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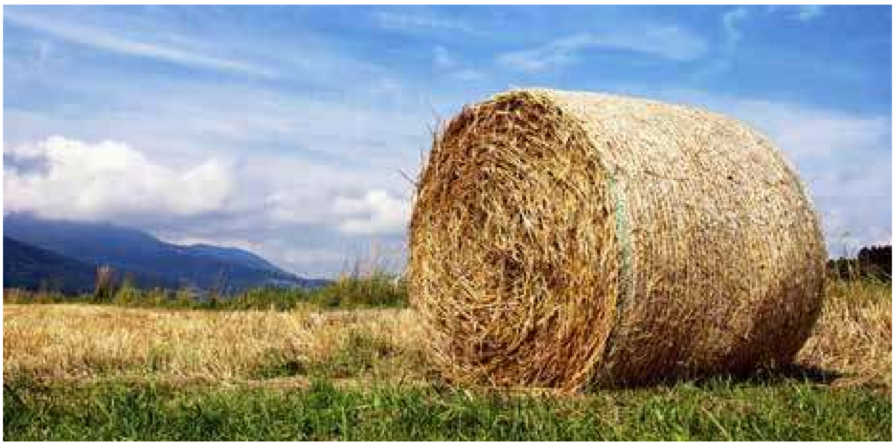

Analysis of the Yield Enhancement Network (YEN) database to investigate Nitrogen Use Efficiency (NUE) metrics

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1 EXECUTIVE SUMMARY

1.1 Glossary

Crop Quality – Measure of grain or seed nutrient content required to meet the needs of the end market e.g., protein content of milling wheat grain, oil content of oilseed rape seed.

Nitrogen Harvest Index (NHI) – Proportion of N in the grain or seed in relation to the N in the whole crop (Grain N offtake / Total crop N uptake).

Nitrogen Use Efficiency (NUE) – How efficiently applied nitrogen (N), or N available in the soil, is used by the crop in terms of either crop N output (grain or seed N content), or crop dry matter output (i.e., yield). The most appropriate NUE measure to use depends on the objective and context of the question being investigated.

Plant Growth Regulator (PGR) – Chemicals used to modify crop growth, such as reducing height and increasing branching.

RB209 – Nutrient management guide for UK growers and advisors to make the most of organic materials and balance the benefits of fertiliser use against the costs, both economic and environmental.

Restricted Maximum Likelihood (REML) – Analysis using linear mixed models i.e. linear models that can contain both fixed and random effects. This means it can thus be used to analyse unbalanced designs with several error terms (which cannot be analysed by ANOVA).

Yield Enhancement Network (YEN) – Industry funded networks established by ADAS connecting agricultural organisations and farmers who are striving to improve crop performance. Network focuses range from crop performance across the main arable crops, crop nutrition, and crop carbon footprints.

1.2 Summary

Nitrogen (N) fertiliser is a key component supporting and enhancing crop productivity. However, there are significant concerns over the environmental and economic costs associated with N inputs on farm. Consequently, it is essential to improve the efficiency of the use of N fertilisers to ensure optimum crop productivity and minimal losses to the environment. One of the barriers to achieving this goal is the multitude of ways nitrogen use efficiency (NUE) is defined in the agriculture industry.

To better understand how a range of crop types on UK farms are performing in terms of NUE, the Yield Enhancement Network (YEN) database was analysed. The YEN networks were established by ADAS >10 years ago to support on-farm learning-by-sharing and thus enhance farming progress. During this time a large dataset has been formed which consists of more than 4,000 crop yields and over 650,000 points of explanatory data.

Before the analysis was undertaken, 12 NUE metrics were defined to ensure NUE was assessed across a range of contexts including crop yield, crop quality, and environmental perspectives. The most useful NUE metric to use depends on the question being asked. For example:

1. To indicate efficiency of crop N use to produce yield:
   kg grain yield/kg N available (kg/kg)
2. To indicate efficiency of fertiliser to improve crop quality (protein content):
   N removed in harvested grain (%)
3. To indicate potential risk of losing applied N to the surrounding environment:

N balance for crop N offtake (kg N/ha), which calculates the net amount of applied N fertiliser left in the field after harvest

The YEN dataset was exploited in this project to calculate the average and variation in the range of NUE metrics defined across the main crop types in the YEN dataset of winter wheat, barley, oats, oilseed rape (OSR), beans and peas. Spring and winter crops for beans, peas, barley, and oats were grouped into the same dataset to ensure it was of a sufficient size for analysis. It should be noted that crops entered into the YENs generally produce above UK-average yields.

The key findings from the analysis of NUE metrics included:

- **kg yield per kg N available (kg/kg)**: this was similar among all cereals ranging between 33 and 34 kg/kg, with a much lower average for OSR (15 kg/kg). Generally, the analysis indicated lower efficiency of OSR crops in using N available to produce yield, due to the higher N content and energy demand of OSR seed.
- **N utilisation efficiency (NUtE; kg yield /kg N taken up):** this was greatest for barley and oat crops (41 and 45 kg DM yield/kg N taken up, respectively, compared to 35 kg DM yield/kg N taken up for winter wheat), likely due to the lower total N rate applied. Changing rotations to include more barley and oats could improve farm-level NUE.
- **N uptake efficiency (NUpE; % of total crop N in relation to the N available from the soil and N applied)**: this demonstrated that bean and pea crops fix around two to three times more N than what was available from the soil. NUpEs for beans and peas were, on average, 325 and 224% respectively compared to a range of 68 to 80% NUpE for the other crop types. Including more pulses in rotations could improve overall farm-level NUE.
- **Apparent N fertiliser recovery (%):** on average the results from YEN agreed with the RB209 standard figure of 60%, but the range was very large (10% to >100%) indicating opportunities for improvement; the average recovery for YEN wheat crops was 73% likely due to the high yields.
- **Soil N balance (kg N/ha; the net amount of N left in the soil after harvest)**: an appropriate balance is important: ensuring they are not too high risking N leaching, but they are not too low to compromise the fertility of the soil. Here, soil N balances were between 25 and 50 kg N/ha for the cereal crops and 86 kg N/ha for OSR crops when grain offtake only was considered. These values reduced to between -5 and +19 kg N/ha for the cereal crops if grain and straw were removed. This indicates that if straw is removed there is a risk of soil N balances being depleted, demonstrating the importance of monitoring crop N offtake, and ensuring offtake is sufficiently replaced to maintain soil health and support future crop yields.
- **Grain N offtake:** the data indicated that 7% of YEN crops were over-applied with N fertiliser due to achieving a protein of ≥2 % more than the varietal norm and 2% of crops were under-applied. By measuring grain N levels in the harvested product it is possible to assess the success of crop N management and gain accurate N offtake figures to guide future applications.

A restricted maximum likelihood (REML statistical analysis was undertaken to understand which agronomic factors were associated with the NUE metrics analysed in the YEN database. The datasets for the oat, barley, beans, and pea crops were too small to analyse using REML; associations could only be determined for wheat and barley. This analysis identified similar associating factors to previous analyses which includes a significant influencing 'farm' factor, indicating that the farm the data originated from is having a large influence on NUE related metrics. A better understanding is required to identify what components make up the farm factor, but it is likely to include technology used on farm, farmer mindset, staff training, resources used to make nutrient management decisions etc.

The rate at which N fertiliser was applied associated differently with the different NUE metrics; to increase grain N offtake and N balance, N rate should be increased whereas, to increase kg grain yield/kg N available, NUtE, and grain N recovery, N rate should be reduced. Consequently, decisions on changing N rates to alter NUE should be based on what outcome is desired, e.g., improving crop quality or reducing environmental impact. Use of Plant Growth Regulators (PGRs) and fungicides associated positively with NUE metrics of wheat and barley crops, indicating that it is important to optimise crop management to improve NUE on farm, as N efficiency is increased when yields are increased under the same N application rate. Associations with rainfall and NUE indicated that good establishment and conditions conducive to successful grain fill improved NUE, likely due to the positive impacts on yield.

Based on the analysis undertaken in this report several strategies can be recommended to improve NUE on farm:

- Include more barley and oat crops in the rotation which have a higher NUtE compared to wheat crops
- Include more legumes such as beans and peas in the rotation which do not require N fertiliser and fix around 2-3 times more N than the other main arable crop types
- Monitor grain N offtake by measuring grain nutrient content to make an assessment on the success of the N management approach in a particular crop. Specifically for wheat, grain protein levels can be compared to varietal protein values in the Recommended List to determine whether N was over or underapplied
- Monitor grain and straw N offtake to ensure soil N balances are not being depleted and soil fertility compromised
- Enhancing crop yields using the same N rates will improve NUE. Crop yields can be improved through good crop management, such as use of PGRs and fungicides, and ensuring good establishment and optimal grain/seed fill conditions

One limitation of using the YEN dataset to better understand NUE on farm is the limited information available on the use of organic materials. The YEN database includes data on manure history within a particular field, the main type of manure used and whether manure was applied to the current crop, but completing this information was not mandatory so there are many entries with no data on organic materials. This is being addressed in newer networks such as YEN Zero, but the analysis reported here cannot conclude on the role of organic materials in NUE on UK farms. However, understanding how efficiently organic materials are being used on farm to ensure their value is being fully realised is very important.

Based on the findings of this study, further work was suggested to build a better understanding of NUE of the main UK arable crops and how it can be improved. Suggestions included sourcing 'farm level' data from the YEN entrants where the dataset used in this study originates, to better understand what is behind the 'farm factor' explaining the biggest proportion of the variation in the NUE metrics. Additionally, producing a dataset which collates on farm trials of Enhanced Efficiency Fertilisers (EEFs) to understand the benefit of these products on NUE. The recent Defra project NM0102 reviewed their potential effectiveness in improving NUE, however, information on their use is limited within the YEN database and the majority of on farm trials experimenting with these products are privately funded. Therefore, it would be beneficial to collate experimental data together to understand which products have the most potential to improve NUE on farm.

2 INTRODUCTION

Manufactured fertilisers and organic materials are sources of nutrient inputs to soils, but their production, processing and use causes pollution to the environment and climate change impacts. Fertiliser use is a cause of nutrient-related pollution but plays a key role in enhancing productivity. It is essential to manage nutrient use more effectively to meet government targets for Net Zero, and the 25 Year Environment Plan.

Since the end of summer 2021, global fertiliser prices have increased to unprecedented levels. This has been due to global gas price rises and increased volatility in many market prices and supply chains due to the war in Ukraine. This has reduced the availability of fertilisers for on-farm delivery, providing further incentive to use fertilisers and organic materials more effectively.

Nutrient use efficiency relates nutrient outputs (offtake or yield) to nutrient inputs and can act as an indicator of losses to the environment (Moll et al. 1982). This report specifically focusses on Nitrogen (N) Use Efficiency (NUE). There are many possible formulas for calculating NUE; one simple indicator at both national and farm level for the arable sector is the ratio between N offtake in harvested product(s)/and N inputs (Oenema et al. 2015). NUE will vary by crop and will be influenced by multiple factors including soil type, environmental conditions, and management practices.

Better understanding of NUE and how to optimise it will suggest opportunities to increase efficiency and reduce overall use of fertilisers, so as to address local or specific environmental problems or habitat vulnerabilities (e.g., NVZ limits or ammonia critical thresholds). The EU's Farm to Fork strategy sets out the aim of a 20% reduction in fertiliser use by 2030. We know that there is scope for some farmers to reduce fertiliser applications per hectare (depending on the type of crop) and still maintain productivity, evidenced by on farm data collected by ADAS indicating situations where field N application rates are high but yields are below average or where wheat grain protein is higher than the variety norm (see section 4.2.4). However, further evidence is required to understand where and how reductions can be targeted, what reductions are possible and management practices necessary to achieve these reductions.

ADAS' Yield Enhancement Networks (YENs) were launched in 2012 to support on-farm learning-by-sharing. Through their initial decade YENs have been primarily focused on how crop yields are formed, but YENs now also address issues such as nutritional efficiency (YEN Nutrition) and carbon intensity (YEN Zero). YENs let members share quantitative field-specific intelligence anonymously e.g., grain yield or soil health, so they can see how they stand compared to others within the networks. The combined dataset from all YENs contains >4,000 crop yields, with >650,000 points of explanatory data.

The YEN dataset offers a valuable opportunity to better understand questions around nutrient use efficiency, what is being achieved on farm, and the factors influencing it. Although the YEN dataset can provide important insights into on-farm crop productivity, growers who are part of the YEN networks generally produce above average yields compared to the rest of the country. For example, average wheat yield within the YEN database is 10 t/ha over the 2013-2021 period, compared to the average from all farms of 8 t/ha over the same period (Defra statistics).

2.1 Aims and objectives

The overall aim was to use the YEN database to better understand nitrogen use efficiency and the potential opportunities for reducing nitrogen inputs to agriculture.

The objectives were:

- To understand variation in NUE across the range of crop types covered by the database and understand the influencing factors.
- To understand the differences between farms in the top quartile for NUE and the rest, and to identify practical steps farms could take to improve performance and barriers to implementing these changes.
- To contribute to understanding the impact of reducing nitrogen inputs by e.g. ,10-30% (either overall inputs or replacing with organic material sources).
- To understand how organic materials are being used and how they can be used more effectively – details on which products and handling processes (e.g., slurry storage/separation/length of time prior to incorporation), and the impacts on nutrition and yield.
- Impacts of controlled release fertilisers, urease inhibitors and nitrification inhibitors on nutrient use efficiency, nutrition, yield, and nutrient use.

These aims and objectives will be satisfied within the following task deliverables defined within the project:

- Task 1: Define Nitrogen Use Efficiency (NUE) and its related metrics
- Task 2: NUE metrics calculated for all YEN crop data
- Task 3: Interim report
- Task 4: Report averages and the variation across the dataset for the NUE metrics and multiple nutritional related variates
- Task 5: Undertake REML statistical analysis to assess the influence of agronomic parameters on NUE
- Task 6: Proposal and scoping of further work
- Task 7: Presentation of the results and messages coming from the analysis
- Task 8: Delivery of the final report and summary slide deck

This report will specifically focus on Tasks 1, 2, 4, 5 and 6.

3 TASK 1 – DEFINING NUE & RELATED METRICS

Nitrogen Use Efficiency (NUE) is a widely used term and a component many growers and members of the agriculture industry are looking to improve, due to current economic and environmental pressures associated with the use of N fertiliser. However, NUE can be defined in a multitude of ways and consequently can mean different things to different people. Therefore, it is important to be clear what is meant by NUE in any given context and how it has been calculated. There are two broad ways in which the term NUE is used:

1. As an output of crop N per unit of N available (%)
2. As an output of crop dry matter (DM) per unit of N available (kg DM/kg N)

An important consideration in the use of these terms is whether N fertiliser is applied with the objective of raising yields, or for the return of N as protein in harvested products. As a first step to the YEN database analysis to investigate NUE, several NUE definitions and related metrics were defined to investigate within the analysis (Table 1).

Table 1. Defined NUE metrics investigated in the YEN database analysis

No.	NUE metric	Calculation	Units
1	kg grain yield/kg N available	kg grain yield / (soil N + N fertiliser)	kg/kg
2	kg grain yield/kg N fertiliser applied	kg grain yield / kg N fertiliser applied	kg/kg
3	Grain N offtake	DM yield x grain N%	kg N/ha
4	Total crop N uptake	Grain N offtake + straw N (DM straw x straw N%)	kg N/ha
5	N harvest index (NHI)	Grain N offtake / Total crop N uptake	%
6	N uptake efficiency (NUpE)	Total Crop N Uptake / (soil N + N fertiliser)	%
7	N utilisation efficiency (grain; NUtE)	Grain yield (kg/ha) / Total crop N uptake	kg DM/kg N
8	N removed in harvested grain	Grain N offtake / (soil N + N fertiliser)	%
9	Apparent N fertiliser recovery	(Total crop N uptake – soil N) / N fertiliser applied	%
10	Simple fertiliser recovery	Total Crop N uptake / N fertiliser applied	%
11	N balance for Grain N offtake	N fertiliser applied – Grain N offtake	kg N/ha
11a	N balance for Crop N offtake	N fertiliser applied - Crop N offtake	kg N/ha

The most useful NUE metric to use, which best reflects efficiency of crop N fertiliser use, depends on the question being asked. Generally, it is desirable to get as much of any fertiliser N applied into the crop, the fertiliser N recovery. However, this is a difficult component to quantify due to the uncertainties in how much N is provided by the soil (this is best quantified by measuring crop N uptake when no N fertiliser has been applied), and the variability in grain nitrogen content and NHI. NUE metrics which can be used to indicate efficiency in different contexts include:

1. To indicate efficiency of crop N use to produce yield:
   kg grain yield/kg N available (kg/kg)
2. To indicate efficiency of fertiliser to improve crop quality (protein content):
   N removed in harvested grain (%)
3. To indicate potential risk of losing applied N to the surrounding environment:
   N balance for crop N offtake (kg N/ha), which calculates the net amount of applied N fertiliser left in the field after harvest

4 TASKS 2 AND 4 – AVERAGE & VARIATION OF NUE METRICS

Tasks 2 and 4 were combined due to the fact they both involve the calculation of the defined NUE metrics for all crop YEN data. This section details the methods and results of this analysis.

4.1 Methods

4.1.1 The YEN database

The YEN database includes 4,609 crop entries between the harvest years 2013 to 2021 which were entered into YEN crop competitions, these include:

- Cereal YEN
- Oilseed YEN
- Bean YEN
- Pea YEN
- Grain Nutrient Benchmarking
- YEN Nutrition
- YEN Zero

The data associated with each entry varies depending on how much information was provided by the grower or advisor and which YEN competition the entry was submitted into. Each field and its associated farm which is entered into the YEN has a unique ID which allows the identification of fields and farms that have entered multiple competitions over multiple years. This is particularly valuable in the analysis of the dataset to understand how much 'field' or 'farm' influences different elements of crop productivity.

The YEN dataset contains a large range of field and crop related parameters that are associated with each YEN entry. These parameters include yield, crop type, variety, field location, field history (previous crop, use of cover crops, use of manures, residue management), cultivation regime, soil characteristics (texture, depth, organic matter content, nutrient indices), seed rate, nutritional and ag-chemical inputs, growth stage dates, weather; in addition to a large number of 'measured' components from submitted crop and grain samples (crop biomass, number of ears/pods, harvest index, grain size and number, nutrient content of crop and harvested grain).

Since the YEN has expanded over its 10-year lifetime, the data points are weighted to more recent harvest years. Figure 1 indicates how many crop yields are in the YEN database from each harvest year.

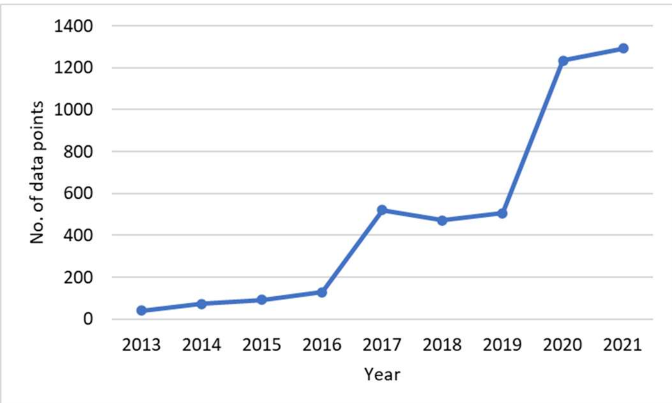

Figure 1. Graph showing the number of crop yield data points in the YEN database across harvest years.

4.1.2 Calculating NUE metrics

The NUE metrics defined in Table 1 were calculated for all the crop entries within the YEN database. Duplicates were first filtered out of the dataset which included entries submitted from the same field in the same harvest year. Entries with no associated yield information were also filtered out of the dataset because a large proportion of the NUE metrics require yield data to be calculated. This led to a total of 4,363 crop entries that were included in the analysis of the NUE metrics.

As an initial step in calculating the NUE metrics, the amount of N available in the soil was determined. Soil N is not measured within the YENs and therefore this parameter had to be assumed using the RB209 Field Assessment Method. This method uses information of the previous crop, the annual rainfall where the field is located, and the RB209 soil category. The RB209 soil category was determined using information of soil texture, depth, and parent rock material. The Field Assessment Method gives an SNS index, consequently, the soil N in kg N/ha was assumed to be within the mid-range of each of these defined indices (Table 2).

This assumption does not consider any N supplied from organic materials, and the YEN dataset does not include detailed information of the quantity and type of any potential use of organic materials. Consequently, for the relevant NUE metrics, the calculations were undertaken in a filtered dataset where it was known that no manures were applied, in addition to the whole dataset, to compare if the NUE metric was influenced by manure use.

Table 2. The assumed soil N content (kg N/ha) of each YEN entry, based on the defined SNS Index from the RB209 Field Assessment Method.

