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Research Review 100

Impact of nutrient scenarios on the performance of cereals and oilseeds varieties (scoping review)

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CONTENTS

1. Abstract

Nitrogen (N) is a macronutrient essential for plant growth and of limited availability in most agro-ecosystems. Synthetic N fertilisers, which are applied to help meet crop demand, are expensive and can damage the environment. Levy payers want to understand how varieties perform under low N input systems. However, the current AHDB Recommended Lists (RL) testing system does not currently evaluate varieties at different N rates.

This project assessed whether there are significant differences in the performance of cereals and oilseeds varieties under varied N scenarios using available literature and datasets. The main evidence base was for winter wheat and oilseed rape (OSR); there were some studies on barley and oats, limited information on triticale but none for linseed and rye.

Evidence for differing relative variety performance at low N rates (variety x N rate interaction) was mixed and particularly limited in reports from UK trials. There was evidence that varieties bred in low-input environments, older varieties and landraces did perform relatively better at lower N inputs.

Although there was not conclusive evidence for current cereal varieties to perform better at lower N inputs, it would be beneficial to levy payers for AHDB to investigate the use of low N rates in variety testing. Therefore, we recommend that some RL trials include winter wheat varieties tested under two N levels: current RL protocol and a reduced N rate. In the short-term, this would aid levy payers in selecting current varieties suited to lower N input. In the longer term, this would stimulate breeders to start selecting in a low-N environment, or to submit varieties that have demonstrated nutrient use efficiency (NUE) and high-yield, low-optimum (HYLO) traits into the trials system where they might not previously have been tested. It was also noted at the stakeholder meeting that breeders need time to adapt and that a phased-approach may be more beneficial.

For OSR, trials are already challenged by weather and pest issues. Additionally, because of the nature of OSR, varieties often need differential and careful management. It has been raised by breeders that the nuances in management required if NUE information was included may not be easy for levy payers to take on board. Overall, it is concluded that OSR RL trials should not include differential N rates.

Recommended Lists review (2022–2023)

Typically, the main RL project runs in five-year phases, with a large-scale public review conducted during each project phase. The need for information on evidence of varietal responses under lower-input scenarios was identified as part of the RL 2022–2023 review, with this scoping review commissioned as part of follow-up activities.

2. Introduction

Nitrogen (N) is an essential macronutrient for crop growth, and it is limiting yield and quality in many agro-ecosystems. The lack of N forms readily accessible by plants such as nitrate, ammonium, urea or amino acids can be remedied by the application of synthetic N fertilisers. These are generated through the Haber-Bosch process that combine N_2, H_2 under high pressure and heat, together with an iron catalyst to produce NH_3. The process itself accounts for 1% of the global energy production. The application of synthetic N fertiliser has increased over the past century from about 10Tg year^{-1} in the 1960s to more than 100Tg year^{-1} in 2015 (Lu and Tian, 2017). Though the widespread application of N fertiliser has led to huge improvements in yield (together with concurrent improvement on crop genetics and agronomic practises), the process of applying synthetic N fertiliser is generally not efficient. Some of the N is lost to the environment, in the form of leaching in waterways and emission as gaseous N_2O (a highly potent greenhouse gas). Thus, there is a strong environmental incentive to reduce the amount of N applied on cropland and yet ensure sufficient yield production and good quality.

Reducing the N requirement for yield production has often been framed as the need to improve crops' N use efficiency (although there are different definitions, a common one for NUE is the ratio of grain produced per unit of N supplied). However, NUE has been reported to differ between crop types. For example, oilseed rape grown in the UK has been estimated to have a NUE of 10 kg seed DM kg N^{-1} compared with 21, 25 and 69 kg DM kg N^{-1} for spring malting barley, feed winter wheat and sugar beet respectively (Sylvester-Bradley and Kindred, 2009).

