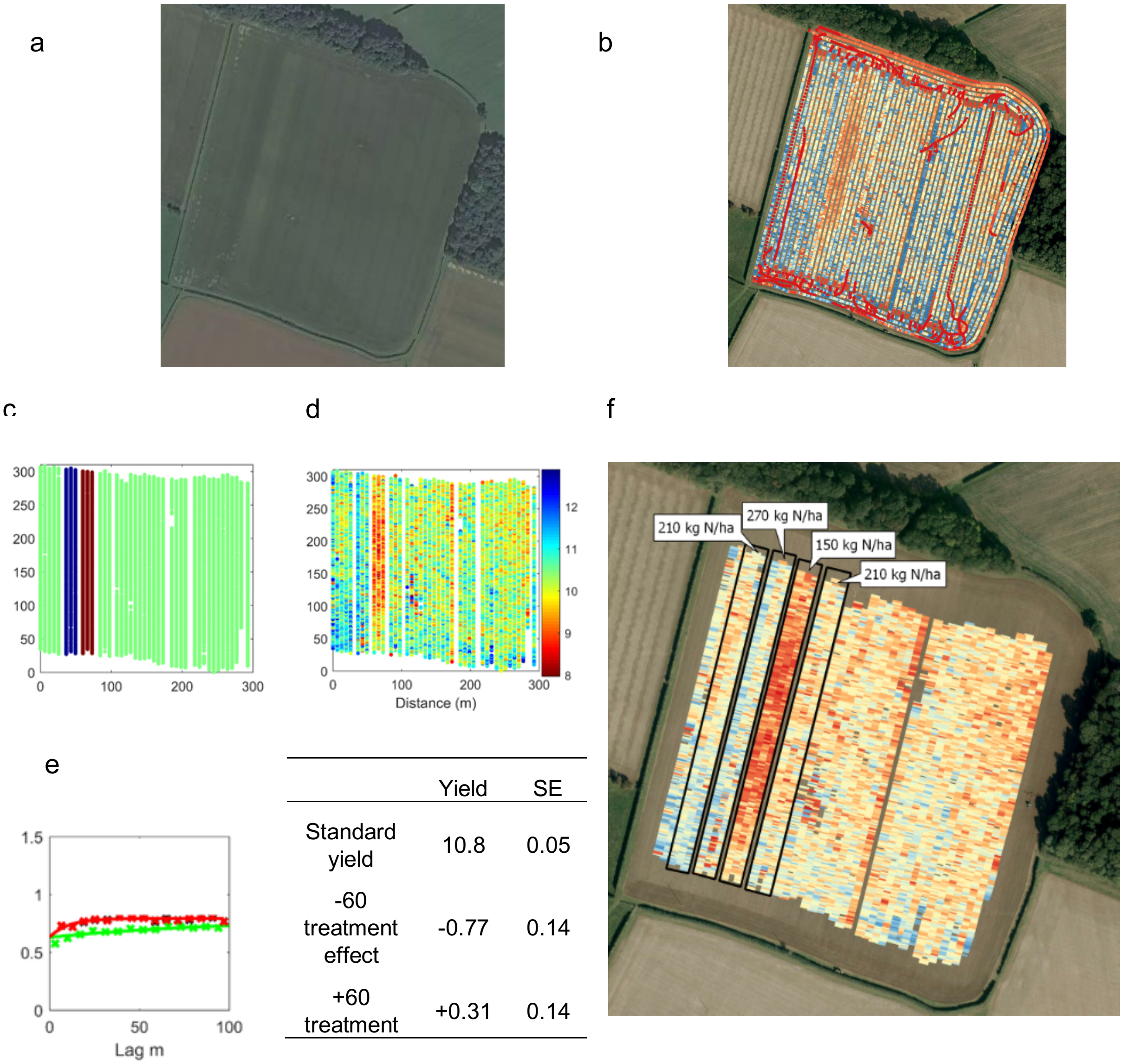
Fig 7. Responses of grain yield (a) and grain protein (b) to farm applied nitrogen from tramline comparisons across ~140 fields from 2014 to 2017.