SNS Index	Soil N kg/ha
0	50
1	70
2	90
3	110
4	140
5	200

To increase the size of the dataset where either grain N% or NHI data was missing, species crop specific averages across the whole YEN dataset were calculated for these parameters. For the related NUE metrics the calculation was undertaken for the raw dataset and for the raw dataset in addition to assumed grain N% or NHI values where the data was missing. A comparison between the resulting NUE metrics was made to understand if the assumed values were influencing the outcome. The NUE metrics for which this occurred included:

- 3: Grain N offtake, where grain N% was assumed
- 4: Total crop N uptake, where NHI was assumed
- 6: NUpE, where NHI was assumed
- 9: Apparent N fertiliser recovery, where NHI was assumed
- 11: N balance for Grain N offtake, where grain N% was assumed
- 11a: N balance for Crop N offtake, where NHI was assumed

The crop species within the YEN dataset were grouped to calculate the NUE metrics, the crop types were grouped into the following categories:

- Winter wheat
- Barley (spring and winter)

- Oats (spring and winter crops)
- Oilseed rape (OSR)
- Beans (spring and winter)
- Peas (spring and winter)

The data within the 95th percentile was used to calculate the NUE metrics to remove any anomalies within the dataset. Boxplots were used to analyse the averages and range in the data across the crop types and metrics calculated. These box plots specifically detailed the minimum and maximum, the median, and the upper and lower quartiles for each metric and related parameters. Several related parameters were calculated in addition to the NUE metrics which included yield (t/ha), fertiliser N applied (kg N/ha), N available (kg N/ha) and grain N%.

Specifically for wheat crops the grain protein achieved for each entry was compared to the grain protein defined in the Recommended List (RL; AHDB Recommended List) for the specific variety grown, to determine if N fertiliser was over or under supplied depending on if the wheat entry achieved a higher or lower grain protein compared to the corresponding varietal RL figure. Manure use within the YEN database was also summarised in the form of simple graphs due to this data not being numeric.

4.2 Results

4.2.1 Manure use in the YEN dataset

Manure use for crop entries is not fully quantified in the YEN dataset in terms of the amount of N input, but a number of questions are asked of YEN entrants to understand the amount of manure applied within seasons and across rotations. This data was summarised for the crop types of winter wheat, barley, and OSR. The oat dataset was not included due to the limited size, and organic materials are not commonly used for bean and pea crops.

Figure 2 shows the proportion of YEN crops that had manure inputs. Although a large proportion of the dataset did not indicate whether manures were used or not (indicated by ‘unknown’), which ranged between 39-50% of the dataset for the different crop types, a significant proportion of the dataset did use manure inputs within their YEN crop entries. Manures were used on 39, 41 and 44% of barley, wheat, and OSR crops respectively. There was no clear pattern of manure use over time, the data was more influenced by the increasing number of entries over time and YEN competitions such as YEN Nutrition being added to the networks of YENs.

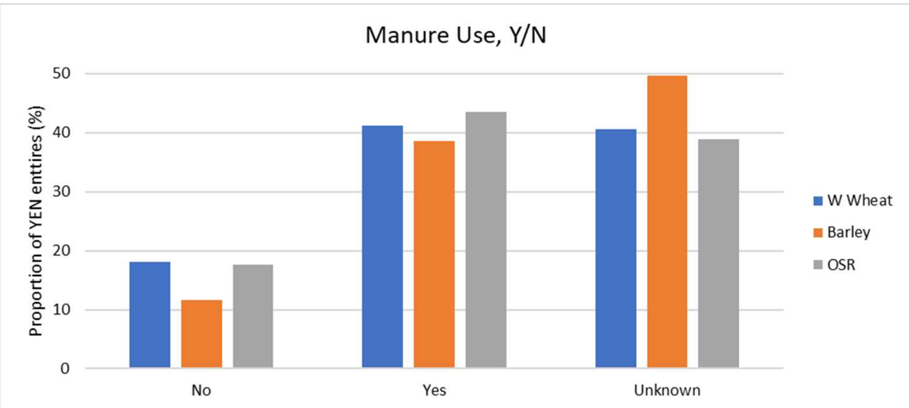

Figure 2. Graph showing the proportion of YEN entries for winter wheat, barley and OSR crops that indicated whether manure was used within the harvest year of the crop. Number of field entries within the dataset were 2,733; 660; and 425 for winter wheat, barley and OSR crops respectively.

Most entries using manures were using them 1 in every 5 years, with 9-13% of YEN entries across the crop types manuring 1 in 2 years, 14-15% manuring 1 in every 3-5 years and 7-16% manuring less than 1 in every 5 years. Only 2% of the YEN entries were manuring every year and 14-22% of entries are not using manures in the rotation (Figure 3).

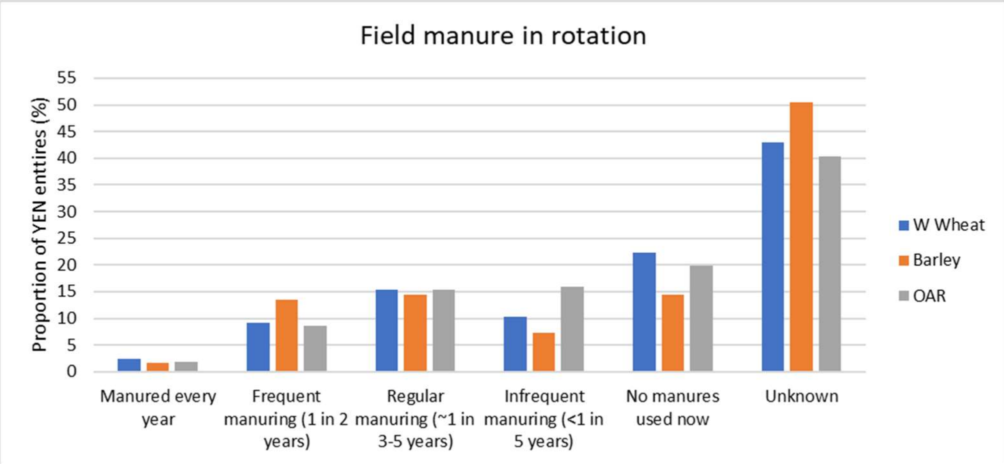

Figure 3. Graph showing the proportion of YEN entries for winter wheat, barley and OSR crops within defined categories indicating the frequency of manure use within the rotation. Number of field entries within the dataset were 2,671; 649; and 417 for winter wheat, barley and OSR crops respectively.

Figure 4 shows the main manure types being used by YEN entrants. These manure type categories were simplified by grouping all FYM materials (this included cattle, duck, horse, pig, sheep, and turkey) into one category and all slurry materials into one category (this included cattle and pig slurry). YEN entrants using manures predominantly used FYM, 13-16% of entries across the crop types, with between 3 and 12% of entrants across the crop types also using biosolids and broiler litter. There were no significant differences in manure use trends between the crop types of wheat, barley and OSR.

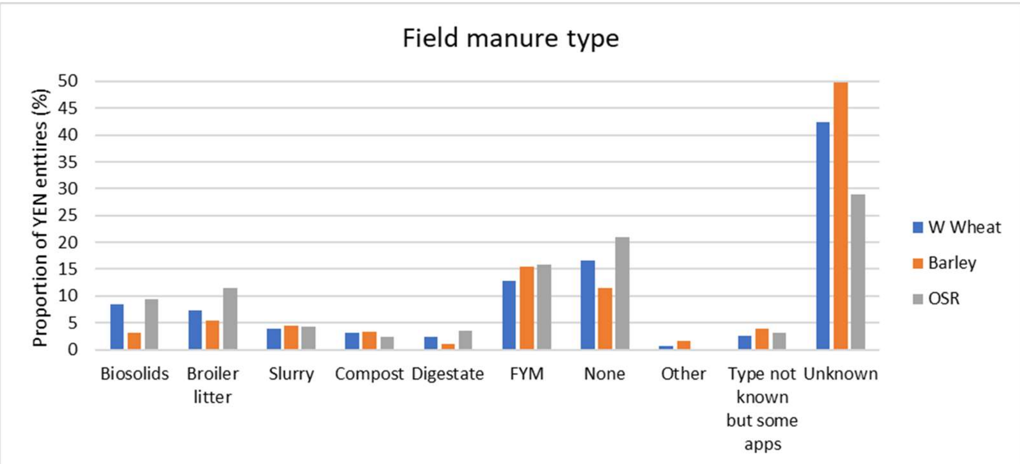

Figure 4. Graph showing the proportion of YEN entries for winter wheat, barley and OSR crops using different manure types within the rotation. Number of field entries within the dataset were 2,733; 660; and 425 for winter wheat, barley and OSR crops respectively.

4.2.2 Comparison of NUE metrics with and without manure use

Related NUE metrics were calculated for a filtered dataset where YEN entrants had indicated no manure inputs were used in the crop management, to understand whether manure use was influencing the calculated NUE metrics. This was undertaken for winter wheat, barley and OSR crop types. The oats dataset was not large enough to separate out entries that had indicated no manure use, and pea and bean crops were not included due to lack of manure use in these crops.

The box plot comparisons are presented in Appendix Tables 1 to 3, generally the calculated NUE metrics did not change significantly when the data was filtered for no manure use. Specifically, for wheat crops the median and range of data were similar between the NUE metrics (Table 3 and Appendix Table 1) and on average around 30% of the wheat dataset included crops where no manure use was indicated.

The NUE metrics calculated for barley crops also did not appear to be influenced by manure use with most metrics having similar median and upper and lower quartile values (

Appendix Table 2). However, the range in the data did differ for the amount of N fertiliser applied (Table 3) and N available, with higher minimum values where no manure use was indicated (60 and 130 kg N/ha for N fertiliser applied and N available respectively), compared to the full dataset (0 and 50 kg N/ha for N fertiliser applied and N available respectively). This is due to lower N fertiliser rates in crops where manure was used and is also seen in the British Survey of Fertiliser Practice which shows around 20 kg N/ha less N applied where manure is used. The median value for grain N recovery was lower for barley crops where no manure use was indicated, 53 and 47% for the full dataset and no manure used dataset respectively, which may be a consequence of having lower N available. On average the proportion of the barley dataset where no manure use was indicated was 18%.

For OSR crops the calculated NUE metrics where no manure use was indicated were very similar in terms of the median and range of the datasets (

Appendix Table 3). However, like barley crops, where no manure use was indicated, the dataset had a higher minimum value for N fertiliser applied and N available (180 and 250 kg N/ha for N fertiliser applied and N available respectively), compared to the full dataset (40 and 70 kg N/ha for N fertiliser applied and N available respectively). On average 28% of the OSR dataset indicated no manure was used.

When comparing the dataset where no manure use was indicated to the full dataset, for the key NUE metric of kg yield/kg N available for the three crop types, the similarities can be seen (Table 3). The median values are only around 1 kg/kg lower where no manure was used.

Table 3. Table showing median values and range in the dataset when filtered for YEN entrants who indicated no manure was used, compared to the full dataset, for the NUE metrics N fertiliser applied (kg N/ha) and kg grain/kg N available (kg/kg).

Crop type	Quartile	N fertiliser applied (kg N/ha)		kg grain/N available (kg/kg)	
		Full dataset	No manure used	Full dataset	No manure used
Wheat	Min	0	0	17.5	18.4
	Median	225	230	34.2	33.1
	Max	312	350	45.5	45.2
Barley	Min	0	60	12.3	23.4

	Median	133	133	34.2	33.0
	Max	220	225	53.7	48.5
OSR	Min	40	180	6.5	8.1
	Median	220	225	15.2	14.7
	Max	339	308	23.1	21.6

4.2.3 Calculated NUE metrics

The box plots summarising the average and variation of the calculated NUE metrics and related parameters for the YEN dataset are presented in Appendices Tables 10 to 19, this section summarises this analysis and compares NUE between the different crop categories. The NUE metrics presented include where grain N% and NHI were assumed where the data was missing, to increase the size of the dataset. These metrics were preferred over the metrics calculated using the raw dataset, except where the differences were too large. The comparison of calculated metrics using the raw dataset vs. the assumed grain N% and NHI values are reported in Appendices Tables 4 to 9. N balance is not reported for pea and bean crops due to not being able to take account of N fixed by the crops.

Yield and N available

Generally, yields of crops entered into the YEN networks are higher than the national average. Figure 5 shows the median yields across the crop categories with wheat yields averaging 10 t/ha, OSR 4.4 t/ha, and beans and peas averaging 4.5 and 4 t/ha respectively. Yields of barley and oat crops include both winter and spring crops and the median values for the YEN dataset were 7.1 and 6.6 for barley and oat crops respectively. The range in these crop yields is large within the YEN database (indicated by the error bars in Figure 5) with minimum yields across the crop types being around 1 t/ha. Maximum yields are also high with the highest wheat yield achieved, within the 95th percentile of the dataset, being 13.3 t/ha and the highest OSR yield being 5.9 t/ha.

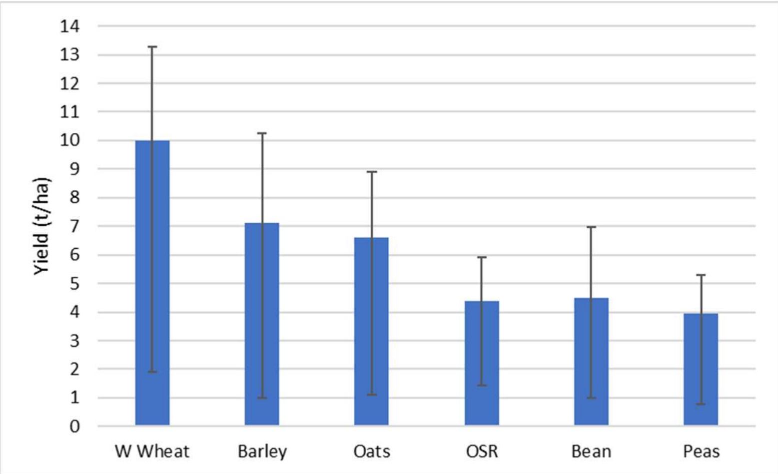

Figure 5. Graph showing median yields (t/ha; standard moisture content) for the different crop categories within the YEN database. Error bars are the minimum and maximum of the dataset.

The median N rate applied to YEN crops was very similar for wheat and OSR crops, with a total N rate of 225 and 220 kg N/ha respectively (Figure 6). This is greater than the average N rate applied to UK crops which averages 184 and 179 kg N/ha for wheat and OSR respectively (British Survey of Fertiliser Practise). The maximum N rate applied to these crops were high at 312 and 339 kg N/ha for wheat and OSR respectively. The amount of N applied to barley and oat crops is around 100 kg N/ha lower compared to wheat crops. Nationally the average N rate applied to spring barley is 100 kg N/ha and for winter barley is 144 kg N/ha (British Survey of Fertiliser Practise). The minimum N rates applied to the cereal crops were nil N, likely due to nutrition being supplied using organic materials. A very similar pattern between crop types was seen for N available (Figure 7) due to the fact this is the amount of fertiliser N applied and an assumed soil N supply based on the RB209 Field Assessment Method.

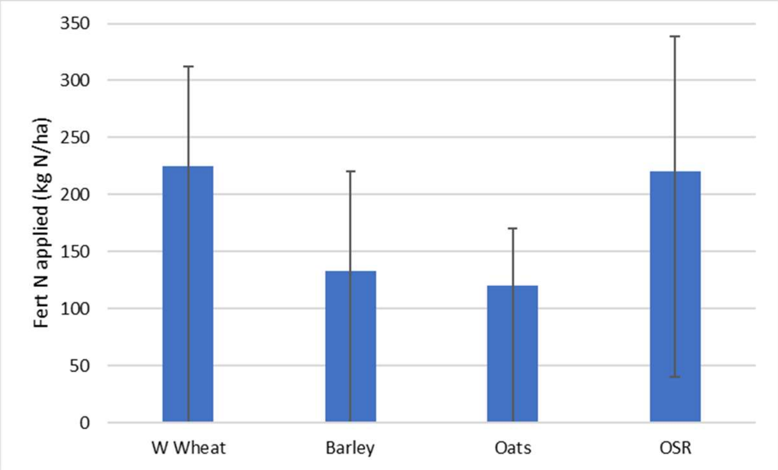

Figure 6. Graph showing median N fertiliser applied (kg N/ha) for the different crop categories within the YEN database. Error bars are the minimum and maximum of the dataset.

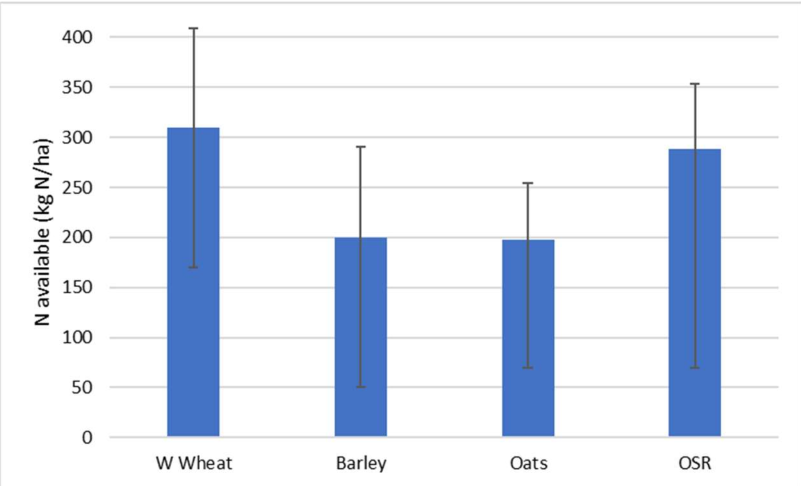

Figure 7. Graph showing median amount of N available (kg N/ha), soil N supply and N fertiliser applied combined, for the different crop categories within the YEN database. Error bars are the minimum and maximum of the dataset.

Crop N uptake and yield achieved from N available

Figure 8 shows NUE of the different crop categories in terms of the amount of yield achieved for each unit of N available. As expected, NUE of beans and peas is high with medians of 68 and 57 kg grain produced for each kg N available, with maximum values of 102 and 76 kg grain respectively. This is due to these legume crops fixing N themselves rather than being fully reliant on N available in the soil and provided in organic materials and inorganic fertiliser. Median values of NUE across the cereal crops were very similar, ranging between 33 and 34 kg yield/kg N available. NUE of OSR crops was the lowest of the crop categories, with a median NUE half that of the cereal crops at 15 kg grain/kg N available.

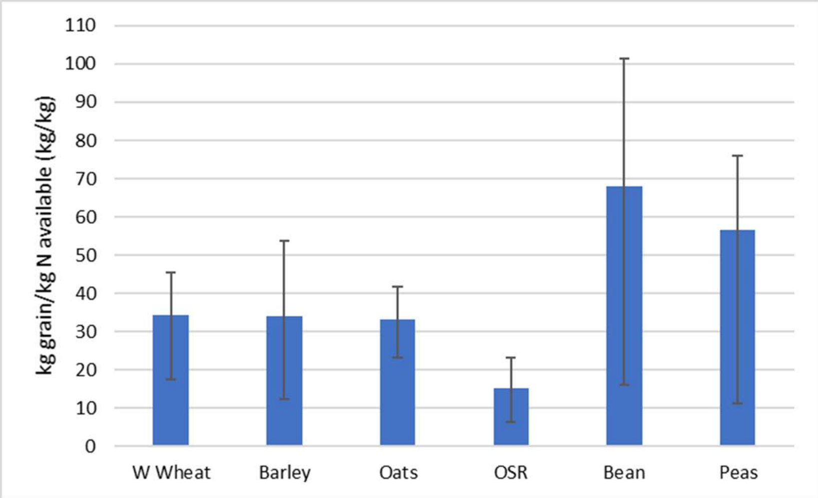

Figure 8. Graph showing median values for NUE metric kg grain/kg N available (kg/kg) for the different crop categories within the YEN database. Error bars are the minimum and maximum of the dataset.

The NUE increases slightly when calculated based on yield produced for each unit of N applied, with winter wheat having a lower NUE of 43 kg grain/kg N applied compared to barley and oats which had medians of 52 and 53 kg grain/kg N applied respectively (Figure 9). This higher NUE in barley and oat crops is due to the lower N rate applied to these crops. This is commonly seen in NUE studies where lower rates of N are used more efficiently than higher rates due to initial N applications having a greater impact on yield than the last few kg of N (demonstrated by the N response curve which shows a law of diminishing returns with increasing rates of N). NUE for OSR crops was low with a median of 20 kg grain/kg N applied, a factor of a high average N fertiliser rate with lower yields than the cereal crops.

The range in NUE within the crop types is large, specifically within the cereal crop types, with minimum values below 10 kg/kg and maximum values between 65 and 88 kg/kg with the wheat, barley, and oat crop types (Figure 9). These minimum values are likely to be for crops where high rates of N were applied, and final yields were poor. Whereas the high NUE figures are where crop yields were high and N rates were low, likely to be at sites with high soil residual N and/or where optimum N applications have taken place to ensure high crop fertiliser recovery.

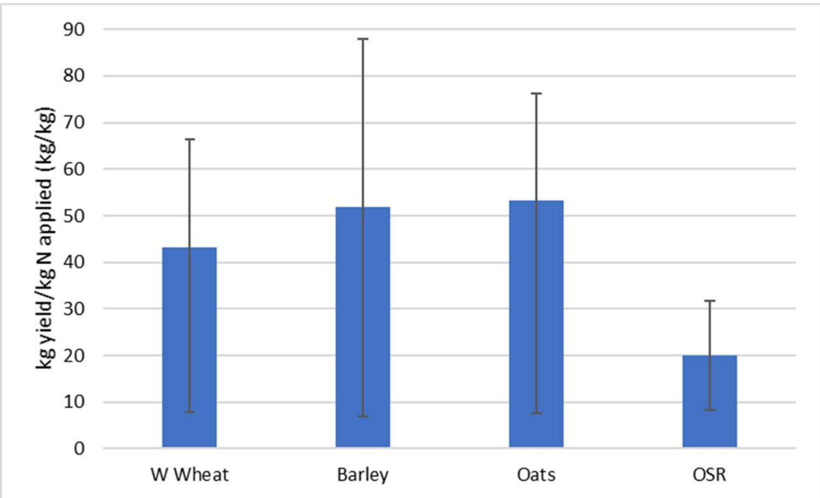

Figure 9. Graph showing median values for NUE metric kg grain/kg N applied (kg/kg) for the different crop categories within the YEN database. Error bars are the minimum and maximum of the dataset.