Following the invasion of Ukraine, there was a huge increase in the price of fertiliser; prices more than doubled but in 2023 returned to the 2021 levels (USDA). Farmers have also started to apply lower level of N fertiliser for varying reasons: to ensure that their production remain profitable; to align with regenerative agricultural practices; and for environmental benefits. However, there is no current official mechanism for providing information to farmers and agronomists on whether the crop varieties that they have selected would still perform well under lower N levels (and how this may change the management of said varieties). While trials conducted for the RL include treatments with and without fungicides as well as with or without PGR (plant growth regulator), there are no differential N treatments. The Recommended List (RL) system provides information on yield, quality, disease resistance and agronomic traits in recommended and descriptive lists with the purpose to provide an industry-wide perspective of the most appropriate varieties for different users across the industry. New verities entering the RL system must show a positive 'balance of features' (compared with varieties on the lists) to be added to the trials and be recommended. These features could include advantages in yield, pest or disease resistance, agronomic characteristics and quality characteristics (or a combination). The system currently follows 'RB209' guidance with the aim to ensure that yield is not limited by lack of nutrition. Rates for some trials are adjusted to meet specific quality targets, such as in milling wheat and malting barley. Currently, there are no criteria to look at the responsiveness of a given variety to nitrogen. This is also the case for protocols for the National Listing trials and widely spread amongst breeders' plots, though some breeders are starting to test under low N.

AHDB are currently reviewing the Recommended List testing system, and have had feedback from levy payers that they want to understand how varieties perform under low N input systems. However, a change in testing system would incur additional costs so it is important for AHDB to understand whether the additional information gained from a more complicated testing system would be of benefit to levy payers.

Therefore, the aim of the project was to provide evidence to inform AHDB's RL review by assessing whether there are significant varietal differences in cereal and oilseed performance under varied N scenarios using available literature and datasets.

To achieve this, we set out 4 objectives:

(1) Collate and review relevant reports/papers/datasets. Gather industry intelligence from breeders on further data sources via a stakeholder meeting.
(2) Summarise findings from unpublished NIAB trial data.
(3) Conduct a meta-analysis of data,
(4) Identify knowledge gaps and horizon scanning.

3. Materials and methods

3.1. Scoping review methodology

3.1.1. Grey literature review

An explanatory database was developed to tabulate the methodology and results from 'grey' literature relating to crop varietal differences in N use efficiency (NUE) metrics and/or changes in yield and grain protein ranking orders at different N rates. Here, 'grey' literature was defined as non-peer-reviewed sources and most commonly referred to AHDB and DEFRA project reports but also included information from industry partners. This review identified 16 relevant published project reports and one unpublished source from an industry partner assessing wheat, barley, oilseed rape, or oat responses in the UK. The CINTRIN project trials did include a few triticale varieties as control for high NUE.

3.1.2. Peer-reviewed literature review

Peer-reviewed publications were identified by searching using specific key word "wheat" (or other crop types including "oilseed rape", "barley" or "oat"), "N" "varieties" and identifying publications cited within the last 25 years. All publications report studies in the UK, France or Europe. An explanatory database was developed to tabulate the methodology and results from 'peer-reviewed' literature, as described above. No peer-reviewed publications were found for 'linseed', "triticale" or "rye" crop types. The relationship between root morphology and grain yield was not considered as part of the literature review with limited or no reference to root morphology reported in the reviewed grey and peer-reviewed literature.

4. Results

4.1. Lexicon of nomenclature of NUE indices

This review will assess varietal differences in a range of N use efficiency metrics (NUE). Baxter and Clarke (2022) defined several NUE metrics (Table 1) and concluded different NUE metrics are relevant in different contexts. Given an increasing number of farmers are interested in reducing N rates without compromising crop yields, *kg grain yield per kg N available* is the most appropriate metric to indicate efficiency of crop N to produce yield. Other NUE metrics relevant for farmers include *N removed in harvested grain (%)* to indicate efficiency of fertiliser to improve protein content, and *N balance for Grain N offtake (kg N ha^{-1})* to measure applied N leaching to the surrounding environment. Rothamsted Research (2020) defined other NUE metrics (Table 2) and used different nomenclature for the same calculations outlined by Baxter and Clarke (2022) (Table 1). Grain protein deviation (GDP) was also measured in other reports (Shewry *et al.* 2013; Shewry *et al.* 2020) and may be of particular interest to breeders screening for milling varieties. The current review identified *kg grain yield per kg N available* as the most common reported metric.