In using tramline comparisons to judge whether N rates are appropriate for individual fields or farms, it is important to consider the confidence that the yield differences between N rates are due to the treatment, rather than inherent spatial variation. We have taken the simple approach of using the difference between the two standard N treatments that surround the +/-60kg comparison as indicating the spatial variation. This is obviously crude & potentially erroneous, but it is at least doable by a farmer and is better than simply comparing means with no replication. We find that across our 143 tramline comparisons, the difference in financial margin between the standard treatments is greater than that between the treatments in 71 fields, meaning we cannot be conclusive about appropriate N levels on half the fields tested. This can be improved using the spatial analysis discussed later. Of the fields with differences greater than those between the standard treatments, 36 were super-optimal (lowest N rate giving highest margin), 17 optimal (standard N rate giving highest margin) and 21 sub-optimal (highest N rate giving highest margin).

Across farms

Utilising spatial analysis

Figure 8 shows results from analysis of one field where standard N rates were evidently low. Using full spatial analysis enables standard errors to be put on yield estimates and treatment effects, giving confidence intervals. We have found least significant differences (LSD) for treatment effects in tramline trials to typically be around 0.5 t/ha, similar to plot trials, though we have instances of LSD below 0.3 t/ha, as below. Precision can be improved with replication.



	Yield	SE
Standard yield	10.8	0.05
-60 treatment effect	-0.77	0.14
+60 treatment	+0.31	0.14

Fig 8. Example analysis of field Rnn9 with aerial imagery of field showing N effect (a), unprocessed yield data (b), treatment areas (c) and cleaned combine data during GUI processing (d), semi-variogram (e) along rows (green) and between rows (red), final yield map (f)

Learnings

Through the course of the LearN project we learnt an enormous amount about conducting, analyzing & reporting farmer trials, working with farmers and about nitrogen responses. Key learnings are summarized below.

Estimating Fertiliser N requirements

The farmers involved in LearN were a self-selecting group of farmers who were chosen because their farms were broadly similar without large expected variation in N requirements (low-fertility long term arable without livestock or frequent manuring). Nevertheless, considerable variability in N optima, yields and protein was observed. We know that managing N fertilizer 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 nitrogen.

On average N fertilizer recommendations are correct. The evidence shows that the farmers in this study are also getting their N rates about right on average, though these are engaged growers who evidently put a good deal of thought into their management of fertilizer. There is variability in N requirements at the field level, we have found no strong evidence of consistent differences in N requirements between farms, despite consistent significant differences in achieved yields and proteins between farms. The variability in N requirements observed between the fields here is beyond that which current recommendation systems or soil measurements can predict. Whilst tramline trials are a useful tool to check gross differences in N inputs where recommendations are uncertain, they are not guaranteed to provide definitive answers. 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 optima, and variation between farms that we now know does not indicate consistent differences in N requirement. It is possible that in-season crop sensing could provide a route to better estimating differences in N requirements between and within fields, but we caution that our experience in developing and testing new approaches to estimate N requirements shows that it is much easier to make N recommendations economically worse than it is to improve them (Kindred et al., 2012; 2016).

We have found that, within the bounds of what is normally applied in the UK, the benefits from improving N recommendations, and the penalties for being wrong, are surprisingly modest. Around ~200kg N/ha yield responses to N are relatively flat, such that changes in yield are broadly matched by changes in the spend on fertilizer. With perfect prediction of N optima margins in this study could be improved from an average of £1403/ha for current practice to a possible £1426/ha. This starts from an average N rate of 240 kg N/ha, considerably higher than current national average N applications to wheat crops of 192 kg/ha (Defra, 2017). It is possible that larger gains and losses would be apparent from this lower starting point. There are implications for many of the claims made of precision farming technologies & services offered around variable rate nitrogen.

On farm trials and Farmer experience

Over the past five years we have interacted with scores of engaged farmers who enthusiastically conduct their own on-farm trials, looking at nitrogen and a host of other issues. We see huge potential from connecting the learnings that are being made individually by farmers, and there are large opportunities to utilize on-farm trials to answer fundamental research questions. However, we were probably rather naïve when we set out with regard to the ease with which robust conclusions can be drawn from individual tramline trials.

We've found that spatial variation almost always exceeds the variation caused by the treatments imposed. Trials where the treatment effects are visually obvious, such as in Fig 8, are very rare, comprising no more than 10% of trials. The spatial variation within fields is such that any two areas will always give different yields, so it is necessary to judge our confidence that any difference in yield between treatment areas is really due to the treatment imposed. Assessing the variation between replicate tramlines gives a simple but crude indication of the underlying variation between tramlines. Assessing at least one replicate of the standard tramline is crucial, to enable at least some judgement to be made. However, we've seen that using this approach alone we have to forgo firm conclusions on half of fields. Ideally all treatments would be replicated, as this substantially improves confidence. However, we frequently find that UK fields are not large enough to replicate treatments in comparable areas, especially where double tramlines are required due to spinning disc applications.