On average the pea and bean crops in the YEN dataset have twice as high grain N% compared to the cereal crops (Figure 10). Pea and bean grain N% medians were 4.0 and 4.5% respectively. Grain N% for the cereal crops were similar with 2.0, 1.8 and 1.9% for wheat, barley and oat crops respectively, OSR grain N% is higher than cereal crops with a median of 3.2%, this partly explains the higher N demand of this crop compared with cereals.

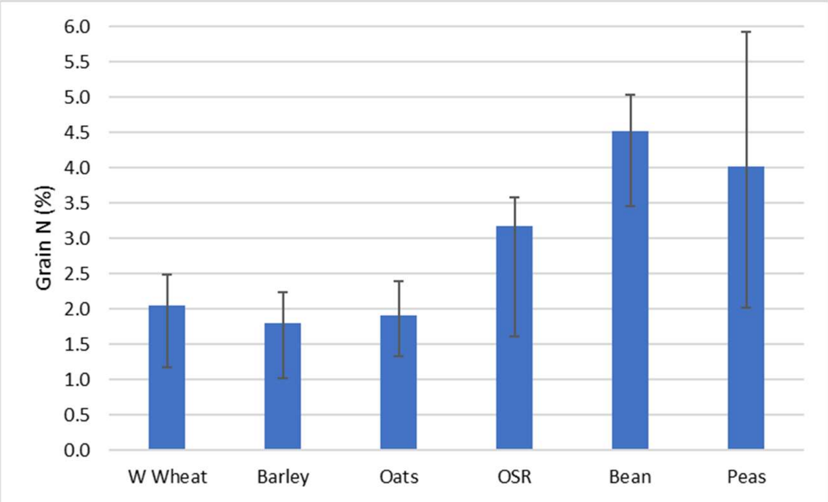

Figure 10. Graph showing median values for Grain N (%) for the different crop categories within the YEN database. Error bars are the minimum and maximum of the dataset.

Grain N offtake is determined by yield and grain N%, the median and range in the YEN dataset for this NUE metric is presented in Figure 11. Wheat and bean crops had similar median grain N offtakes of 172 and 175 kg N/ha respectively. However, the N being taken off the field in wheat crops is a combination of soil and applied N, whereas bean (and pea) crops are also taking off N which the crop has biologically fixed. The maximum grain N offtakes for these two crop types are 236 and 270 kg N/ha for wheat and beans respectively, indicating the large N offtake possible in these crops.

Offtake in pea crops is on average 38 kg N/ha lower than bean crops due to the higher grain N% and slightly higher median yield in bean crops. Grain N offtake is higher in OSR crops compared to oats and barley, despite the higher yields in these cereal crops. Median offtake is 128 kg N/ha for OSR crops and 106 and 107 kg N/ha for barley and oat crops respectively, likely driven by the higher grain N% of OSR crops.

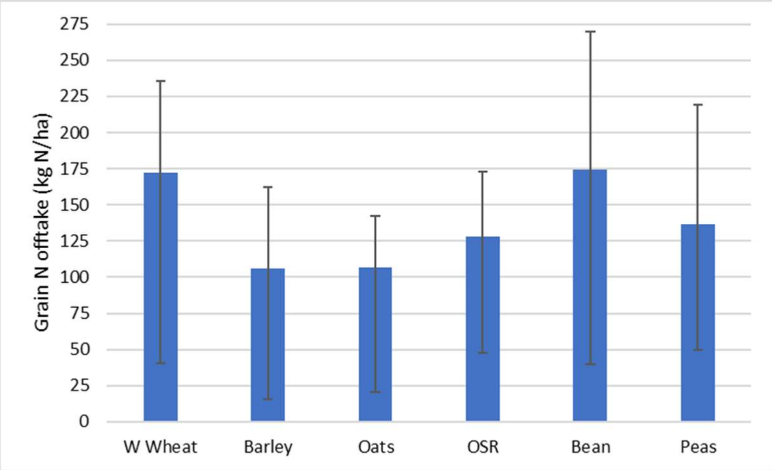

Figure 11. Graph showing median values for Grain N offtake (kg N/ha) for the different crop categories within the YEN database. Error bars are the minimum and maximum of the dataset.

Crop N uptake follows a very similar pattern to grain N offtake when comparing the different crop types (Figure 12). Total crop N uptake for wheat is greater than beans (256 and 235 kg N/ha for wheat and bean crops respectively), despite a similar grain N offtake. This is due to a higher NHI in beans compared to wheat, of 85% and 74% for bean and wheat crops respectively (Figure 13), indicating that bean crops are translocating more of the N taken up by the crop into the grain. Crop N uptake is greater in OSR crops compared to peas (216 and 157 kg N/ha for OSR and pea crops respectively), again indicating the high N demand of this crop despite its lower yield. NHI of OSR crops is the lowest of the crop categories with a median of 63%, indicating the lower efficiency of translocating N taken up by the crop into the grain.

Total crop N uptake was similar for pea, barley, and oat crops, ranging between 140 to 157 kg N/ha. Pea crops had a greater NHI of 80% compared to 75 and 74% for barley and oat crops respectively, driving the greater grain N offtake in pea crops.

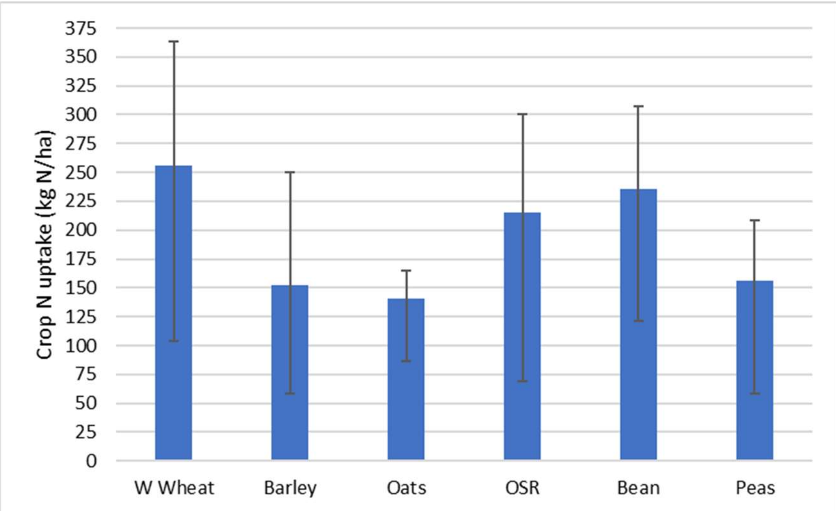

Figure 12. Graph showing median values for Crop N offtake (kg N/ha) for the different crop categories within the YEN database. Error bars are the minimum and maximum of the dataset.

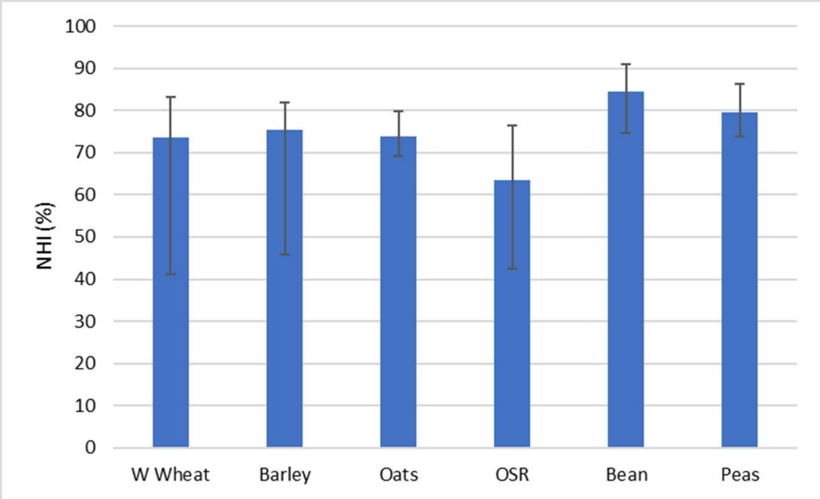

Figure 13. Graph showing median values for Nitrogen Harvest Index (NHI; %) for the different crop categories within the YEN database. Error bars are the minimum and maximum of the dataset.

N uptake and utilisation efficiency

N uptake efficiency (NUpE) defines the proportion of N taken up by the crop compared to how much N is available from the soil and N fertiliser applied. Figure 14 shows the median, minimum, and maximum values for the different crop categories in the YEN dataset for NUpE. This demonstrates the ability of bean and pea crops to fix their own N as the median NUpE of these crops are 325 and 224% for bean and pea crops respectively, indicating that these crops fix around two to three times more N than available in the soil. Additionally, the maximum NUpE's for these crops were 448 and 298% for bean and pea crops respectively.

NUpE of the other crop types are similar, with median figures being within ~10% range. NUpE was greatest in wheat crops with a median of 80% whereas NUpE medians ranged between 68 to 72% for barley, oat and OSR crops respectively.

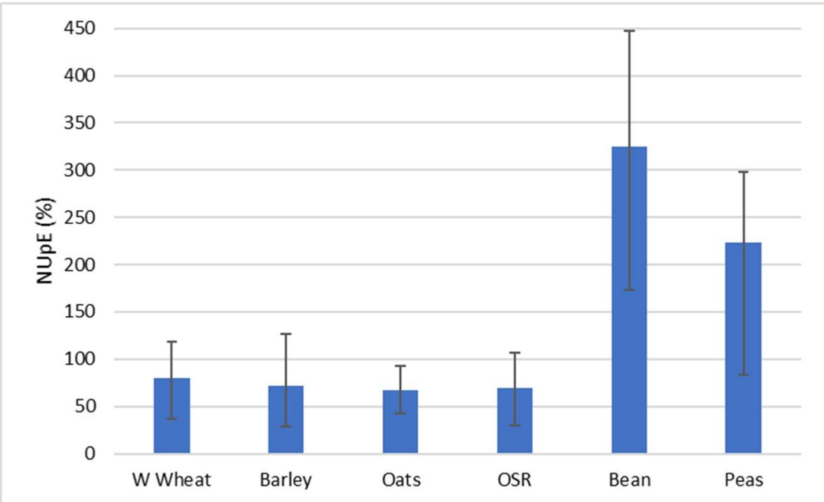

Figure 14. Graph showing median values for Nitrogen Uptake Efficiency (NUpE; %) for the different crop categories within the YEN database. Error bars are the minimum and maximum of the dataset.

N utilisation efficiency (NUtE) indicates the efficiency at which crops convert N taken up into yield (kg DM yield/kg N crop uptake). Figure 15 indicates the greater NUtE of barley and oat crops compared to other crop types. These crops produced 41 and 45 kg of DM yield for each kg of N taken up for barley and oat crops respectively, reaching a maximum of 55 and 53 kg DM/kg N respectively. The NUtE of wheat crops was slightly lower with a median of 36 kg DM/kg N likely driven by the higher total crop N uptake in wheat crops compared to barley and oats.

NUtE was similar between OSR, bean and pea crops, ranging between 19 and 21 kg DM/kg N. This is likely to be driven by the high N demand of the seed of these crops.

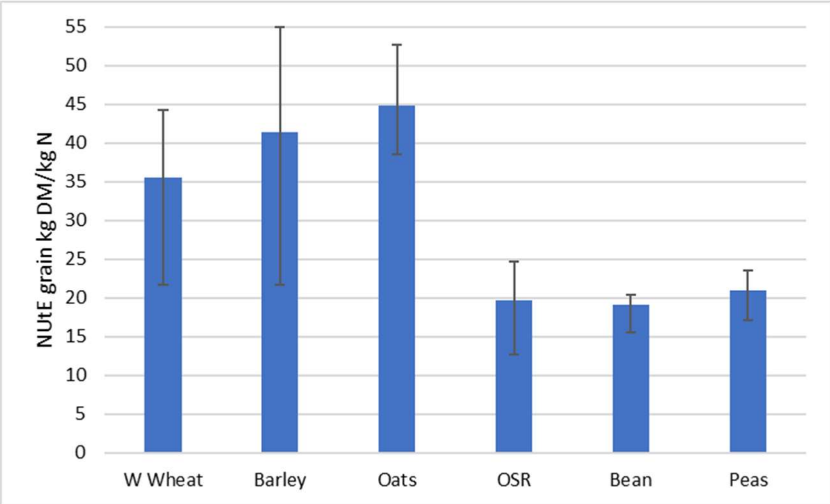

Figure 15. Graph showing median values for Nitrogen Utilisation Efficiency (NUtE; kg DM/kg N) for the different crop categories within the YEN database. Error bars are the minimum and maximum of the dataset.

N recovery

Grain N recovery, or N removed in the harvested crop, indicates the proportion of N taken off by the grain compared to the amount of N available in the soil and from N fertiliser applied. This is similar to NUpE but only considers grain offtake rather than whole crop N uptake. Consequently, differences between crop types are similar (Figure 16) with a high grain N recovery in bean and pea crops of 271 and 207% respectively. Grain N recovery was similar between the other crop types, ranging between 47 in OSR crops to 59% in wheat crops. These similarities across crop types indicate that the N available is being managed to support yield and grain N% to a similar proportion across crop types.

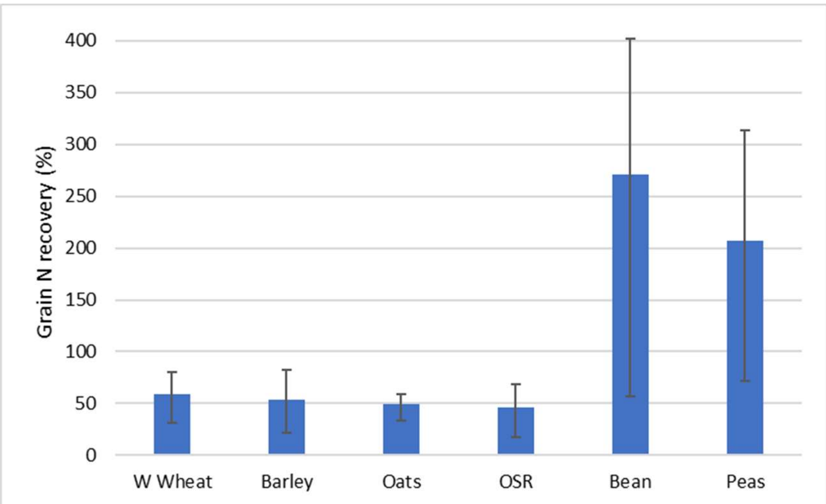

Figure 16. Graph showing median values for Grain N recovery (%) for the different crop categories within the YEN database. Error bars are the minimum and maximum of the dataset.

Apparent N fertiliser recovery assumes the crop captures all the available soil N supply and the remaining crop N uptake is supplied by the N fertiliser applied. These figures should be treated with caution due to the assumed soil N supply using the RB209 Field Assessment Method. Pea and bean crops are not considered in this NUE metric as no N fertiliser was applied. Apparent fertiliser recovery ranged between 44 to 73% (Figure 17), averaging 59% across the crop types, a figure very close to the RB209 suggested N fertiliser recovery of 60%. The range in apparent fertiliser recoveries was large across YEN crop entries, with just 3% being achieved in a barley crop to up to 125% being achieved in a wheat crop, indicating sufficient room to improve fertiliser recovery across these main arable crops where the proportion is around 60%.

Oat crops had the lowest apparent N fertiliser recovery with 44%, this may be a factor of an overestimated soil N supply or more N fertiliser applied than the crop required. It should also be recognised that this crop has the fewest field entries which reduces confidence about the conclusions that can be drawn for this crop.

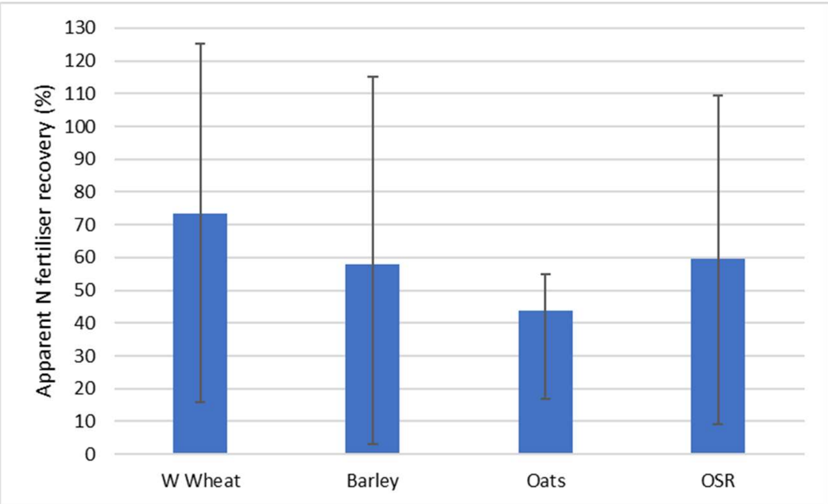

Figure 17. Graph showing median values for Apparent N fertiliser recovery (%) for the different crop categories within the YEN database. Error bars are the minimum and maximum of the dataset.

Simple N fertiliser recovery is a cruder method to estimate N fertiliser uptake by crops as it does not consider the N supplied by the soil. Consequently, median figures across the YEN crop categories ranged between 94% in oat crops to 106% in wheat and barley crops (Figure 18).

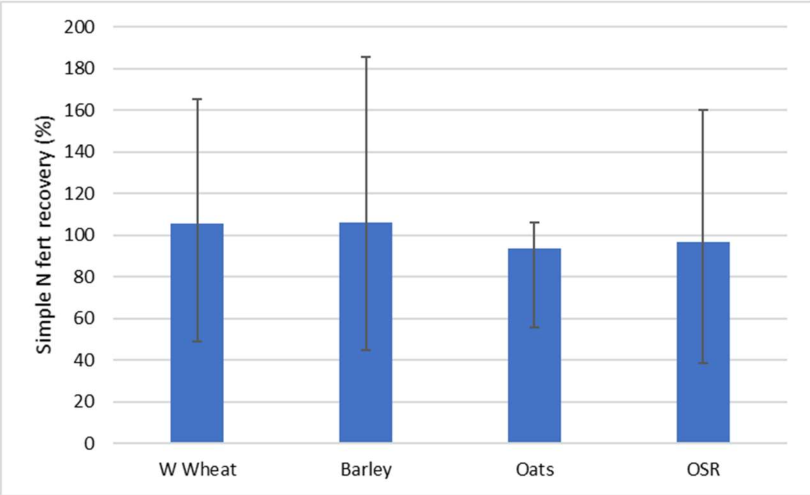

Figure 18. Graph showing median values for Simple N fertiliser recovery (%) for the different crop categories within the YEN database. Error bars are the minimum and maximum of the dataset.

N balance

N balance for grain and crop offtake calculates how much N is left in the field after the crop has been harvested. This is an important NUE metric to be aware of as it indicates if there is too much N left in the field which will be at risk to leaching into the surrounding environment (Lord et al., 2006), or whether soil N supplies are being reduced, causing the reduction in soil fertility (Oliveira et al., 2022). N is an important food source for soil microbes which are crucial in decomposing crop residues and soil organic matter to cycle the nutrients. Consequently, the N balance should be a positive figure to ensure soil fertility is maintained.

There was a large range in N balance across YEN crop entries demonstrating the large differences in yield, grain N% and N fertiliser applied. Minimum N balances were as low as -199 kg N/ha for barley crops where straw is removed and as high as +161 kg N/ha for OSR crops where just grain is taken off (Figure 19 and Figure 20). N balance was greater in OSR crops with a median of 86 kg N/ha for grain N offtake, this is due to the high residual N in the crop biomass left in the field after harvest. Median N balance for grain N offtake in wheat crops was 51 kg N/ha but had a median value of 3 kg N/ha if the straw is removed.

N balance is lower in barley and oat crops, with a median of 25 and 30 kg N/ha for barley and oat crops respectively for grain N offtake. This is likely due to the higher crop N uptake in these crops and the lower N rate applied. If straw is removed the N balance reduces to -5 and +19 kg N/ha for barley and oat crops respectively.

N balances when straw is baled could be as much as 150 kg N/ha for wheat, barley and OSR, indicating the potential to reduce soil N residues in some situations.