Table 1: NUE metrics identified by Baxter and Clarke (2022).

No.	NUE metric	Calculation	Units
1	kg grain yield per kg N available	kg grain yield / (soil N + N fertiliser)	kg kg^{-1}
2	kg grain yield per kg N fertiliser applied	kg grain yield / kg N fertiliser applied	kg kg^{-1}
3	Grain N offtake	DM yield x grain N%	kg N ha^{-1}
4	Total crop N uptake[1]	Grain N offtake + straw N (DM straw x straw N%)	kg N ha^{-1}
5	N harvest index (NHI)	Grain N offtake / Total crop N uptake	%
6	N uptake efficiency (NUpE)[2]	Total Crop N Uptake / (soil N + N fertiliser)	%
7	N utilisation efficiency (grain; NUtE)[3]	Grain yield (kg/ha) / Total crop N uptake	kg DM kg N^{-1}
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^{-1}
11a	N balance for Crop N offtake	N fertiliser applied - Crop N offtake	kg N ha^{-1}

[1] - Referred to as BioNUp in Rothamsted Research (2020).

[2] - Referred to as BioNUpE in Rothamsted Research (2020).

[3] - referred to as GrainNUtE in Rothamsted Research (2020).

Table 2: NUE indices identified by Rothamsted Research (2020).

Variable/Indices	Definition	Units	Calculation	Notes
Grain N Uptake	Grain N uptake	kg N ha^{-1}	Grain yield * grain N%	Here, uptake reflects content at final harvest, as no correction is made for losses e.g. by volatilization.
Straw N Uptake	Straw N uptake	kg N ha^{-1}	Straw yield * straw N%	As above
Grain NUE	Grain N use efficiency	kg grain per kg N available	BioNUpE * GrainNUtE	
GPD[1]	Grain protein deviation	%N	See text for details[1]	

[1] - GDP was calculated as follows: grain N% was regressed against grain yield, and then GPD calculated as the deviation (positive or negative) from the regression line for each point. Separate regressions were fitted for each level of N fertilization (Rothamsted Research, 2020).

The indices mentioned above describe the plant processes involved in taking up, assimilating and relocating N to the grain. Swarbreck *et al.* (2019) have discussed the advantages and drawbacks associated with such indices. Other indices have also been put forward that characterise the response and sensitivity to N such as the economic N optimum and the tolerance. The economic N optimum is described as the amount of N required to maximise profit (Sylvester-Bradley and Kindred, 2009). Applying less N than the economic optimum leads to profit loss because the potential yield is not realised. N application above the economic optimum also leads to profit loss, as the cost of applied fertiliser is greater than the revenue of additional produced yield and can also cause environmental issues. The economic N optimum is therefore determined by the value of fertiliser as well as grain produced, known as the breakeven ratio (BER). This quantifies the amount of grain (kg) required to pay for one kg of applied fertiliser. However, to calculate the economic N optimum requires field experiments to measure yield under 5 to 6 N levels, which can be intensive and costly to manage.

Indices that are taken from the abiotic stress response literature have been used to determine varietal differences in N response (Table 3). Bandyopadhyay *et al.* (2022) used a range of stress indices to investigate differences in N response amongst different accession of foxtail millet. In wheat, the tolerance index has been used to characterise new varieties in the French registration system since 2014 (CTPS and GEVES, 2017). For this purpose, the tolerance index is equal to the difference between yield under optimal N less the yield under N deficient overall divided by the yield under optimal N. Though not used in a UK context, the N tolerance should be of interest to farmers considering reducing N application rates.

Table 3: Stress indices as indicator of N response used in Bandyopadhyay *et al.* (2022).