Farmers have different standards of proof to scientists, and it can be challenging to communicate the importance of accounting for the spatial variability; it can be dismissed as 'just statistics' rather than recognizing the real risks of drawing false conclusions from inappropriately accepting simple means as real differences. This flows through into consideration of how trials are set out in the field in the first place, ensuring that treatment areas selected are as comparable as possible without major confounding differences. Ideally past yield maps should be consulted, but we find it 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.

We also see wide variation in how trials are combined. It is not possible to provide a 'one-size-fits-all' protocol for harvesting line trials, as the optimal harvesting procedure depends on the width of the combine header relative to the tramline or treatment width, as well as the attitude of the farmer and harvesting team. Best results are often achieved where combine position is pre-defined, for example in controlled traffic (CTF) systems (though this can mean much data is wasted that crosses tramline boundaries). Several farmers in LearN 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 often severely limits the confidence that can be made in the comparison, because the information on the surrounding contextual spatial variation is lost. It also restricts the chance to see if treatment effects are effective across the full length of the field, across different soil types and yield potentials, or whether what appear to be effects are just confounding patches. Part of the motivation for limiting the length of treatments is the perceived risk of lost profits. We've shown that losses average only £10/ha from reducing N rates by 60 kg/ha, and there was no average loss from increasing rates. So with typical 2 ha tramlines the cost in lost yield is likely to be only £20, which is inconsequential in relation to the possible learning that could be made. There are greater concerns for milling wheat crops where risk of failing to meet protein specification was feared. However, there were in fact very few milling crops where the low N rate fell below 12% protein where standard rate was above 12%. We therefore strongly advocate conducting tramline trials along the full length of the field.

Since beginning this project we have strengthened our protocols around recording the precise locations of tramlines and treatments. One of the biggest uncertainties can be in judging whether individual combine runs are within or without the treatment area, or whether it straddles the treatment boundary. Knowing how the trial was harvested as well as combine width, make & model can all help analysis, so should be recorded.

These learnings have fed into a guide for on-farm trials that we have produced (ADAS 2018; www.adas.co.uk/services/agronomics) to help set out the principles to achieve robust conclusions from on farm experiments.

The feedback from farmers involved in LearN has been positive. For most it has given them confidence that their N rates are not far out, for some it has raised questions over rates could be slightly higher or slightly lower. One farmers comment was that he has learnt to 'chill out' about nitrogen, where he was constantly worrying about small fine tuning adjustments.

There certainly is an engaged community of farmers in the UK who are already conducting on-farm trial or are open to it. However, this by no means includes all farmers. To ensure good participation it is crucial to make 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. There will however always be farmers 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.

Improving spatial analysis in tramline trials

We have shown that whilst simple comparisons of tramline means are reasonably achievable by farmers, and they can be useful, they are not satisfactory; for half the trials we were unable to draw firm conclusions over which N rate was best, and for others there is still a risk of giving misleading conclusions. This applies however well placed the comparison areas are and however meticulously the experiment is harvested.

Using SDA spatial analysis provides robust estimates of treatment effects as well as providing estimates of the confidence we can have in any comparison. This is a major step beyond the simple repetition of a standard treatment in comparisons. However, it is not yet widely accessible, and it takes some level of training, skill and time to implement. ADAS is providing SDA analysis as a service and is seeking ways to make it available to farmers.

There is much development that would be beneficial for the agronomics process, including routine inclusion of tramline boundaries and locations of wheelings within analyses, and inclusion of prior information on spatial variation via co-variates or specified zones.

There is also a need to work with combine manufacturers to improve the quality of yield maps to enable finer precision.

Conclusions

Nitrogen is not responsible for most of the variation within and between fields farms and years – other factors are. Determining the cause of these differences, and whether they can be managed & overcome, should be a primary question for the agricultural industry and agricultural research community.

We believe that working with networks of farmers using appropriate concepts, metrics and tests within the 'Agronomics' appoach, as demonstrated here, will give the fastest route to progress providing robust answers to questions that matter (Sylvester-Bradley et al., 2018).

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