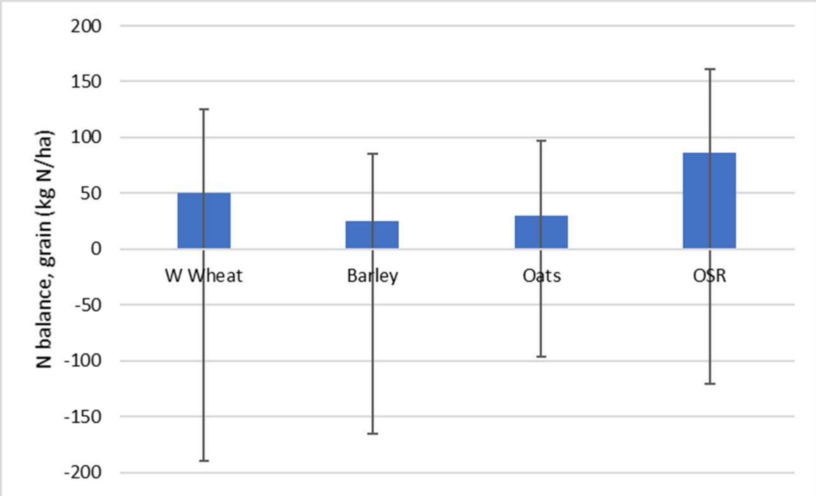

Figure 19. Graph showing median values for N balance for Grain N offtake (kg N/ha) for the different crop categories within the YEN database. Error bars are the minimum and maximum of the dataset.

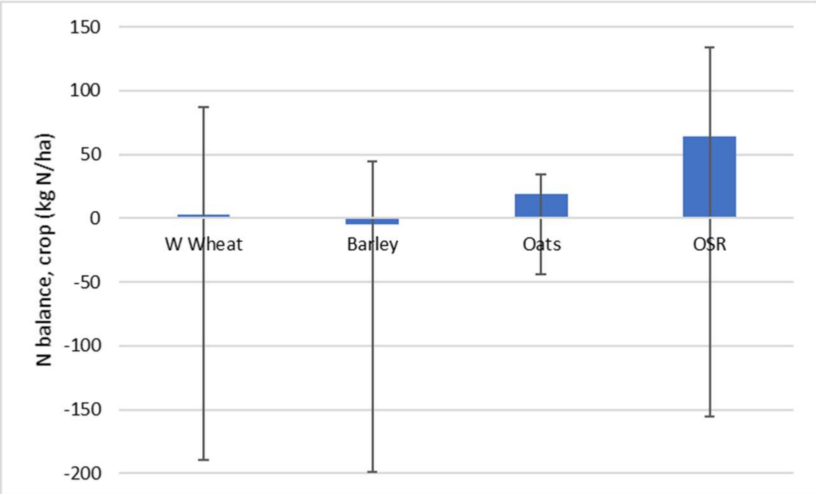

Figure 20. Graph showing median values for N balance for Crop N offtake (kg N/ha) for the different crop categories within the YEN database. Error bars are the minimum and maximum of the dataset.

4.2.4 Wheat protein achieved vs. RL protein

Grain protein of winter wheat YEN crops were compared to the protein value listed in the AHDB Recommended List (RL) for the specific variety that was grown. As grain protein is a heritable trait in wheat, the protein achieved can indicate whether N was under or over supplied when compared to the corresponding varietal protein value given in the RL. These comparisons were made for winter wheat feed crops. Milling wheat varieties were not used because they were likely to have had additional N applied to help them achieve enhanced grain protein required for milling.

This included a comparison of 835 YEN crops and indicated that 7% of these crops achieved a grain protein more than 2 percentage points greater than the variety norm in the RL and 2% achieved a grain protein of 2 percentage points or lower compared to the variety norm (Figure 21). Consequently, this indicates that 7% of the YEN winter wheat feed crops are likely to be over applying N fertiliser and 2% may have been under-applying. As a rule of thumb, grain protein that is 1 percentage point greater than the norm indicates that the N applied was about 50 kg N/ha greater than the economic optimum.

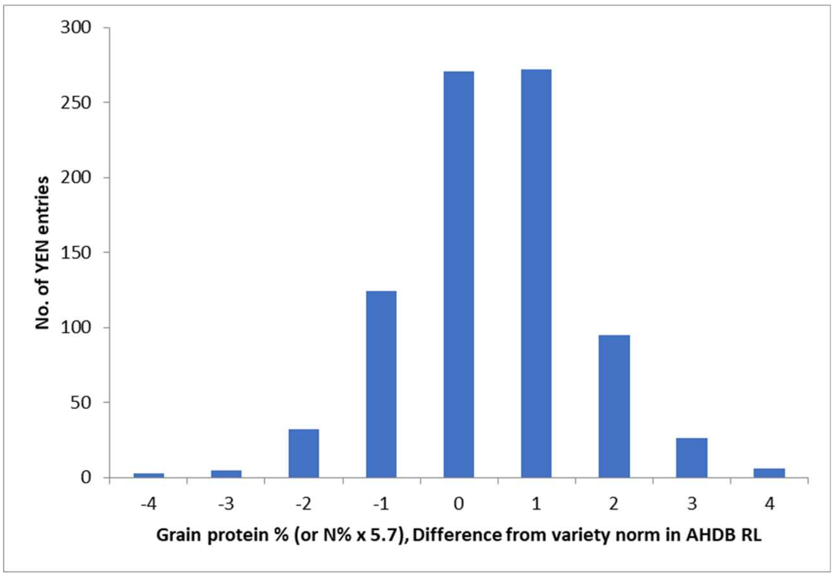

Figure 21. Histogram showing the difference in grain protein of winter wheat feed crops compared to the variety norm listed in the AHDB RL.

4.3 Task 2 and 4 Summary

The key findings from calculating the range of defined NUE metrics and related parameters include:

- A significant proportion of YEN crops (specifically wheat, barley and OSR crops) used manures in their crop nutrition, ranging between 39 to 44%.
    - Commonly used manure types included FYM, biosolids, and broiler litter.
- Manure use did not appear to influence the median values of the calculated NUE metrics. However, lower minimum N fertiliser applied and N available values (soil N + fertiliser N) were seen in the barley and OSR datasets without manure use, due to higher N rates applied where manure was not used.
- N rates applied for wheat and OSR crops were highest, at 225 and 220 kg N/ha respectively.
    - Median N rates applied for barley and oat crops was around 100 kg N/ha lower compared to wheat and OSR crops.
- NUE of cereal crops in terms of kg grain/kg N available were very similar, ranging between 33 to 34 kg yield/kg N available. NUE of OSR was less than half that of cereal crops with a median of 15 kg grain/kg N available.
- Grain N% was twice as high in bean and pea crops compared to cereal crops, indicating the ability of these crops to fix N biologically. Bean and pea crop grain N% ranged between 4 to 4.5% compared to 1.8 to 2% for cereal crops. Median grain N% of OSR crops was 3.2%, which helps explain the higher N demand of this crop.
- OSR had the lowest NHI of the crop categories with 63%, indicating lower translocation of N taken up by the crop into the seed. Whereas NHI's for the other crop categories ranged between 74 to 85%.
- Bean and pea crops fix around two to three times more N than was available from the soil, indicated by median NUpE of 325 and 224% for bean and pea crops respectively.
    - NUpE in the other crop types ranged between 68 to 80% with the highest NUpE in wheat crops.
- Barley and oat crops were most efficient at converting N taken up into yield, with NUtE medians of 41 and 45 kg DM yield/kg N taken up for barley and oat crops respectively, likely driven by around 100 kg N/ha lower crop N uptake in barley and oats compared to wheat.

- There was a relatively small range in grain N recovery (%) between the cereal and OSR crops (47 to 59%), indicating that across these crop types the amount of N available is being managed to a similar proportion to support yield and grain N% in these crops.
- Apparent N fertiliser recovery matched the RB209 standard figure of 60% across the crop types. Fertiliser recovery was high in wheat crops with a median of 73%, but low in oat crops with a median of 44%.
    - However, the oat dataset is smaller than the other crop categories and therefore should be met with caution.
- It is important that N balance is maintained at a suitable level to ensure good soil fertility without risking N losses to the environment. N balance for grain N offtake was high for OSR crops with a median of 86 kg N/ha. If straw is removed N balances were low for the cereal crops, potentially negatively impacting soil fertility, with median values ranging from -5 to +19 kg N/ha. N balance could be as low as minus 150 kg N/ha for wheat, barley and OSR if the straw is removed. Nationally, about 80% of barley crops and 70% of wheat crops have their straw removed (British Survey of Fertiliser Practice).
- Comparing wheat feed crop grain protein values with the varietal norm listed in the RL indicated that 7% of YEN crops were over-applied with N fertiliser due to achieving a protein of 2 percentage points or greater than the varietal norm and 2% of crops were under-applied.

5 TASK 5 – REML ANALYSIS

The aim of Task 5 was to used Restricted Maximum Likelihood (REML) analysis to assess the influence of a range of parameters (soil, fertiliser, manure, establishment, agrochemicals, and rainfall) on NUE metrics.

5.1 Methods

Initially, a biplot analysis was carried out to investigate whether it was appropriate to undertake separate REML analysis on all the NUE metrics calculated in Task 2. For all the data in the Cereal YEN database described above, a multi-variate biplot analysis was carried out in Genstat (VSN International) including all NUE metrics in addition to some crop and soil parameters (yield, crop biomass, HI, grain N%, SNS, N fertiliser applied; Figure 22).

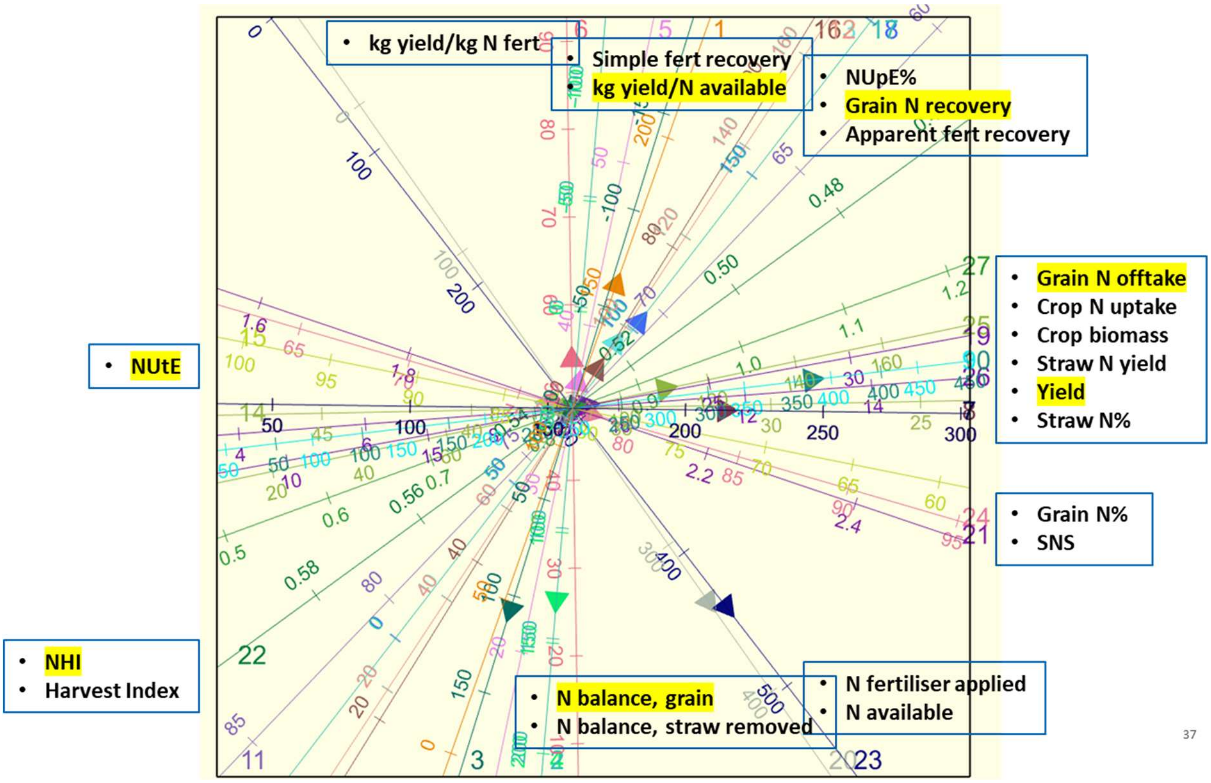

Figure 22. Biplot examining relationships among Cereal YEN NUE metrics, plus soil and crop parameters.

The biplot showed groupings of NUE metrics (Figure 22) which was unsurprising as some metrics were calculated using similar data. These grouped metrics were likely to have resulted in very similar associations when REML analyses were run, therefore it was decided to carry out further analyses on the metrics highlighted in yellow in Figure 22. These were:

- Grain N offtake, assumed N%
- N balance, assumed N%
- kg grain/kg N available
- Grain N recovery
- NHI
- NUtE grain
- Yield

Data were split into crop types: wheat, barley, OSR, peas and beans for REML analysis. REML makes it possible to analyse linear mixed models i.e., linear models that can contain both fixed (e.g., treatments) and random (e.g., block) terms. REML is useful as it can analyse data that includes more than one source of error variation, can cope with unbalanced designs, and has a powerful prediction algorithm. Therefore, it was suited to this dataset which is unbalanced and has a significant amount of missing data, as it was not obligatory for the farmers to provide all data that was requested. REML results in 'associations' rather than effects of one thing on another.

Initial analyses were carried out to investigate the most appropriate random terms to include in the analyses. Then each of the NUE metrics listed above were tested with their associations with various parameters, grouped as follows:

- **Manure**: Field history, manure in rotation, manure type, manure Y/N
- **Soil**: RB209 texture, SOM, pH, P, K, Mg indices
- **Fertiliser**: N type, N rate, no. applications
- **Field**: Crop type milling/feed, previous crop, residue fate, grass history
- **Establishment**: Cultivation, seed rate
- **Ag-chemicals**: Plant Growth Regulator (PGR), herbicides, fungicides
- **Rainfall**: Months grouped to approximate to development phases: Foundation (Nov – March), Construction (Apr – May), Production (Jun-July)

Analyses were initially run on the wheat dataset. The barley dataset was a lot smaller than that of wheat which meant a lot fewer analyses could be run successfully. The OSR and pea and bean datasets were even smaller, so it was not possible to run any analyses for these. REML is an iterative process, so if data are too sparse or disparate, it will not converge.

5.2 Results: Winter Wheat

An initial exploration of the winter wheat data showed that the following proportions of variation in yield and NUE metrics were explained more by Farm than other factors (Table 4). The exception was NHI which was explained more by year.

Table 4. Percentage variation in yield and NUE metrics accounted for by year, farm, field, latitude and RB209 soil category. NUE metric 8, Grain N recovery analysis would not run so is not included.

	Yield	1. yield/N available	3a. Grain N offtake assumed N%	5. NHI (%)	7. NUtE (grain)	11b N Balance (assumed N%)
Year	24%	2%	9%	32%	21%	3%
Farm	28%	28%	29%	4%	18%	29%
Field	7%	0%	6%	0%	5%	11%
Latitude	6%	0.2%	0%	0%	3%	0%
RB209 soil category	0.3%	5%	3%	0.2%	0%	3%

As latitude explained so little of the variation, that was excluded; the others were included as random terms in the subsequent analyses of the winter wheat data.

There were significant associations between N rate and the majority of NUE metrics examined, as well as yield (Table 5). Yield increased by 5 kg/ha per kg increase in N rate, which approximates to the typical break-even ratio for the economic optimum N rate. There were both positive and negative associations between NUE metrics and N rate. Positive associations showed: Grain N offtake (NUE metric 3a) was 0.19 kg/ha more N was taken off in the grain with every kg more N applied; and N balance (NUE metric 11b) was 0.81 kg/ha higher per kg N fertiliser (Table 5). This means that, although more N is getting into the grain with more N applied, a larger proportion is left behind in the soil. This is consistent with the significant reductions in yield/N available (NUE metric 1) and grain N recovery (NUE metric 8) seen with increasing N rate. There was also a significant reduction in N utilisation efficiency (NUE metric 7) with increasing N rate (Table 5). With these associations it should be noted that REML analysis shows linear associations whereas the relationship between N rate and yield is non-linear.

There was only one significant association with N form (type); Yield/N available (NUE metric 1) and this was driven by a high value for ammonium sulphate (AS), a result that should be treated with caution as only 15 entries recorded the use of this.

As with N rate, there were positive associations between the number of N applications and both yield and grain N offtake (NUE metric 1).

Table 5. Associations between: N rate, N fertiliser type and the Number of N applications, and selected NUE metrics plus yield. Significant ($P<0.05$) associations are highlighted red (negative) or green (positive) for continuous variables. Significant associations with categorical fixed terms are detailed in text. No text = no significant association.

NUE metric /parameter	N rate	N type	No. N apps
Yield t/ha	+5 kg/ha yield per kg N		+197 kg/ha yield per application
1 Yield/N available	-0.096 kg yield/kg N available per kg N	Driven by AS highest but only 15 entries	
3a. Grain N offake assumed N%	+0.19 kg/ha N offtake per kg N		+8.2 kg/ha N offtake per application
5. NHI (%)	Won’t converge	Won’t converge	Won’t converge
7. NUtE (grain)	-0.019 NUtE per kg N		-0.72 NUtE per app.
8. Grain N recovery (%)	-0.13% per kg N		+1.71% per app.
11b N Balance (assumed N%)	+0.81 kg N/ha per kg N		-8.20 kg N/ha per application

There were few significant associations between yield or NUE metrics and aspects of manure use so not all metrics were included in the table (Table 6). The YEN dataset does not include both fertiliser N rate and manure N rate, so fertiliser N rate was included as a random term to remove any impact of fertiliser N rate (Table 6). Regular manuring was associated with higher yield and yield/N available, potentially due to lower N available figures where manure was used. Consequently, this association with manure use and higher yield/N available may not be seen if the N applied from manures was included in the dataset. There was also an indication that regular manure use was associated with higher grain N offtake.

Table 6. Associations between Manure: history, in rotation and type, and selected NUE metrics plus yield. Significant associations with categorical fixed terms are detailed in text. No text = no significant association.

NUE metric /parameter	Manure history	In rotation	Manure type
Yield t/ha	↑regular manuring		
1 Yield/N available		Highest from Manured every year and Manured regularly	
3a. Grain N offake assumed N%	With Fert N in random term no significant associations but trend was similar to previous analysis – regular manuring highest		

Soil parameters were frequently associated with NUE metrics, although significance was sometimes at the 10% rather than 5% level (Table 7). The associations with soil texture were often driven by a particular soil type or the 'unknown' category. There was a significant positive association between soil organic matter (SOM) and grain N recovery with an increase in 0.34% per percent increase in SOM. In contrast, there was a decrease of 0.19 kg NUtE associated with an increase of 1% SOM. NUtE was also negatively associated with pH. There were trends for increases in yield associated with higher P and Mg index; there were no significant associations with K index. Increasing P index was also associated with higher grain N recovery and Mg was positively associated with grain N offtake (Table 7).

Table 7. Associations between Soil: Texture, Organic Matter (%), pH, P index, Mg Index, and selected NUE metrics plus yield. Significant associations are highlighted red (negative) or green (positive) for continuous variables. Significant associations with categorical fixed terms are detailed in text. No text = no significant associations. NB K Index was examined but there were no significant associations.

NUE metric /parameter	Texture	SOM	pH	P	Mg
Yield t/ha	P<0.1 (driven by unknown)			P<0.1. ↑ with ↑ index	Low at index 0
1 Yield/N available	High – shallow over chalk		-		
3a. Grain N offake	P<0.1 (driven by unknown)				General with ↑ index
7. NUtE (grain)		-0.19 NUtE per % SOM	-0.90 NUtE per unit of pH		
8. Grain N recovery (%)		+0.34% per % SOM		↑ with ↑ index	Significant but no clear trend
11b N Balance	driven by high unknown	P<0.1 -1.4 kg per % SOM			Significant but no clear trend

Associations between variety type and yield or NUE metrics were unsurprising; feed varieties were associated with higher yields, yield/N available and NUtE whilst milling varieties were associated with a greater grain N offtake (Table 8).

The previous crop category 'Uncropped' was associated with higher yields, grain N offtake and NUtE whereas cover crops were associated with lower yields and NUtE (Table 8). The cover crops finding is consistent with results of a previous analysis of the YEN dataset.

Table 8. Associations between: Variety type, Previous crop, and Residue fate, and selected NUE metrics plus yield. Significant associations with categorical fixed terms are detailed in text. No text = no significant associations. NB Grass history was examined but there were no significant associations.

NUE metric /parameter	Milling/feed	Previous crop	Residue fate
Yield t/ha	Milling lowest	Cover crops low, forage & uncropped high	
1 Yield/N available	Feed highest		
3a. Grain N offake assumed N%	Milling highest	Uncropped highest	Driven by unknown
5. NHI (%)			Returned highest
7. NUtE (grain)	Milling lowest	Cover crops low, forage & uncropped high	

There were significant associations between the number of PGR applications and yield, as well as several NUE metrics (Table 9). There was a 0.55 t/ha yield increase associated per application of PGR, a finding which is consistent with a previous analysis of the Cereal YEN database. Yield/N available, grain N offtake and grain N recovery were also significantly associated with the number of PGR applications. When fungicide associations were examined, only grain N offtake was positively associated with the number of fungicide applications; previous analysis has also shown positive associations with yield.

Table 9. Associations between the number applications of: Plant growth regulator (PGR), Fungicides and Herbicides and selected NUE metrics plus yield. Significant associations are highlighted red (negative) or green (positive) for continuous variables.