Trait	Description	Adapted From
Tolerance index (TOL)	$Y_{HN}-Y_{LN}$	Rosielle and Hamblin (1981)
Mean Productivity Index (MPI)	$(Y_{LN}+Y_{HN})/2$	Hossain et al. (1990)
Geometric mean productivity (GMP)	$\sqrt{}(Y_{LN}*Y_{HN})$	Ramirez and Kelly (1998)
Stability index (SI)	Y_{LN}/Y_{HN}	Bouslama and Schapaugh (1984)
Stress Susceptibility Index (SSI)	$\{1-(Y_{LN}/Y_{HN})\}/\{1-(\text{mean } Y_{LN}/\text{ mean } Y_{HN})\}$	Rameeh (2015)
Nitrogen use efficiency (NUE grain)	Grain dry weight/ N supplied per plant	Moll et al.(1982)
Y_{LN}=Mean value in stress(N10/N25); Y_{HN}= Mean value in control(N100); Y_{LN} mean & Y_{HN} mean= average value of the trait in all genotypes at stress(N10/N25) and control(N100) conditions, respectively.		

4.2. Review of literature

4.2.1. Wheat

Here, we report evidence published in the literature assessing varietal differences in wheat performance under different N regimes over the past 25 years. We have focused on publications from the UK, France and Western Europe. Most reports focused on winter wheat, with less information available on spring wheat. In spring wheat, Murrinen *et al.* (2006) saw no improvement of NUE in 18 varieties bred between 1901 and 2000 and tested in Finland.

Foulkes *et al.* (1998), examined the performance of 27 winter wheat genotypes (introduced between 1969-1988) under a range of N applications from 0-300 kg ha^{-1} over 22 site and season combinations. The evidence suggested newer genotypes were less efficient in acquiring soil N under no supplementation from N fertiliser. However, Foulkes *et al.* (1998) concluded this has been compensated with a concurrent improvement in fertiliser recovery.

Barraclough *et al.* (2010) evaluated 39 elite commercial milling and feed cultivars, supplemented with five rates of N in the range of 0-350 kg ha^{-1} (in a 3-way split). Experiments were conducted over four years in multi-factorial field trials at Rothamsted Research (Southeast England). Using REML analysis they show a highly significant variety x N rate interaction for all variables tested (including grain yield, harvest index, grain N%, total N uptake, N harvest index). Overall, they show no correlation in the ranking of yield at 200 kg ha^{-1} and zero for total N-uptake, thus indicating a strong variety x N rate interaction.

Barraclough *et al.* (2014) evaluated 20 wheat (mostly winter wheat varieties) under low (no fertiliser addition) and high N levels (200 kg ha^{-1}) in southern England in the season 2004-2005. They reported the interaction between N rate and Genotype tended to be 'small and not significant', however, the ANOVA results were not stated.

Sylvester-Bradley and Kindred (2009) reviewed the progress towards improving the use of N fertilisers by winter wheat (and spring barley). They also reported differences in NUE (as kg dry matter per unit N available) amongst crop species, highlighting that triticale, rye, spring barley and winter oat tended to show greater NUE compared to winter wheat. The review focussed on wheat varieties introduced between 1977-2007 and their performance under varied N levels (generally 6 levels from 0 to 350 kg ha^{-1} so that economic N optima could be calculated). They reported that wheat yields at optimum fertiliser levels had increased by 0.55 t ha^{-1} per decade, from the late 1970s to the 2000s, whilst yields without N fertiliser improved by 0.21 t ha^{-1} per decade. Overall, they argued that "in order to elicit faster improvement in NUE on farms, breeding and variety testing should be conducted at some sites with more than one level of applied N, and that grain N%, N harvest index, and perhaps canopy N ratio (kg ha^{-1} green area) should be measured more widely." Similarly, Brancourt-Hulmel *et al.* (2005) argued that the indirect selection of lines under high N level was never as efficient as the direct selection of lines under low N for low N environments.