NUE metric /parameter	PGRs	Fungicides	Herbicides
Yield t/ha	+0.55 t/ha per application		
1 Yield/N available	+1.3 kg yield/kg N available per app.		
3a. Grain N offake assumed N%	+10.0 kg per app.	+6.6 kg per app.	
5. NHI (%)	Won't converge	Won't converge	Won't converge
7. NUtE (grain)	P<0.1 -0.5 NUtE per app.		
8. Grain N recovery (%)	+1.8% per app.		
11b N Balance (assumed N%)			

There was a significant negative association between seed rate and yield whereby there was a reduction of 0.34 t/ha per 100 seeds/m^2 increase in seed rate (Table 10). The same relationship has been found in a previous Cereal YEN analysis, although the yield reduction was greater in the previous analysis. In this analysis there was also a significant negative association between seed rate and grain N recovery. There were no significant associations between Cultivation method and yield or any NUE metric.

Table 10. Associations between: Seed rate and cultivation method, and selected NUE metrics plus yield. Significant associations are highlighted red (negative) or green (positive) for continuous variables. Significant associations with categorical fixed terms are detailed in text. No text = no significant associations

NUE metric /parameter	Seed rate	Cultivation
Yield t/ha	-0.00034 kg/ha per seed/m^2	
1 Yield/N available		
3a. Grain N offake assumed N%	P<0.1	
5. NHI (%)	Won't converge	Won't converge
7. NUtE (grain)		
8. Grain N recovery (%)	-0.02% per seed/m^2	
11b N Balance (assumed N%)		P<0.1. Negative for strip tillage. Similar for plough, min till, direct drill

There were significant negative associations between rainfall during the foundation development phase (sowing to the start of stem extension) and both yield and grain N offtake (Table 11) i.e., wetter winters would be associated with lower yields. There was also a significant negative association between rain during the production (grain filling) phase and yield, as well as NHI and NUtE.

Table 11. Associations between total rainfall during development phases: Foundation (Growth Stage 00 – 30), Construction (GS31 – 65), Production (GS65 – Harvest), and selected NUE metrics plus yield. Significant associations are highlighted red (negative) or green (positive) for continuous variables. Significant associations with categorical fixed terms are detailed in text. No text = no significant associations

NUE metric /parameter	Foundation	Construction	Production
Yield t/ha	-2.1 kg/ha per mm rain		-4.3 kg/ha per mm rain
1 Yield/N available			
3a. Grain N offake assumed N%	-0.05 per mm rain		
5. NHI (%)			-0.03% per mm rain
7. NUtE (grain)			-0.02 NUtE per mm rain
8. Grain N recovery (%)			
11b N Balance (assumed N%)			

5.3 Results: Winter and Spring barley

An initial exploration of the winter and spring barley data showed that the following proportions of variation in yield were explained by:

Year	34%
Farm	33%
Field	3%
RB209 soil category	1%
Latitude	0.4%

Since the soil category and latitude explained so little of the variation, these were not included as random terms in the REML analysis.

The barley dataset was a lot smaller than that of wheat. Initial analyses included all the NUE metrics that were used in the wheat analyses, but due to the small dataset these often failed to run. Therefore, it was concluded that only three of the NUE metrics could be included: 1. Yield/N available; 3a. Grain N offtake (assumed N%); and 11b. N balance (assumed N%), plus yield.

Due to the small dataset, the results from the barley analyses should be treated with caution.

Tables of results of the barley analyses can be found in Appendix Tables 20 to 26 (REML analysis). Associations between N rate and both yield and yield/N available were consistent with the wheat results; a positive association with yield and negative association with yield/N available. However, the increase in yield per kg increase in N was a lot higher than that of wheat at 17 kg/kg.

Regular manuring in a rotation appeared to be associated with higher grain N offtake, but the significance of the result in this analysis was driven by a very low average in the ‘unknown’ category. There were no associations between the history of manure and either yield or NUE metrics.

The only significant association with crop type was yield whereby feed varieties yielded 1.5 t/ha higher than malting varieties, but unlike with wheat, there were no associations with NUE metrics. There was a significant association between yield/N available and previous crop, driven by a very high average for grass/forage.

Increased numbers of applications of both PGRs and fungicides were associated with higher yields; 0.92 t/ha and 0.45 t/ha higher per PGR and fungicide application, respectively. As with wheat, there was a significant negative association between seed rate and yield. No NUE metrics showed significant associations with any management factors.

5.4 Task 5 Summary

The key findings from the YEN wheat dataset REML analysis of winter wheat can be summarised as follows:

- ‘Farm’ explains a large proportion of variation in yield (28%) and most NUE metrics – more than ‘Year’, ‘Field’, ‘Soil Type’ or ‘Latitude’. The exceptions were NHI and NUtE where ‘Year’ explained more variation than ‘Farm’.
- **N fertiliser:** Yield, Grain N offtake and N balance were positively associated with N rate whereas Yield/N available, NUtE and grain N recovery were negatively associated. Similar associations were seen for the number of N applications. This highlights the importance in defining which elements of NUE are being targeted. N product/type has previously been shown to be associated with yield whereby liquid N was associated with lower yields. This wasn’t evident from this analysis.

- **Manure:** There were few significant associations, but regular manuring was associated with higher yields and higher yield/N available. Manure type was not significantly associated with yield or NUE metrics in this analysis.
    - The association with manure use and higher yield/N available may be a factor of lower N available where manures were used. This association may not be present if the quantity of N applied from manures was included in the dataset.
- **Soil:** Grain N recovery was positively associated with SOM and P index; NUtE negatively associated.
- **Milling vs. Feed** associations were unsurprising: Feed varieties had the highest yield, Yield/N available, NUtE; milling varieties had the highest grain N offtake.
- **Previous crop:** Cover crops as a previous crop were associated with lower yields and low NUtE. Previously uncropped fields showed associations with higher yield, Grain N offtake and NUtE.
- **Agchems:** More PGR applications were associated with higher Yield, Yield/N available, Grain N offtake, Grain N recovery. More fungicides were associated with higher Grain N offtake. In previous analyses of the YEN database, both PGRs and fungicides were associated with higher yields.
- **Seed rate:** Was negatively associated with yield (consistent with previous analyses of the Cereal YEN dataset) and Grain N recovery.
- **Rain:** Yield and Grain N offtake were negatively associated with rain in the Foundation (sowing to the start of stem extension) development phase, and Yield, NHI and NUtE negatively associated with rain in Production (grain filling) phase.

The barley dataset was significantly smaller which meant that it was only possible to run analyses on Yield and 3 NUE metrics. Generally, the barley findings were similar to those resulting from the wheat data analysis:

- **Fertiliser:** As was found with wheat, Yield was positively, and Yield/N available was negatively associated with N rate.
- **Manure:** Regular/Frequent manuring was associated with higher grain N offtake.
- **Soil:** REML wouldn’t run with most soil parameters. However, low Yield/N available and Grain N offtake were associated with shallow soils, but these soils also had a high N balance.
- **Rain:** Yield/N available was negatively associated with rain in the Production (grain filling) phase.
- **Agchems:** Yield was positively associated with PGR and fungicide use.
- **Seed rate:** Was negatively associated with yield.

6 TASK 6 – PROPOSAL & SCOPING OF FURTHER WORK

Based on the findings of this study and limitations of the YEN dataset in meeting some of the objectives defined at the beginning of this project, the following further work is proposed to build a better understanding of NUE of our main arable crops and how it can be improved:

1. Source 'farm level' data from the YEN entrants where the dataset used in this study originates, to better understand what is behind the 'farm factor' explaining the biggest proportion of the variation in the NUE metrics and related parameters. This can be undertaken using a survey to answer questions of YEN entrants such as:
    a. How are staff trained on farm to make nutrient management decisions e.g., FACTS training?
    b. What sort of agronomist is used on farm e.g., independent, own advisor, commercial agronomist?
    c. Is RB209 used to make nutrient management decisions?
    d. What technology is used on farm for nutrient management e.g., variable fertiliser rate applications?
    e. Do you measure the N content of your organic materials?
2. Create a dataset of ADAS led on-farm trials of Enhanced Efficiency Fertilisers (EEFs) including urease/nitrification inhibitors and controlled/slow-release fertilisers to better understand the benefit of these products on NUE.
    a. ADAS would need to make sure the data can be shared publicly before undertaking this further work.
3. Analyse N response curves for scenarios which include use of EEFs and/or inhibitors.

Additionally, we recognise that the YEN database does not contain detailed information regarding the use of organic materials on farm. We have not suggested further work that includes investigating the role of organic materials in improving NUE due to the fact there is no known dataset that could help answer this question, as there is limited on farm data regarding the use of organic materials. YEN Zero is the newest of the YEN networks, currently in its second year. This YEN is collating more detailed information on organic materials such as quantity and type of material applied, application method, timing of application and whether N was measured in the material. However, it will take a couple more years of the YEN Zero network running to build a dataset large enough to analyse using the methods in this project. The YEN database would also benefit from asking growers for measured soil N contents to get a more detailed picture of N availability to the crop and N balances, but soil N is not commonly measured on a seasonal basis on farms.

It is important to understand how efficiently organic materials are being used on farm to ensure their value is being fully realised. These resources can be a challenge to manage effectively as there are large variations in their nutrient contents within and between organic material types, and the availability of the nutrients to the crop is very dependent on the soil and weather conditions. The best strategy for users of organic materials is to understand the material's nutrient content, apply under the most appropriate conditions using the best technology, and to adjust inorganic fertilisers in line with the amount of plant available nutrients supplied by the organic materials. The ongoing Defra-funded project 'Development and evaluation of a free to use nutrient management planning tool' (NM0105) will address some these areas within the management of organic materials on farm.

7 DISCUSSION AND CONCLUSIONS

NUE is a widely used term and an important component of crop management. Many growers and key players across the agriculture industry are looking to improve NUE, due to economic and environmental pressures. However, NUE is not a simple parameter to define as it depends on the question being posed e.g., whether the focus is on yield, crop quality, or the environment (Dobermann, 2005). Consequently, when referring to NUE it is important to define how it is calculated. This report outlined several ways NUE can be defined depending on the question, with three key parameters suggested to indicate NUE related to yield (kg grain yield/kg N available), crop quality (Grain N offtake/kg N available), and risk of loss of N to the environment (N balance: N fertiliser applied minus crop N offtake).

7.1 Analysis of NUE metrics across multiple crop types in the YEN database

These defined NUE metrics were calculated for the >4,000 crop yield entries in the YEN database which showed a large range in NUE and related parameters across the dataset. This analysis has given a better understanding of N fertiliser use across the main arable crop types, the efficiency of N fertiliser use to produce yield and grain N content, the proportion of fertiliser recovered by crops and the N balance of the field when the crop is harvested. Specifically, this analysis indicated the high N demand of OSR crops and the lower efficiency of OSR in using N available to produce yield. However, basing NUE metrics on yield for OSR could be misleading as OSR seeds contain 50% more energy, have a higher dry matter content and more than double the economic value per kg of seed compared with wheat (Sinclair and de Witt, 1975). N utilisation efficiency and NHI of OSR crops in the YEN dataset agreed closely with these NUE metrics assessed in a range of OSR varieties which had a mean of 21 kg DM/kg N NUtE and a mean of 62% NHI (Berry et al., 2010).

Cereal species, peas and beans are more comparable as their yields are measured at the same moisture content, and their seed has a similar energy density and economic value. Generally, barley and oat crops had higher NUE than wheat crops and the NUE analysis indicated that bean and pea crops fix around two to three times more N than what is available in the soil. Muurinen et al. (2007) agreed with the differences in NUE between wheat, barley, and oat crops, finding higher grain N content and lower NUE in wheat compared to barley and oat spring crops. This indicates that NUE can be improved on a whole farm basis through changes to crop rotations, by including more leguminous crops such as peas and beans and growing more oat and/or barley crops as an alternative to wheat crops.

Reassuringly, apparent N fertiliser recovery values were close to the 60% figure stated in RB209, with wheat crops having a recovery higher than this at 73%. This indicates that on average, a sufficient proportion of the N fertiliser being applied is being recovered and utilised by the crop. However, fertiliser recovery, in addition to the other NUE metrics analysed in this report, had a wide range in values within each of the crop species, demonstrating that there are a proportion of farms where NUE is poor, and improvements can be made. It is this range in the dataset which supports the REML analysis to understand what management and agronomic related factors associate with improved NUE on farm.

The N balance analysis i.e., how much N is left in the soil after the crop has been removed, demonstrated that if grain and straw is removed from the field in cereal crops after harvest then the N balance can often be negative which could deplete soil N residues if continued over several years. Lower levels of N left in the soil could lead to reduced environmental losses, but if a negative N balance is maintained over seasons this could impact yields (Lord et al., 2006; Oliveira et al., 2022). This demonstrates that growers need to monitor nutritional offtakes to ensure balances are not being depleted and soil fertility compromised. This can be achieved through measuring grain nutritional contents and making assumptions of nutrient harvest indices to quantify offtake of grain and straw.

N balances to ensure minimal losses to the environment are specific to each site based on soil characteristics and geographical location of the field; as soil texture, soil depth, and over winter rainfall will influence how easily soil is leached to the surrounding environment. There is no agreed optimum N balance for maintaining/enhancing soil fertility and minimising the risk of nitrate leaching. The optimum N balance is likely to be influenced by the balance of mineralisation/immobilisation of the soil. Immobilisation of N generally only occurs if the C:N ratio is high which might be a result of straw incorporation or application of high C:N material like paper waste. The C:N ratio of most soils (inherent organic matter) tends to be around 10-12 and C:N ratio of microbes in the soil around 5-6. The general consensus is that the switch between an N mineralising environment to immobilising is at C:N ratios of about 25 (i.e., immobilisation occurs under C:N > 25; Chen et al., 2014). Therefore, agricultural soils should be maintained at a C:N ratio below 25 to ensure N in the soil is being mineralised and made available to the growing crop, reducing the need for synthetic N input.

7.2 How crop quality can indicate efficient N management

Comparison of wheat protein levels to the AHDB Recommended List is a good indicator of whether the N supply was optimal. Normal protein responses of 1% relate to a change in total N applied of 50 kg N/ha (Sylvester-Bradley and Clarke, 2009). Protein deviations of ±2% or more relate to error in total N applied of 100 kg N/ha or more, costing >£100 at 2021 prices and closer to £200/ha at 2022 prices. This comparison in YEN winter wheat feed crops indicated that 7% of crops were over fertilised by 100 kg N/ha or more, and 2% were under-fertilised. Consequently, there is opportunity in some situations to reduce on farm N rates through improved nutrient management planning which considers the available N in the soil, and the expected yield and grain protein of the crop, to get to a better estimate of crop N requirement.

Early indications from YEN Zero data are that some growers are effectively using organic materials to reduce the use of synthetic N fertilisers. Specifically, a particular YEN Zero entrant applied cattle slurry to their wheat crop entries and zero synthetic N fertiliser and achieved an average yield of 9.2 t/ha. This compares to the UK average yield of 8 t/ha and the average N application rate for UK wheat crops of 184 kg N/ha. This demonstrates that with the right management and technology (ensuring correct application), organic materials can play a role in reducing use of synthetic fertilisers.

7.3 Statistical analysis of agronomic factors which associate with NUE

The REML analysis showed there were both positive and negative associations between N rate and different NUE metrics. This demonstrated the importance of defining what is meant by NUE in a particular situation. To increase grain N offtake and N balance, N rate should be increased. Whereas, to increase kg grain yield/kg N available, NUtE, and grain N recovery, or to reduce N balance, N rate should be reduced. Consequently, decisions on changing N rates should be based on what outcome is desired, e.g., improving crop quality or reducing environmental impact. However, reducing N rate would have a negative impact on grain yield with consequences for food security if this was scaled up to the whole country. ADAS carried out a review for AHDB in 2022 (Review of high fertiliser prices, 2022). This demonstrated that, for wheat and barley, reducing the amount of N applied by 50 kg N/ha from the optimum (at a break-even ratio of 5:1) would reduce yields by 0.36 t/ha. Over the average UK wheat and barley area of ~2.9 m ha this would equate to 1.04 Mt less grain if the grain:fertiliser price ratio stayed the same.

As with previous analyses of the YEN dataset the REML analysis in this project indicated a significant farm factor influence on NUE. This demonstrated that the farm the data originates from is having a large influence on NUE related metrics. Better understanding is required on what specifically comprises the farm factor (e.g., management approaches, technology used on farm, staff training etc.) but this association is significant because it demonstrates that it is possible for management practices to improve NUE. Other factors shown to be associated with NUE metrics included specific management practices associated with greater yield (including use of PGRs and fungicides, and lower seed rates). This indicates that by optimising crop management to enhance yields, NUE will be improved due to greater yields produced for the same rate of N applied.

Use of organic materials have the potential to reduce the requirement for inorganic N without reducing yield. Feed varieties of wheat have a greater yield per kg of available N than milling varieties, indicating that feed varieties should be grown over milling varieties if NUE is to be improved on farm. Greater soil organic matter and P index were positively associated with some NUE metrics, showing the importance in maintaining and improving soil health to enhance NUE. Wetter winters and grain filling periods have been associated with lower NUE metrics, probably as a result of the effect of these factors to reduce yield. There were no associations between NUE metrics and fertiliser product type, use of cover crops or fertiliser product type.

7.4 Relationship between N rate and NUE

NUE metrics are directly related to the amount of N applied. A standard N response curve details the increase in yield as N rate increases, with greater yield increases at the lower N application rates, which level off to a point where additional N applied does not increase yield further (Figure 23). The economic optimum N rate is defined as the rate at which the cost of additional N applied is not covered by the value of grain produced from that additional N. The break-even ratio (BER) is influenced by the cost of the N fertiliser and for several years the BER for wheat has been 5:1, i.e., 5 kg of grain pays for 1 kg of N fertiliser. However, recently N fertiliser prices saw a dramatic increase which raised the BER to 10:1. This higher BER lowers the economic optimum N rate due to the higher cost of the N fertiliser (Figure 23). In the standard N response curve shown in Figure 23 the economic optimum N rate is 192 and 142 kg N/ha for a BER of 5 and 10 respectively.

Grain protein has a different relationship with N rate compared to yield, with protein (and grain N content) increasing steadily as N rate increases after an initial flat response (or dip in some cases) (Figure 23). Consequently, crop products which require a high grain N content for the end market need to be managed with higher N application rates, such as milling wheat. The protein achieved in the standard N response curve for feed wheat (which have lower grain protein concentrations than milling wheats at the BER) shown in Figure 23 is 10.85 and 9.89% for the BER's of 5 and 10 respectively, influenced by the different economic optimum N rates.

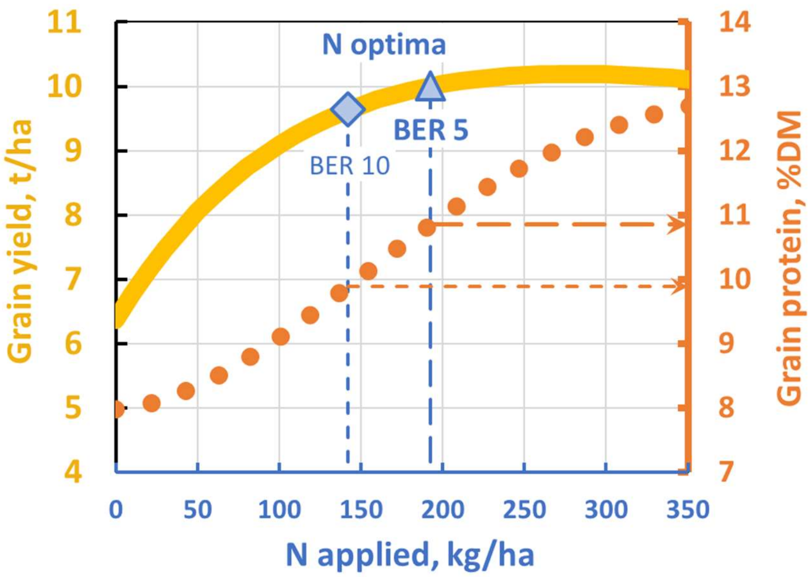

Figure 23. Standard N response curve demonstrating the relationship between N rate and yield and protein of a feed wheat crop. BER represents the break-even ratio at 5:1 and 10:1 in terms of kg of grain required to pay for a kg of N fertiliser (Berry et al. 2022).

The relationship between NUE metrics calculated in this report and N rate applied are shown in Figures 24-27. As mentioned previously, NUE, in terms of yield achieved for each unit of N available, tends to fall as N rate increases. This is evident in Figure 24 where kg grain/kg N available steadily declines as N applied increases, the NUE at the BER of 5 in this scenario is 35.7 kg yield for each kg N applied. A standard soil available N of 90 kg N/ha was assumed in this scenario. The N balance (for grain N offtake) has the opposite relationship with N rate applied as the quantity of N left in the field post-harvest increases with N rate, due to the proportion of N applied taken up by the crop reducing. The N balance is negative at N rates lower than 150 kg N/ha in this scenario, due to the yield and protein content of the grain (defined in Figure 23) resulting in the grain N offtake being greater than the N applied. At a BER of 5 the N balance is positive at 29 kg N/ha.

Due to grain protein increasing with N rate, evidenced in Figure 23, the NUE metric of Grain N offtake also increases with N rate applied (Figure 26). At the BER of 5, grain N offtake is 161 kg N/ha in this scenario. However, the proportion of N available recovered by the grain has a negative relationship with N rate (Figure 27), due to the relationship of NUE declining with N rate, mentioned above. The grain N recovery at a BER of 5 in this scenario is 58%. These response curves of different NUE metrics and N rate demonstrate that N management should be adjusted differently depending on which element of crop output is looking to be altered. Efficiency at which the crop uses the N available will reduce as the N available/N rate applied increases. Whereas, crop quality, in terms of grain N content, will increase as N available/N rate applied increases.

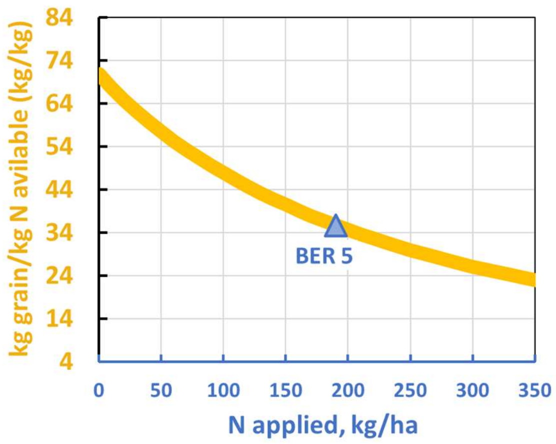

Figure 24. Relationship between NUE metric kg grain/kg N available (kg/kg) and N applied, based on the standard N response curve assumptions in Berry et al. (2022)

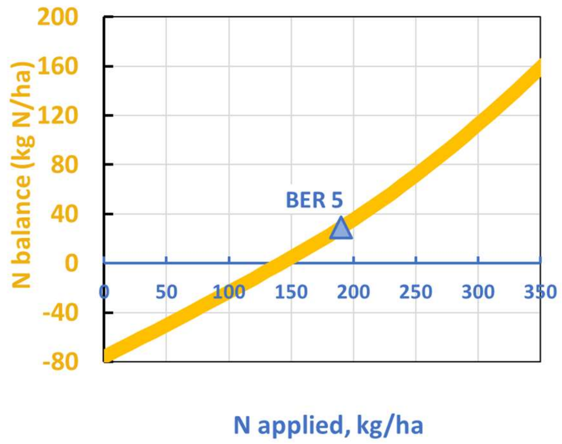

Figure 25. Relationship between NUE metric N balance for grain N offtake (kg N/ha) and N applied, based on the standard N response curve assumptions in Berry et al. (2022)

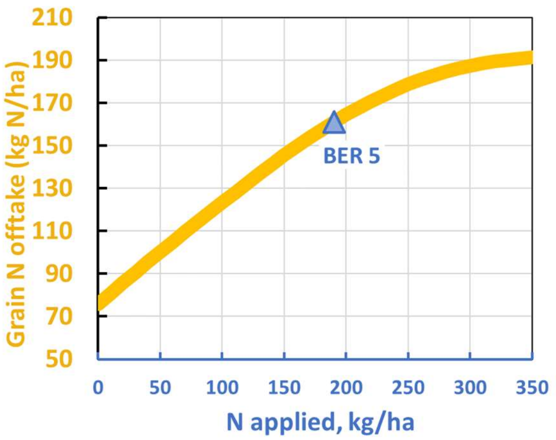

Figure 26. Relationship between NUE metric Grain N offtake (kg N/ha) and N applied, based on the standard N response curve assumptions in Berry et al. (2022)

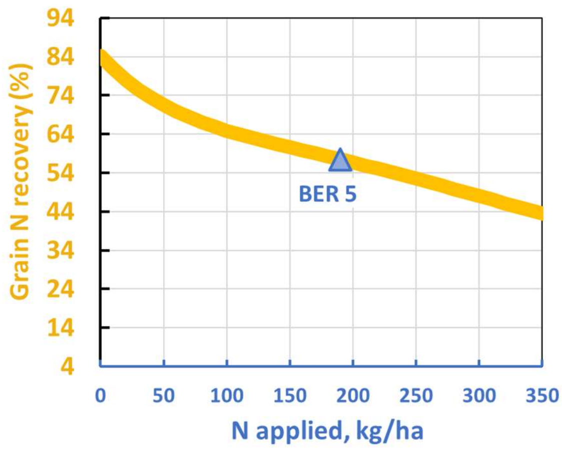

Figure 27. Relationship between NUE metric Grain N recovery (%) and N applied, based on the standard N response curve assumptions in Berry et al. (2022)

7.5 Use of EEFs to improve NUE

NUE could potentially be improved using Urease Inhibitors (UIs; reduce NH_3 emissions), Nitrification Inhibitors (NIs; reduce N_2O production and NO_3 leaching) or Slow/Controlled Release Fertilisers (S/CRF). These were defined and their effectiveness reviewed as part of the Defra project 31280, Creating and Enabling Regulatory Environment for Enhanced Efficiency Fertilisers. Unfortunately, information about the use of these products were not collected as part of the YEN data collection and so it was not possible to draw conclusions on their impact on NUE metrics here. However, Defra project 31280 concluded that: 1. There was good evidence that the NI DCD is effective at reducing N_2O emissions following N applications, although this varies by soil type; 2. The UI nBTPT reduces NH_3 losses and improves N use efficiency of urea-based fertilisers; and 3. There was little published evidence to support changes in recommended practice based on the use of CRF i.e., there was limited evidence to support that the use of polymer coated urea can lead to a reduction in either total N fertiliser rates or the number of split applications. Reduction factors used in the UK GHG Inventory include a 70% and 44% reduction in ammonia volatilisation for urea and UAN products respectively when used with a urease inhibitor, and a 44% reduction in nitrous oxide emissions when a nitrification inhibitor is used with N fertiliser applications. It should be recognised that nitrous oxide emissions usually represent only about 1% of the total N fertiliser applied (for Ammonium Nitrate fertiliser products), therefore Nis are unlikely to have a substantial impact on NUE metrics because of reducing nitrous oxide emissions.

7.6 Further work and optimal NUE metrics to use

Further work is needed to better understand how EEFs and inhibitors can be used to improve NUE and what specific factors are behind the 'farm' description of YEN crop entries which is having a significant influence on the calculated NUE metrics. Additionally, improved knowledge of how organic materials are being used on farm would identify management practices that should be focussed on to ensure organic materials are used as effectively as possible to improve NUE and reduce synthetic fertiliser use. The YEN database has been shown to be a valuable resource to demonstrate how efficiently nitrogen fertilisers are being used on UK farms in terms of crop yield, crop quality and environmental impacts. However, there are limitations to the dataset which have been stated in this report. In addition to the fact that the dataset relies on growers to provide the information. Consequently, there are missing values, and the accuracy of the data is reliant on the farmer or advisor inputting the information correctly and collecting crop samples that are representative of the whole field.

Defining and calculating a range of NUE metrics within this project has indicated that depending on the question being posed, the most useful NUE metrics to use are:

1. To indicate efficiency of crop N use to produce yield:
    a. kg grain yield/kg N available (kg/kg)
2. To indicate efficiency of fertiliser to improve crop quality:
    a. N removed in harvested grain per kg of available N (%)
3. To indicate potential risk of losing applied N to the surrounding environment:
    a. N balance (kg N/ha), which calculates the net amount of applied N fertiliser left in the field after harvest

Through the analysis described in this report several strategies can be recommended to improve NUE on farm:

- Include more barley and oat crops in the rotation which have a higher NUtE compared to wheat crops
- Include more legumes such as beans and peas in the rotation which do not require N fertiliser and fix around 2-3 times more N than the other main arable crop types
- Monitor grain N offtake by measuring grain nutrient content to make an assessment on the success of the N management approach in a particular crop. Specifically for wheat, grain protein levels can be compared to varietal protein values in the Recommended List to determine whether N was over or underapplied
- Monitor grain and straw N offtake to ensure soil N balances are not being depleted and soil fertility compromised
- Enhancing crop yields using the same N rates will improve NUE. Crop yields can be improved through good crop management, such as use of PGRs and fungicides, and ensuring good establishment and optimal grain/seed fill conditions

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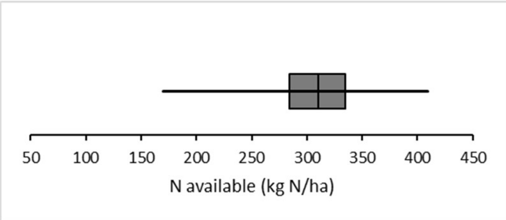
APPENDIX

Comparison of NUE metrics with and without manure use

Appendix Table 1. Table showing box plots for NUE metrics calculated for winter wheat crops for the full dataset (first column) and filtered for entrants that indicated no manure was used in the crop inputs (second column).

All data | **No manure used**



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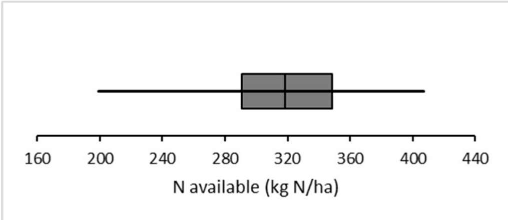

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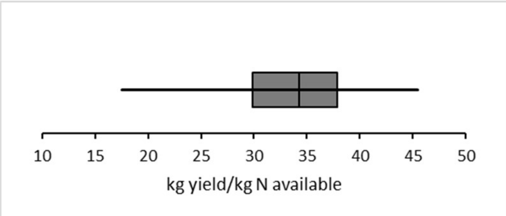

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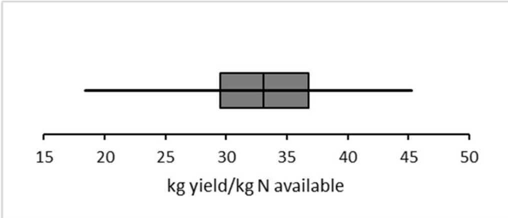

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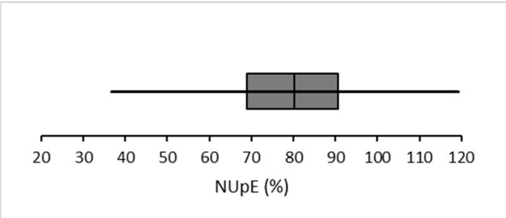

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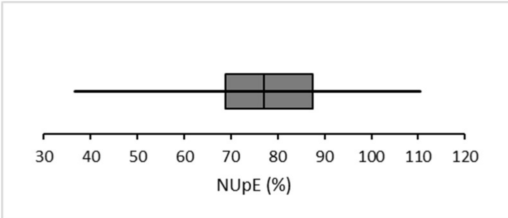

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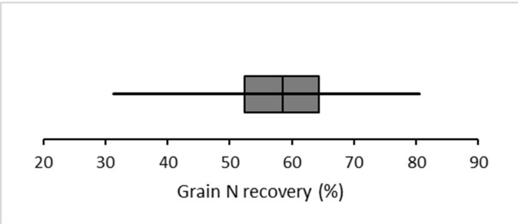

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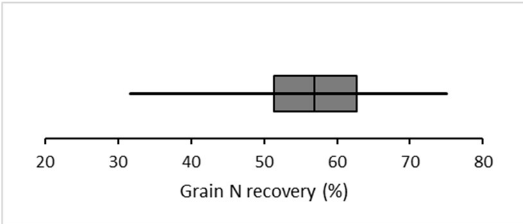

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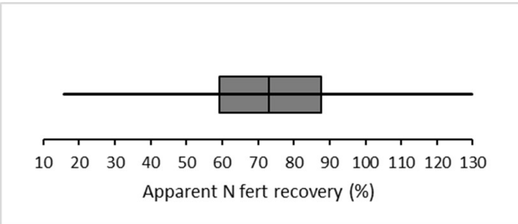
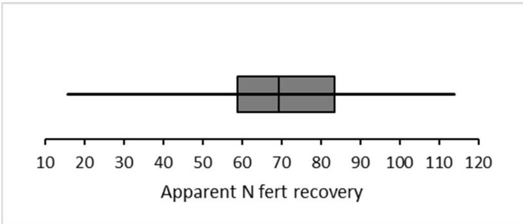


n = 398



n = 117

Appendix Table 2. Table showing box plots for NUE metrics calculated for barley crops for the full dataset (first column) and filtered for entrants that indicated no manure was used in the crop inputs (second column).

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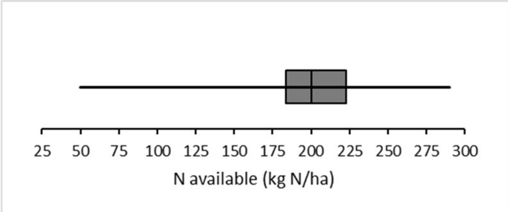

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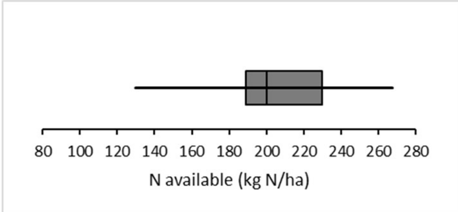

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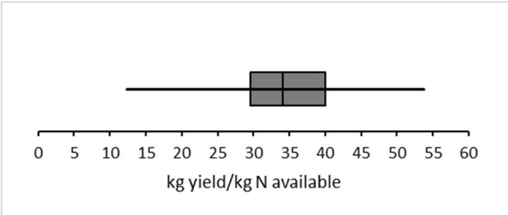

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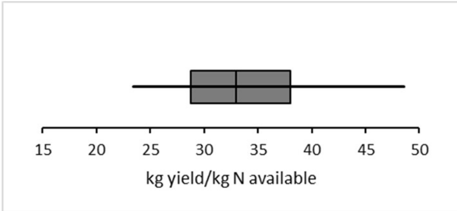

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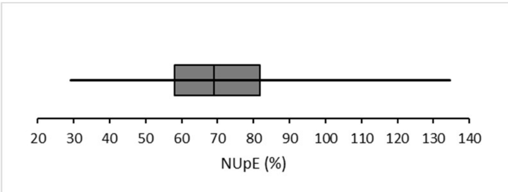

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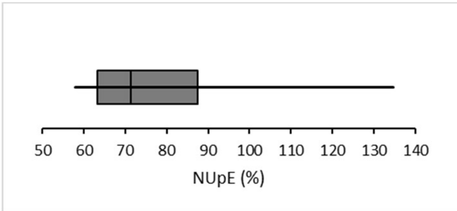

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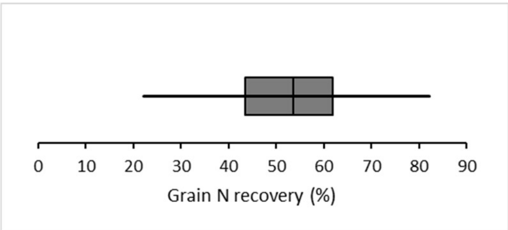

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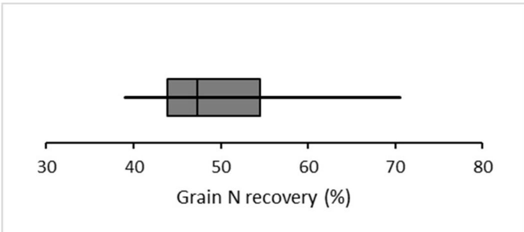

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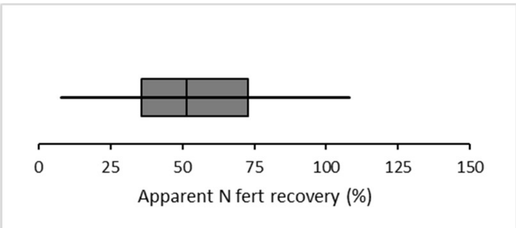

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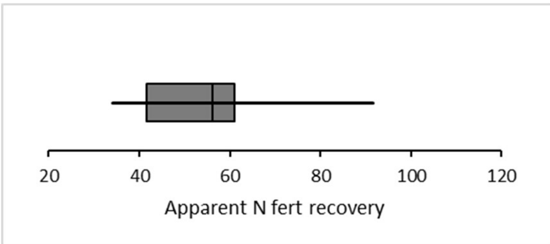
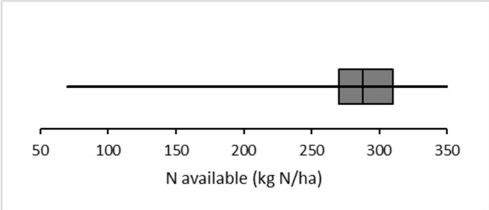


n = 9

Appendix Table 3. Table showing box plots for NUE metrics calculated for OSR crops for the full dataset (first column) and filtered for entrants that indicated no manure was used in the crop inputs (second column).

All data



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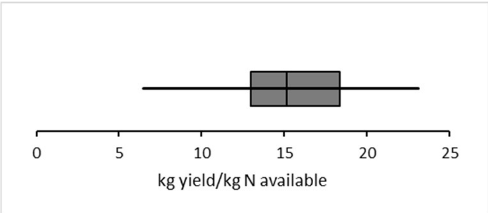

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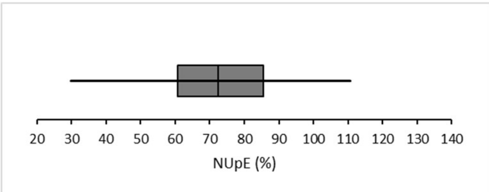
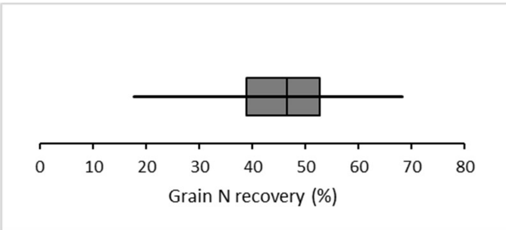


n = 96



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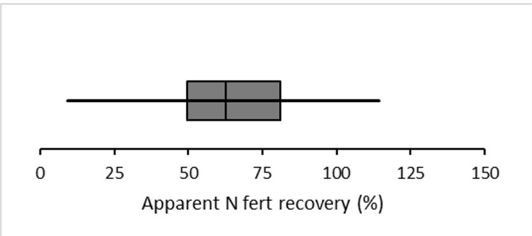
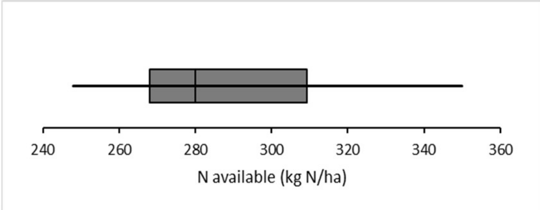


n = 95

No manure used



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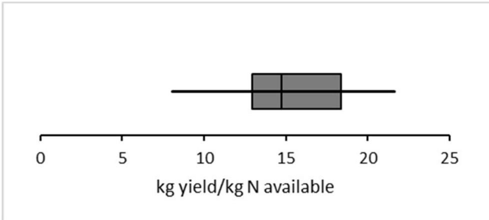

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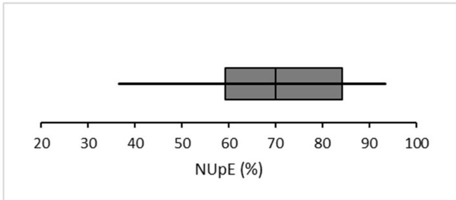
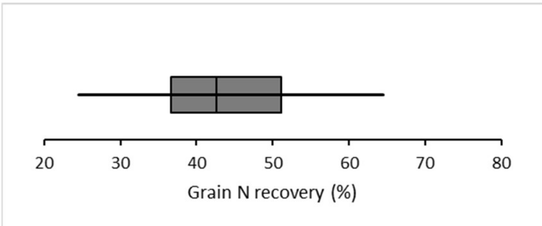


n = 22



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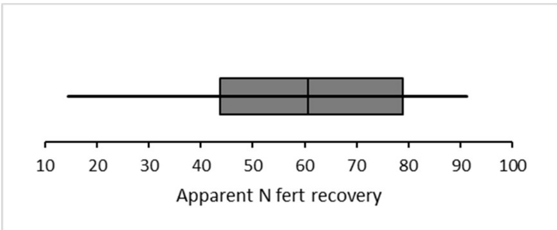


n = 22

Comparison of NUE metrics for assumed grain N% and NHI

The relevant NUE metrics which were calculated for each crop category with and without the assumed metrics of grain N% and NHI are shown in Appendix Tables 4 to 9. For winter wheat crops the median and minimum and maximum values for these metrics were very similar where the raw dataset was used compared to where grain N% or NHI values were assumed where the data was missing (Appendix Table 4). The only differences which occurred included a lower minimum crop N uptake when NHI is assumed (55 and 104 kg N/ha for with and without NHI assumed) and consequently a lower median (235 and 256 kg N/ha for with and without NHI assumed) and maximum value (335 and 364 kg N/ha for with and without NHI assumed). Additionally, the range in N balance for Crop N offtake was greater when NHI was assumed, -225 to 96 compared to -189 to 87 for with and without NHI assumed. This indicates that the assumed NHI figure is greater than that calculated for YEN entries where the data is available.

Appendix Table 4. Table of NUE metrics with and without assumed grain N% and NHI for winter wheat crops.