Cormier *et al.* (2013) tested 225 winter wheat varieties released between 1969 and 2010 (mostly released between 1985 and 2010) in Europe under two N rates in four experiments. They reported significant Genotype (G) x N rate interaction for grain yield, grain protein content and NUE. The year of registration had a significant effect on G x N rate interaction for yield and NUE. Modern varieties had a G x N rate interaction that increased yield in high N, with a corresponding decrease in low N. These G x N rate interactions could be explained by variation in quality classes (more recent varieties tended to be higher yielding but had lower grain protein content (GPC) and precocity (time needed to reach flowering). In a follow up study Mini *et al.* (2023) defined tolerance indices and identified specific QTL regions underpinning tolerance to low N.

Laperche *et al.* (2006) evaluated the performance of doubled haploid lines from a cross between Récital and Arche which showed a differential N response, under two N levels (optimal and 60-144 kg ha^{-1} less than optimal) at three sites over two years. Overall, there was a significant G x N rate interaction for grain yield, thousand kernel weight (TKW), grain number per m^{-2} and HI under all environments. Whilst there was no significant G x N rate interaction in one year at one site, this was significant in the rest.

Przystalski *et al.* (2008) assessed whether there is a need to set up a separate variety testing system for organic farming. They analysed barley, spring wheat, winter wheat, and winter triticale experiments conducted in Denmark, Sweden, the Netherlands, France, Switzerland, the UK and Germany. These were conducted over two to four years except for the Swedish Barley experiments which lasted 11 years. They found high genetic correlations for most traits between both organic and non-organic system. Despite this, the chances of agreement in observed ranking orders was moderate, suggesting that combining information from both organic and non-organic systems is beneficial.

This review identified ten relevant sources of 'grey' literature reporting N response experiments in winter and spring wheat. Morris *et al.* (2022) assessed three winter milling wheat varieties and reported no interaction between N rate and variety for grain protein. Similarly, Weightman *et al.* (2011) assessed two contemporary milling wheat varieties and reported no interaction between N rates and variety for N harvest index (NHI), total biomass or crop N uptake, as well as no consistent change in grain protein rankings across sites and seasons. A separate study evaluating five contemporary milling varieties and one feed variety at three N rates also reported no significant interaction between variety and N rates for yield or grain protein (Shewry *et al*., 2013).

However, separate analysis encompassing a range of UK milling and feed varieties as well as European commercial and hybrid varieties identified a significant interaction between N rate and variety for grain protein (Shewry *et al*., 2020). Specifically, two Group 1 varieties, two German low protein breadmaking varieties and one Danish variety were found to have significantly higher grain N content than the other 33 varieties tested and maintained performance at fertiliser rates below farm standard levels.

Other reports assessing varieties from a larger time period did present significant differences in NUE metrics and yield rankings between older and newer varieties (Sylvester-Bradley *et al*., 2008; Rothamsted Research, 2020). Experiments conducted by Rothamsted research from 2004 to 2019 assessed 43 varieties released between 1964 and 2016 at four different N rates and found yields significantly correlated with variety release date across all varieties and significantly correlated with NHI within UKFM Group 1 varieties (Rothamsted Research, 2020). Yield increases were primarily due to improvements in N uptake efficiency (NUpE) and N utilisation efficiency (NutE) at higher N rates. This caused newer varieties to yield more than older varieties at higher N rates, whilst also maintaining high grain protein content within milling varieties. Similar findings were reported from N response experiments ran from 2005-2007 assessing two contemporary and two older (~1980s) varieties (Sylvester-Bradley *et al*., 2008). Here, higher yielding modern varieties had increased NUpE, apparent fertiliser and N offtake, but not NutE, at higher N fertilisation rates compared with older varieties.

An experiment conducted at one Scottish site for one season showed that a blend of four modern varieties achieved a similar yield to a single modern variety at a 90 kg ha^{-1} lower optimum N rates (Gilchrist *et al*., 2012). Other unpublished data from Scottish Agronomy showed yield ranking orders for 10 modern varieties at two N rates were identical apart from one variety performing relatively worse at the reduced N rate (Scottish Agronomy, 2024). Here, the average decrease in yield was 0.15 t ha^{-1} when N rate was reduced by 36 kg ha^{-1} from a farm standard rate of 180 kg ha^{-1} This finding is similar to a previous AHDB review which reported a reduction in N by 30 kg ha^{-1} from optimum rates caused a ~0.2 t ha^{-1} yield reduction in cereal crops (Sylvester-Bradley and Kindred., 2021), suggesting reductions in N input rates will decrease crop production.

Previous reports have attempted to identify 'HYLO' varieties which can produce High Yields with Low N Optimum and represent an opportunity to reduce N fertilisation rates without compromising production (Sylvester-Bradley *et al.*, 2015; Ligeza *et al.*, 2017). Cross-site analysis conducted over three growing seasons assessed 21 varieties and identified a triticale variety (Grenado) and a Danish wheat variety (Mariboss) conforming to the HYLO type. These varieties were bred under low N conditions and also had low NHIs and were late to senesce, whilst modern UK wheat varieties commonly achieved high yields due to high N requirements. Sylvester-Bradley *et al.* (2015) also reported milling varieties had larger optimum N rates than all feed varieties despite similar yields, suggesting there is less scope to reduce input rates in milling varieties without reductions in grain protein and milling quality. Similarly, Ligeza *et al.* (2017) assessed 52 varieties at a single site for one season and identified three triticale varieties, two Danish varieties and one modern UK variety (Siskin) which conformed to the 'HYLO' type. These varieties also had low grain protein, suggesting this is an important trait for breeders to target to reduce N requirements, although statistical analysis was not present in this report, suggesting these findings were not conclusive.

Overall, there is strong evidence in the peer-review literature supporting varietal differences in winter wheat performance under different N regimes. However, reports from the grey literature consistently show that varieties released in a similar time period do not differ in metrics of NUE or yield and grain protein ranking orders, suggesting there is little scope for farmers to reduce applied N rates without reducing productivity with the current varieties. This is an important conclusion as feed variety selection should not change if farmers reduce N fertilisation rates to reduce farm-level environmental impacts. Further consideration should be given to farmers aiming to reduce N fertilisation rates when growing milling wheat varieties due to the negative effects on grain protein which may cause a crop to not meet milling specifications.

However, other reports suggest there is a historical basis for breeding to indirectly improve NUE metrics at higher N rates when targeting increased wheat yields. Whilst these improvements have led to increased optimum N rates and thus increased input rates and yields, there is no robust evidence in the grey literature to suggest modern domestic varieties can perform at lower fertilisation rates without compensatory losses in yields or milling qualities. Nonetheless, there are reports suggesting European markets (e.g. Denmark) have been able to produce 'HYLO' varieties capable of maintaining yields at relatively low N rates due to breeding the varieties at low N rates, but these varieties are not cultivated in the UK. Therefore, there is scope for UK breeders to investigate low N breeding programmes to screen for low grain protein varieties which can perform better at reduced N rates. There should also be strong interest in these varieties from farmers who want to reduce the carbon footprint of their wheat production.

4.2.2. Barley

This review identified six scientific papers and four AHDB reports assessing N response experiments in winter and spring barley. Sylvester-Bradley and Kindred (2009) assessed the N use efficiency (NUE) over multi-site experiments conducted in the UK between 2003 and 2007. In the 12 spring barley experiments that showed a response to N, optimal N rates related significantly to the optimum grain yield. Sylvester-Bradley and Kindred (2009) also reported that modern spring barley varieties significantly out-yielded the old varieties at all N levels, however, there was no significant difference between optima of modern and old spring barley varieties. Sylvester-Bradley and Kindred (2009) concluded that optimum N amounts for spring barley are clearly related to grain yield, but none was due to genotype.

In 2011, Bingham *et al.* carried out a retrospective analysis of the effects of nearly 75 years of breeding on the NUE of spring barley during the breeding period from 1931 to 2005. Bingham *et al.* (2011) selected 15 varieties, selected to be as genetically dissimilar as possible that were grown at three site-year combinations in NE of Scotland grown with zero or 110 kg N ha^{-1} supplied as ammonium nitrate. Averaged across sites and years, breeding was shown to increase yield and NUE (grain yield N supply) by 1% and 1.2% per year with significant variation found between genotypes in efficiencies of N uptake (NupE; N offtake per unit N supply) and N utilization ($NutE_g$, grain yield per unit N offtake). Bingham *et al.* (2011) concluded NUE was increased through improvements in N uptake and utilization efficiencies, and genotypic differences in NUE, and in particular $NutE_g$, were robust across environments (significant but small G × E interaction). The study identified genotypes that differ in both NupE and NutE and further investigation of the physiological mechanisms responsible was suggested by the authors (Bingham *et al.*, 2011).