NUE metric	Quartile	No assumed values	Assumed grain N% or NHI
Grain N offtake (kg N/ha) *grain N% assumed*	Min	40.21	40.21
	Median	170.86	172.23
	Max	235.91	235.91
Crop N uptake (kg N/ha) *NHI assumed*	Min	103.49	55.09
	Median	255.51	234.64
	Max	363.72	334.66
NUpE % *NHI assumed*	Min	36.70	36.70
	Median	80.20	80.22
	Max	119.23	118.03
Apparent fertiliser recovery *% NHI assumed*	Min	15.80	15.80
	Median	73.10	73.41
	Max	129.67	125.13
N balance (grain only) grain *N% assumed*	Min	-189.43	-189.43
	Median	51.65	50.59
	Max	125.58	125.25
N balance (if straw removed) *NHI assumed*	Min	-189.25	-224.46
	Median	2.89	12.36
	Max	86.94	95.85

There were similar differences in the barley dataset with a lower minimum crop N uptake and additionally lower median and maximum values (Appendix Table 5). The minimum and median crop N uptake values were 24 and 161 kg N/ha where NHI was assumed and 58 and 152 kg N/ha for the raw dataset. The differences for N balance for Crop N offtake were not as great as in the wheat dataset. However, the maximum N balance was higher where NHI was assumed (59 compared to 44 for with and without NHI assumed.

Appendix Table 5. Table of NUE metrics with and without assumed grain N% and NHI for barley crops.

NUE metric	Quartile	No assumed values	Assumed grain N% or NHI
Grain N offtake (kg N/ha) *grain N% assumed*	Min	16.49	15.30
	Median	106.77	106.34
	Max	164.14	162.27
Crop N uptake (kg N/ha) *NHI assumed*	Min	58.37	23.54
	Median	151.83	161.31
	Max	249.84	234.44
NUpE % *NHI assumed*	Min	29.18	29.18
	Median	69.03	71.70
	Max	134.60	126.44
Apparent fertiliser recovery % NHI *assumed*	Min	7.95	3.20
	Median	51.31	57.96

	Max	107.95	115.03
N balance (grain only) grain N% *assumed*	Min	-165.26	-165.26
	Median	22.36	25.26
	Max	85.34	85.34
N balance (if straw removed) *NHI assumed*	Min	-198.87	-198.87
	Median	-4.67	-7.56
	Max	44.26	59.03

Differences in crop N uptake were also apparent when NHI was assumed for the oat crop dataset (Appendix Table 6). There was a larger range in the dataset when NHI was assumed (28 to 195 kg N/ha compared to 87 to 165 kg N/ha with and without NHI assumed), however, the median did not differ to a large extent (146 compared to 140 kg N/ha with and without NHI assumed). Notable other differences in the oat dataset included a higher maximum NUpE when NHI is assumed (92 compared to 69%) and greater median and maximum apparent N fertiliser recovery values when NHI is assumed (52 and 70% compared to 44 and 55% with and without NHI assumed respectively). Additionally, there was a lower trend in N balance for Grain N offtake when grain N% was assumed with a range of -117 to 69 when grain N% is assumed, compared to -97 to 97% for the raw dataset. This caused a lower median N balance figure for Grain N offtake of 14 compared to 30 for with and without grain N% assumed.

Appendix Table 6. Table of NUE metrics with and without assumed grain N% and NHI for oat crops.

NUE metric	Quartile	No assumed values	Assumed grain N% or NHI
Grain N offtake (kg N/ha) *grain N% assumed*	Min	20.20	20.20
	Median	102.04	106.77
	Max	142.36	142.48
Crop N uptake (kg N/ha) *NHI assumed*	Min	86.73	27.67
	Median	140.17	145.50
	Max	165.26	195.18
NUpE % *NHI assumed*	Min	42.24	42.24
	Median	62.47	67.68
	Max	69.00	92.40
Apparent fertiliser recovery % NHI *assumed*	Min	16.73	16.73
	Median	43.86	51.55
	Max	54.90	70.33
N balance (grain only) grain N% *assumed*	Min	-96.68	-117.09
	Median	30.31	13.95
	Max	96.65	68.85
N balance (if straw removed) *NHI assumed*	Min	-43.88	-43.88
	Median	19.22	19.22
	Max	34.32	34.32

For OSR crops the NUE metrics were for the most part very similar to the raw dataset where grain N% or NHI was assumed (Appendix Table 7), with the only differences occurring again in crop N uptake which had lower median and max values when NHI was assumed. The median and max values were 192 and 279 kg N/ha respectively when NHI was assumed, compared to 216 and 301 kg N/ha for the raw dataset.

Appendix Table 7. Table of NUE metrics with and without assumed grain N% and NHI for OSR crops.

NUE metric	Quartile	No assumed values	Assumed grain N% or NHI
Grain N offtake (kg N/ha) *grain N% assumed*	Min	47.24	47.24
	Median	127.17	128.22
	Max	172.91	172.88
Crop N uptake (kg N/ha) *NHI assumed*	Min	68.74	68.74
	Median	215.62	192.04
	Max	300.71	278.62
NUpE % *NHI assumed*	Min	29.74	29.74
	Median	72.39	69.51
	Max	110.73	106.34
Apparent fertiliser recovery % NHI *assumed*	Min	9.06	9.06
	Median	62.74	59.60
	Max	114.39	109.55
N balance (grain only) grain N% *assumed*	Min	-120.73	-120.73
	Median	86.01	86.40
	Max	151.57	160.79
N balance (if straw removed) *NHI assumed*	Min	-155.12	-155.12
	Median	60.60	64.38
	Max	133.79	133.79

When grain N% and NHI were assumed for the pea crop dataset there were a few differences between these NUE metrics and the raw dataset. Specifically, the minimum and median values for grain N offtake were lower when grain N% was assumed, 22 and 126 kg N/ha for the minimum and median values respectively when grain N% is assumed, compared to 50 and 136 kg N/ha for the raw dataset. Additionally, the range in both crop N uptake and NUpE were greater when NHI was assumed, causing a higher median value with 162 and 157 kg N/ha crop N uptake for with and without NHI assumed and 237 and 224% for with and without NHI assumed respectively (Appendix Table 8). Differences in N balance for both Grain N offtake and Crop N offtake were also slightly different when grain N% and NHI was assumed. The median values were -133 and -166 kg N/ha for Grain and Crop N offtake respectively when grain N% and NHI are assumed, compared to -145 and 155 kg N/ha for Grain and Crop N offtake respectively for the raw dataset.

Appendix Table 8. Table of NUE metrics with and without assumed grain N% and NHI for pea crops.

NUE metric	Quartile	No assumed values	Assumed grain N% or NHI
Grain N offtake (kg N/ha) *grain N% assumed*	Min	50.05	21.55
	Median	136.38	126.44
	Max	219.04	219.04
Crop N uptake (kg N/ha) *NHI assumed*	Min	58.68	27.63
	Median	156.48	161.67
	Max	208.44	280.83
NUpE % *NHI assumed*	Min	83.83	39.47
	Median	223.54	236.84
	Max	297.77	401.18
N balance (grain only) grain N% *assumed*	Min	-329.20	-329.20

	Median	-144.65	-133.29
	Max	-77.11	-71.59
N balance (if straw removed) *NHI assumed*	Min	-220.52	-375.63
	Median	-154.70	-165.45
	Max	-95.49	-87.99

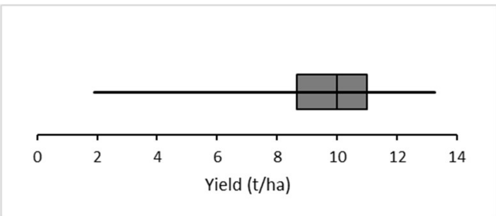
The range in crop N uptake values when NHI was assumed was greater for the bean crop dataset with 51 to 342 kg N/ha when NHI is assumed compared to 121 to 307 kg N/ha for the raw dataset (Appendix Table 9). This was similar for NUpE which ranged from 73 to 494% when NHI was assumed, compared to 173 to 448% for the raw dataset. The maximum N balance for Crop N uptake was lower when NHI was assumed, with 68 kg N/ha compared to 167 kg N/ha for with and without NHI assumed respectively.

Appendix Table 9. Table of NUE metrics with and without assumed grain N% and NHI for bean crops.

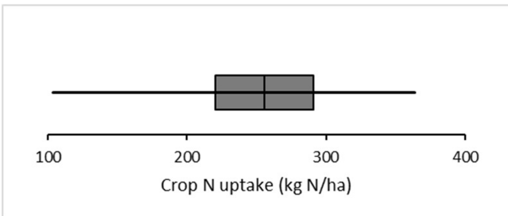
NUE metric	**Quartile**	**No assumed values**	**Assumed grain N% or NHI**
Grain N offtake (kg N/ha) *grain N% assumed*	Min	39.77	39.77
	Median	170.19	174.60
	Max	296.66	296.66
Crop N uptake (kg N/ha) *NHI assumed*	Min	121.08	50.99
	Median	235.35	224.31
	Max	307.01	341.48
NUpE % *NHI assumed*	Min	172.97	72.84
	Median	325.10	339.33
	Max	447.72	493.88
N balance (grain only) grain N% *assumed*	Min	-305.36	-305.36
	Median	-190.39	-190.01
	Max	-59.98	-74.63
N balance (if straw removed) *NHI assumed*	Min	-345.27	-345.27
	Median	-236.29	-217.24
	Max	-167.09	-68.43

Calculated NUE metrics, box plots

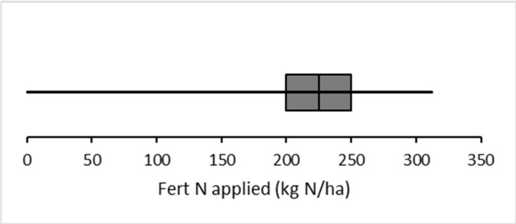
Appendix Table 10. Boxplots of calculated NUE metrics and related parameters for winter wheat crops.



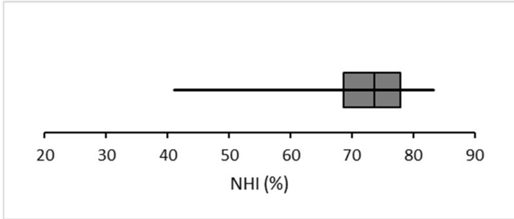
n = 2,158



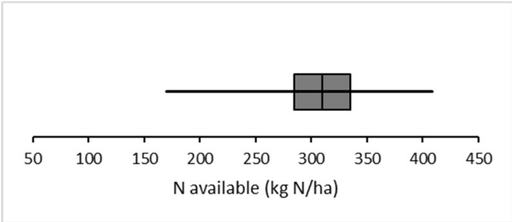
n = 827



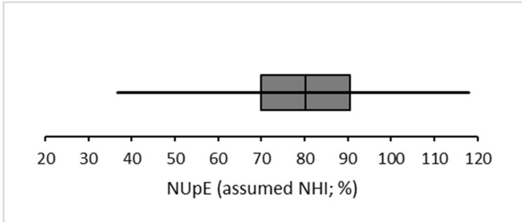
n = 1,239



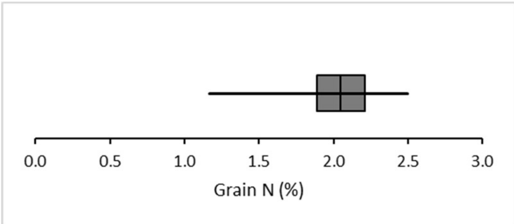
n = 827



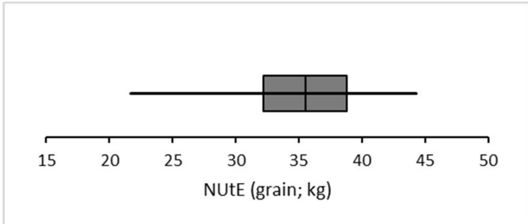
n = 579



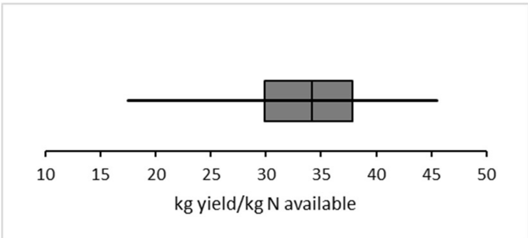
n = 550



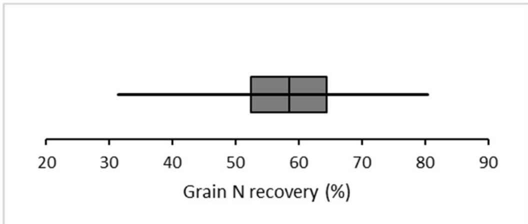
n = 2,032



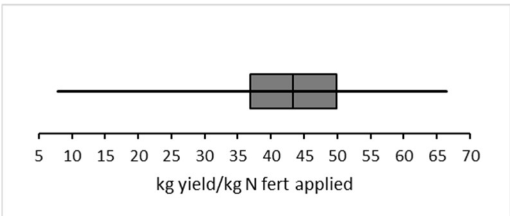
n = 827



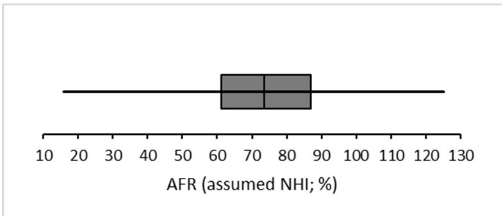
n = 550



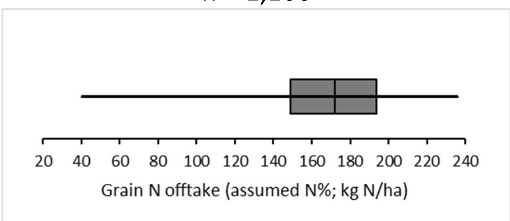
n = 460



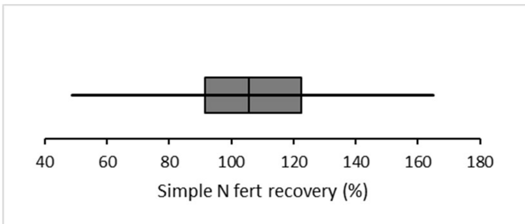
n = 1,166



n = 550



n = 2,158

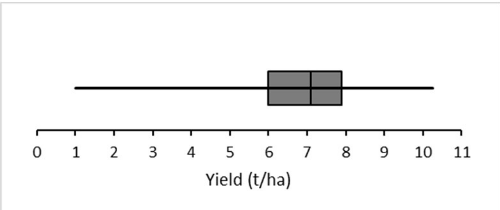


n = 578

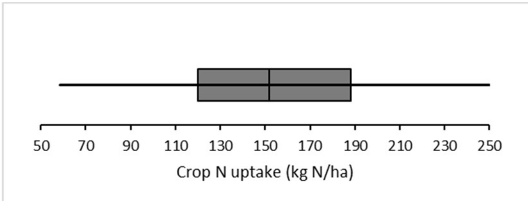
Appendix Table 11. Table showing median and range of data for N balances for winter wheat crops.

NUE metric	Quartile	Values
N balance for Grain N offtake; *grain N% assumed* (n=1,177)	Min	-189.43
	Lower quartile	21.05
	Median	50.59
	Upper quartile	76.13
	Max	125.25
N balance for Crop N offtake (n=581)	Min	-189.25
	Lower quartile	-32.88
	Median	2.89
	Upper quartile	30.95
	Max	86.94

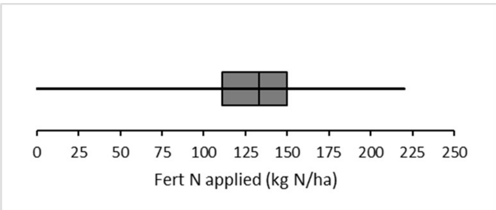
Appendix Table 12. Boxplots of calculated NUE metrics and related parameters for barley crops.



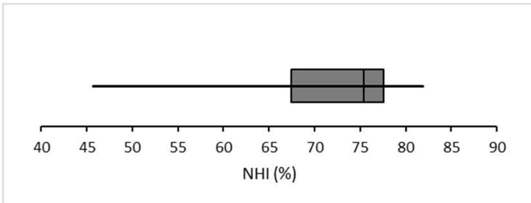
n = 570



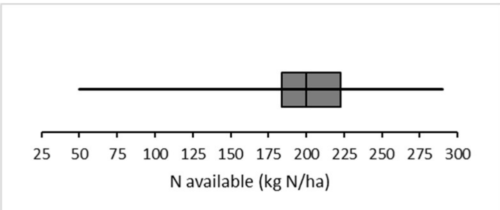
n = 90



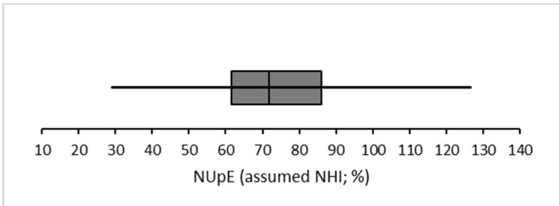
n = 302



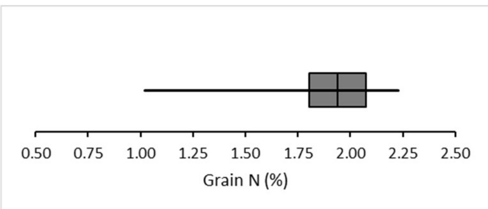
n = 90



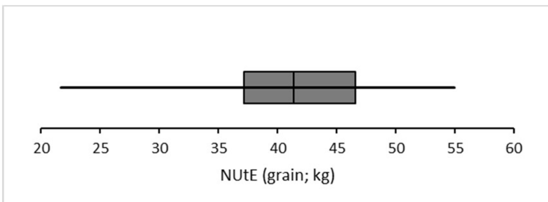
n = 132



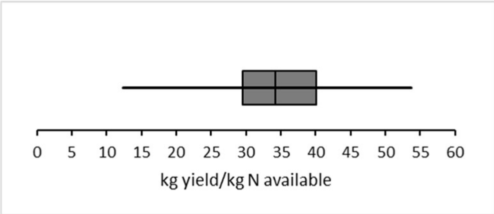
n = 132



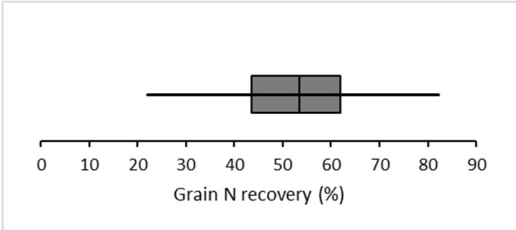
n = 498



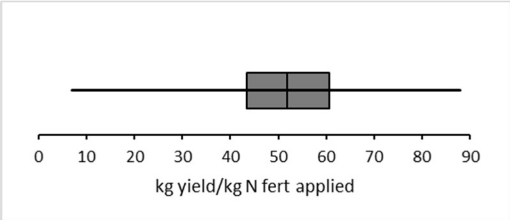
n = 90



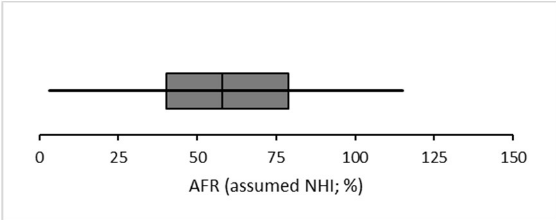
n = 132



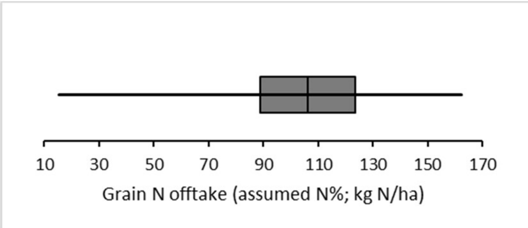
n = 77



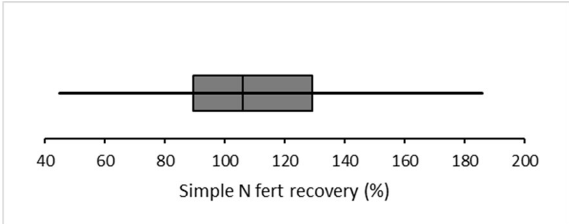
n = 279



n = 128



n = 570

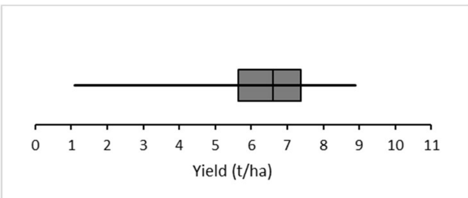


n = 74

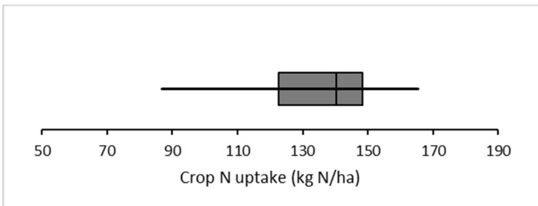
Appendix Table 13. Table showing median and range of data for N balances for barley crops.

NUE metric	Quartile	Values
N balance for Grain N offtake; *grain N% assumed* (n=283)	Min	-165.26
	Lower quartile	-0.99
	Median	25.26
	Upper quartile	43.14
	Max	85.34
N balance for Crop N offtake (n=75)	Min	-198.87
	Lower quartile	-28.52
	Median	-4.67
	Upper quartile	17.18
	Max	44.26

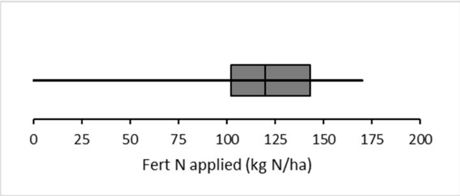
Appendix Table 14. Boxplots of calculated NUE metrics and related parameters for oat crops.



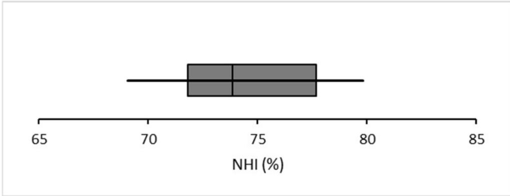
n = 113



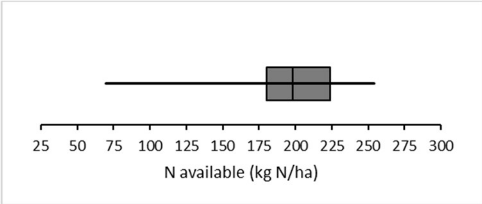
n = 14



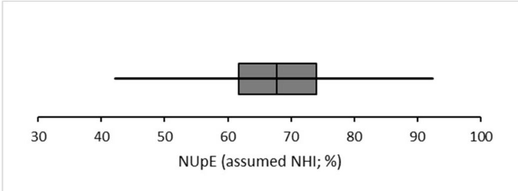
n = 68



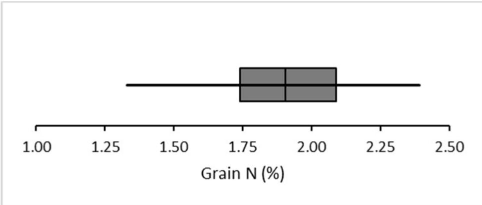
n = 14



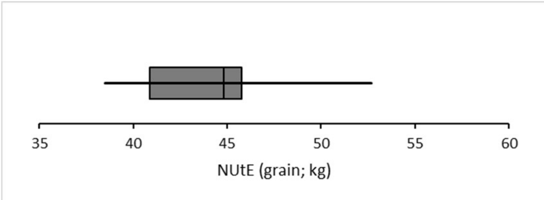
n = 32



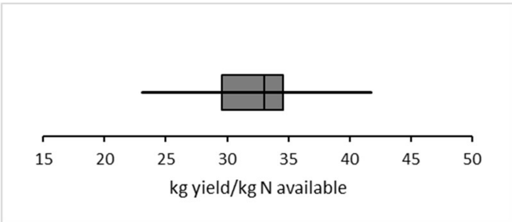
n = 32



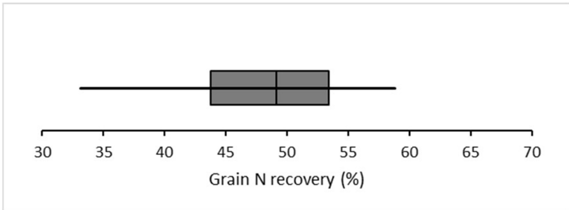
n = 70



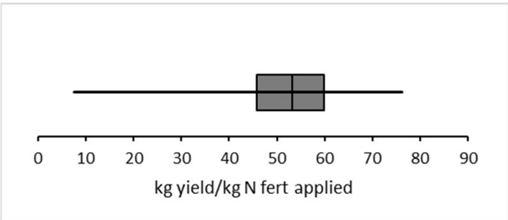
n = 14



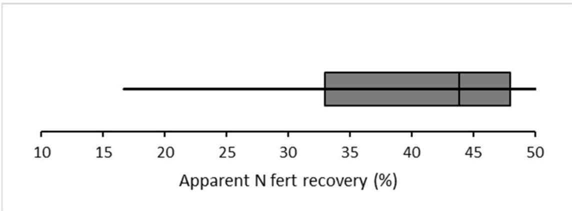
n = 32



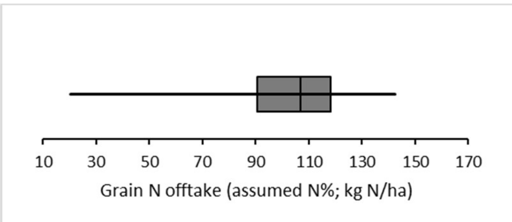
n = 15



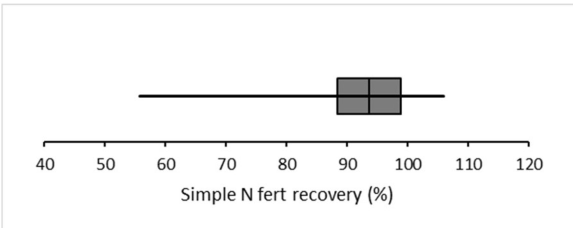
n = 66



n = 10



n = 113

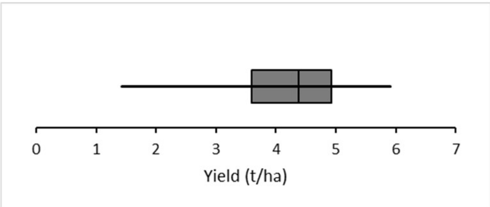


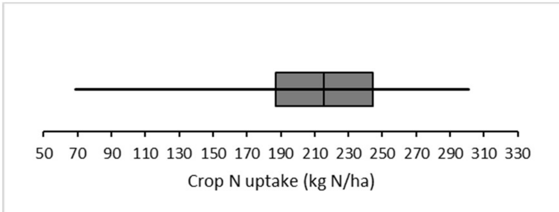
n = 11

Appendix Table 15. Table showing median and range of data for N balances for oat crops.

NUE metric	Quartile	Values
N balance for Grain N offtake (n=31)	Min	-96.68
	Lower quartile	-3.46
	Median	30.31
	Upper quartile	45.66
	Max	96.65
N balance for Crop N offtake; *NHI assumed* (n=11)	Min	-43.88
	Lower quartile	10.90
	Median	19.22
	Upper quartile	29.44
	Max	34.32

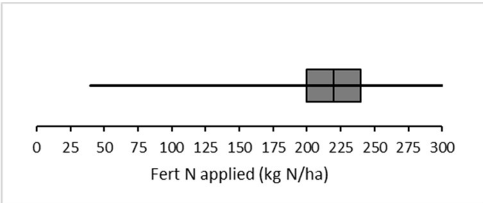
Appendix Table 16. Boxplots of calculated NUE metrics and related parameters for OSR crops.

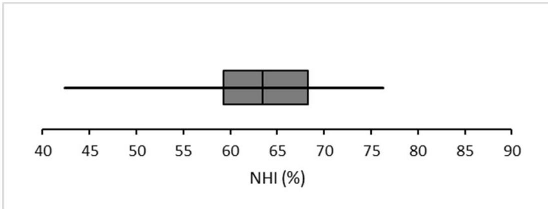




n = 321

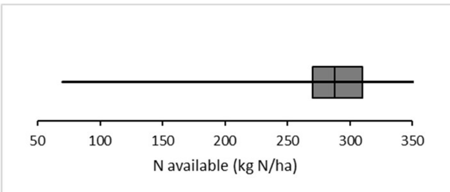
n = 143

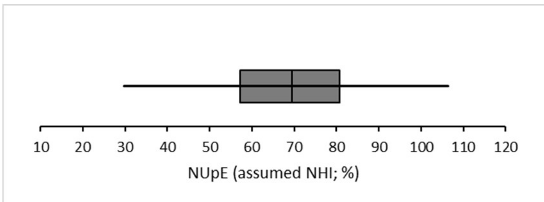




n = 188

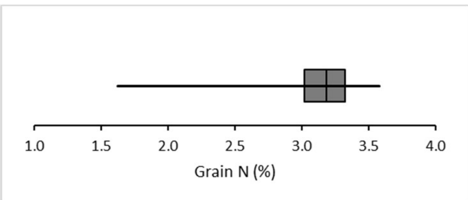
n = 143

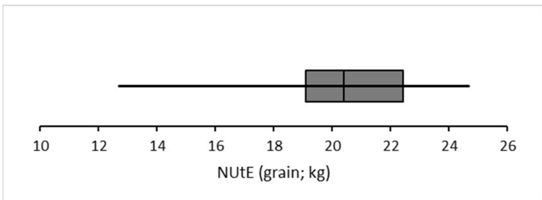




n = 143

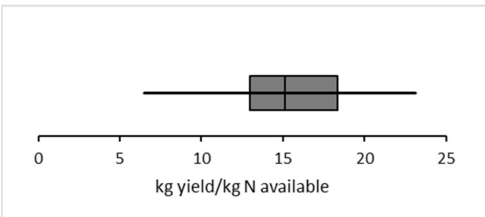
n = 136

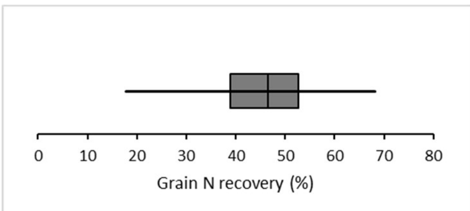




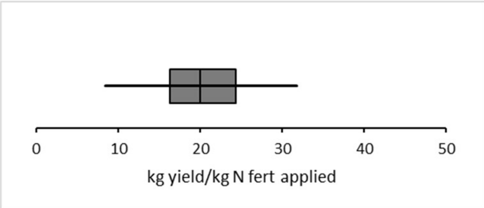
n = 241

n = 143

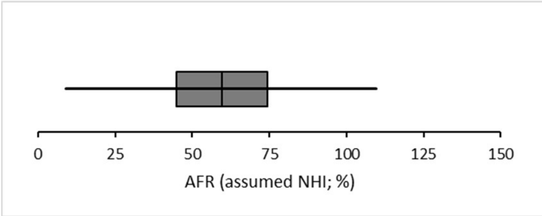




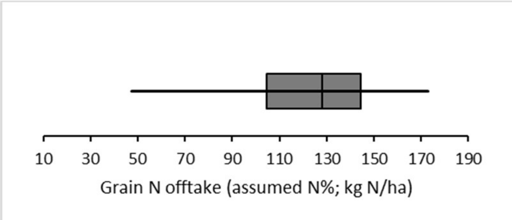
n = 138



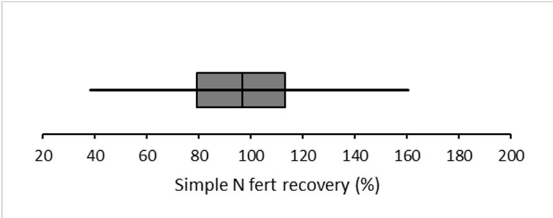
n = 111



n = 168



n = 135



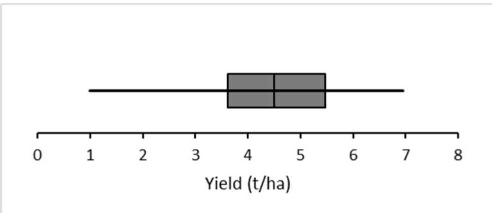
n = 277

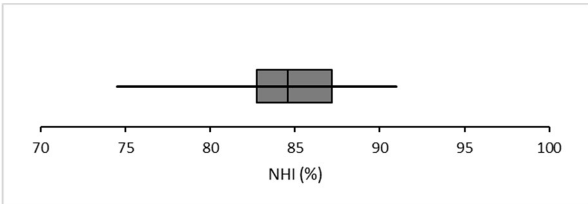
n = 100

Appendix Table 17. Table showing median and range of data for N balances for OSR crops.

NUE metric	Quartile	Values
N balance for Grain N offtake; *grain N% assumed* (n=169)	Min	-120.73
	Lower quartile	58.15
	Median	86.40
	Upper quartile	119.80
	Max	160.79
N balance for Crop N offtake; *NHI assumed* (n=126)	Min	-155.12
	Lower quartile	32.58
	Median	64.38
	Upper quartile	92.77
	Max	133.79

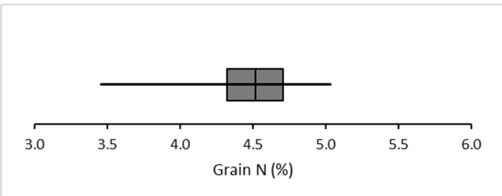
Appendix Table 18. Boxplots of calculated NUE metrics and related parameters for bean crops.

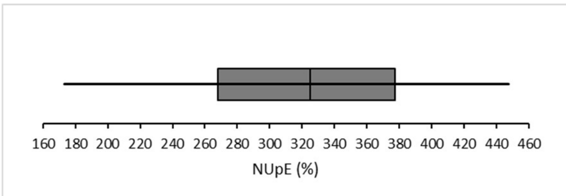




n = 146

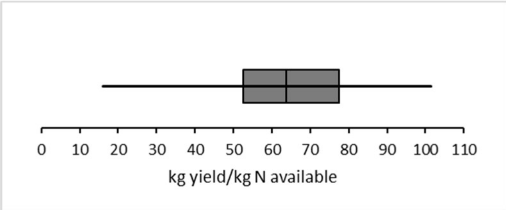
n = 33



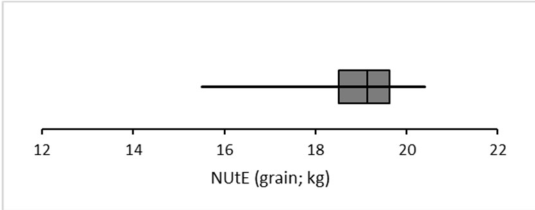


n = 125

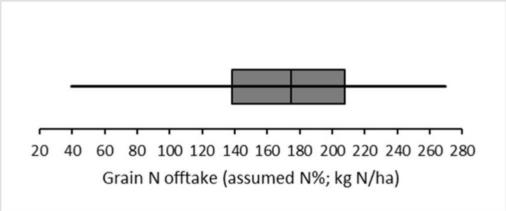
n = 28



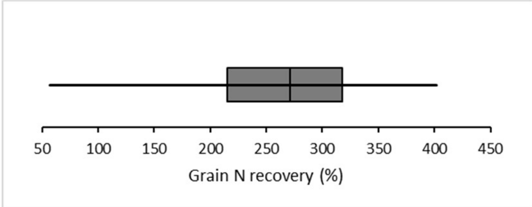
n = 80



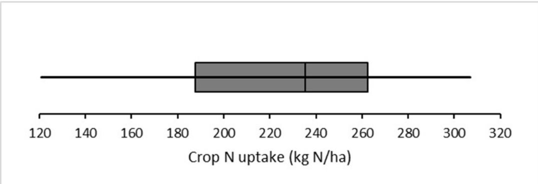
n = 33



n = 146

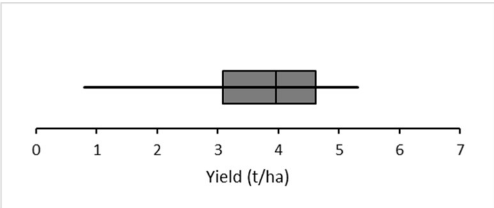


n = 65

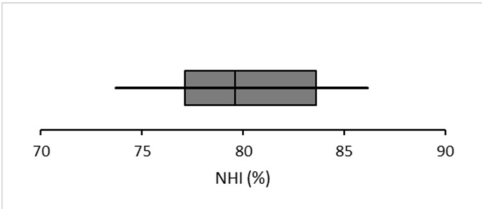


n = 33

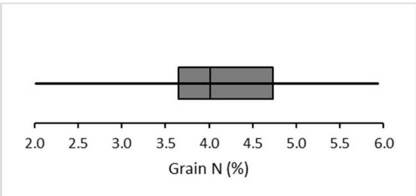
Appendix Table 19. Boxplots of calculated NUE metrics and related parameters for pea crops.



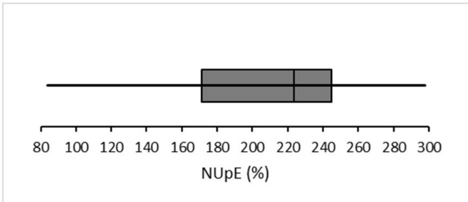
n = 84



n = 10



n = 66



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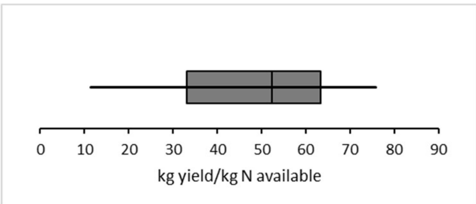
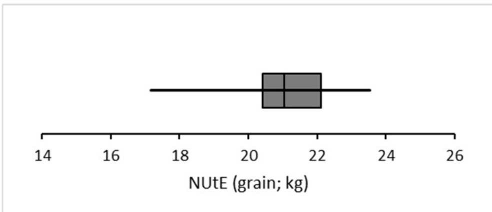


n = 48



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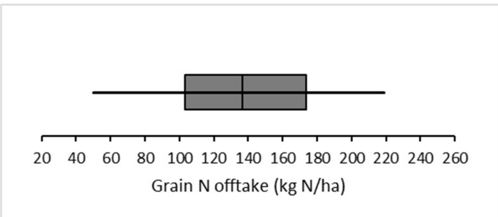
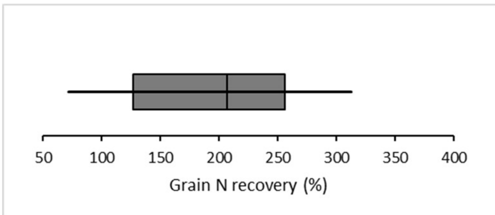
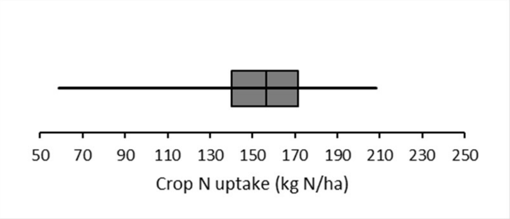


n = 65



n = 36



n = 10

REML analysis

Appendix Table 20. Associations between: N rate, N fertiliser type and the Number of N applications, and selected NUE metrics plus yield in barley. Significant associations are highlighted red (negative) or green (positive) for continuous variables. Associations with categorical fixed terms are detailed in text. Blank = none.

NUE metric /parameter	N rate	N type	No. N apps
Yield t/ha	+17 kg/ha yield per kg N		
1 Yield/N available	-0.083kg yield/kg N available per kg N		Association driven by high Digestate value
3a. Grain N offake assumed N%	Won't converge		
11b N Balance (assumed N%)	Won't converge		

Appendix Table 21. Associations between Manure: history, in rotation and type, and selected NUE metrics plus yield in barley. Associations with categorical fixed terms are detailed in text. Blank = none.

NUE metric /parameter	History	In rotation	Type
Yield t/ha			
1 Yield/N available			Association driven by very high 'Digestate' value
3a. Grain N offake assumed N%		Regular and Frequent categories highest. Significance driven by low 'unknown'	
11b N Balance (assumed N%)	Won't converge		

Appendix Table 22. Associations between Soil Texture, and selected NUE metrics plus yield. Associations with categorical fixed terms are detailed in text. Blank = none. NB REML would not run when organic matter, pH and nutrient indices were included (apart from with yield where there were no associations).

NUE metric /parameter	RB209 texture
Yield t/ha	
1 Yield/N available	Highest with light sands, lowest shallow
3a. Grain N offake assumed N%	Highest deep clays and Organic & peat. Lowest shallow
11b N Balance (assumed N%)	Shallow big positive value but shallow over chalk negative

Appendix Table 23. Associations between total rainfall during development phases: Foundation (Growth Stage 00 – 30), Construction (GS31 – 65), Production (GS65 – Harvest), and selected NUE metrics plus yield. Significant associations are highlighted red (negative) or green (positive) for continuous variables. Associations with categorical fixed terms are detailed in text. Blank = none.

NUE metric /parameter	Foundations	Construction	Production
Yield t/ha			
1 Yield/N available			-0.12 kg yield/kg N available per mm rain
3a. Grain N offake assumed N%	Won't converge		
11b N Balance (assumed N%)			

Appendix Table 24. Associations between: Variety type, Previous crop, and Grass history, and selected NUE metrics plus yield. Associations with categorical fixed terms are detailed in text. Blank = none. NB Grass history was examined but there were no significant associations. NB. There were no associations with residue fate.

NUE metric /parameter	Crop type	Previous crop	Grass history
Yield t/ha	Feed 1.5 t/ha higher than malting		Significant but no obvious trend
1 Yield/N available		Driven by very high value for grass/forage	
3a. Grain N offake assumed N%	Wouldn't converge		
11b N Balance (assumed N%)	Wouldn't converge		

Appendix Table 25. Associations between the number applications of: Plant growth regulator (PGR), Fungicides and Herbicides and selected NUE metrics plus yield. Significant associations are highlighted red (negative) or green (positive) for continuous variables.

NUE metric /parameter	PGRs	Fungicides	Herbicides
Yield t/ha	+0.92 t/ha per PGR application	+0.45 t/ha per Fungicide app.	
1 Yield/N available			
3a. Grain N offake assumed N%	Wouldn't converge		
11b N Balance (assumed N%)	Wouldn't converge		

Appendix Table 26. Associations between: Seed rate and cultivation method, and selected NUE metrics plus yield. Significant associations are highlighted red (negative) or green (positive) for continuous variables. Associations with categorical fixed terms are detailed in text. Blank = none.

NUE metric /parameter	Seed rate	Cultivation
Yield t/ha	-0.009 kg/ha per seed/m^2	Highest from plough based, lowest from direct drill
1 Yield/N available	Won't converge	Won't converge
3a. Grain N offake assumed N%		
11b N Balance (assumed N%)		