A further study by Chappell *et al.* (2017) reported on field trials conducted over consecutive growing seasons from 2012 to 2014. Ten varieties (including a Scottish landrace, Scandinavian and UK recommended varieties) were studied each receiving a total of 65 kg N ha^{-1}. Chappell *et al.* (2017) concluded that there were significant interactions ($p < 0.001$) between variety and year in barley showing that some varieties performed better in some years. Chappell *et al*. (2017) commented that variations in yield between varieties may result from varietal differences in ability to adapt to seasonal variations in weather variables.

A Swedish study undertook field experiments between 1993 and 1994 at three locations (Oscarsson *et al*., 1998). These investigated 10 barley cultivars, fertilised with three N rates of 45, 90 or 135 kg ha^{-1}. The interaction between predetermined and environmental factors were suggested to effect the yield and quality of barley. ANOVA tests showed that the interactions N rate x cultivar and N rate x environment affected the yield significantly but that the N rate factor did not. A Finish study by Muurinen *et al.* (2006) examined the differences in NUE, defined as the crop's ability to produce yield with one available N unit, among spring cereal cultivars, and to determine the achievements of plant breeding in NUE under northern European growing conditions. The study examined 11 spring barley cultivars, grown in 2003 and 2004, that received 70 kg N ha^{-1}. Muurinen *et al.* (2006) concluded that there was no clear trend of NUE and year of release of cultivars in two-row spring barley, probably because breeding for malting barley involves consistent selection for low-protein cultivars. A Danish study (Ortiz *et al.*, 2002) conducted between 1987 and 1989 across the Nordic countries examined 119 cultivars (including 2-row and 6-row spring barleys) using ten agronomic characteristics (including yield) to develop a phenotypic diversity index (PDI). A PDI between each pair of accessions was calculated as the difference between the phenotypes of each characteristic divided by the respective range. The use of a PDI indicated that 6-row germplasm may be clustered according to their geographical origin or decade of release, but this was not observed in 2-row barley germplasm (Ortiz *et al.*, 2002). Detailed PDI by cultivar was not examined to explore genotypic variation at this level, only among breeding pools.

Gilchrist *et al.* (2012) assessed separately two modern spring barley varieties and two modern winter barley varieties in experiments from 2007-2009 and reported no consistent changes in yield or grain N ranking orders across six application rates. Other reports assessed a broader range of varieties from different time periods and observed significant increases in yield (Sylvester-Bradley *et al.*, 2008; Kendall *et al.*, 2017; Kendall *et al.*, 2021.). For example, multi-site experiments conducted from 2005-2007 at six N fertiliser rates assessed two contemporary spring barley varieties with two older varieties from the 1970s and observed significantly greater yields in contemporary varieties despite similar optimum N rates (Sylvester-Bradley *et al.*, 2008). Contemporary varieties also achieved significantly lower grain N content then older varieties at optimum N rates, suggesting the NUE (measured as kg of grain yield formed per kg of soil and fertiliser N) was greater in newer varieties. This report also presented lower optimum N rates and similar yields for malting varieties compared with feed varieties, likely due to improved recovery of soil N. However, overall NUE was not significantly different between malting and feed varieties as improved NUtE for malting varieties was compensated by reduced NUpE (Sylvester-Bradley *et al.*, 2008).

A more recent report assessed seven old and modern winter barley varieties at six fertilisation rates and reported significant increases in yields and optimum rates in modern varieties (Kendall *et al.*, 2017). Similar to wheat, yield increases were driven by significantly improved fertiliser recovery, NUpE and NutE for modern varieties at higher N rates. This suggests there is scope for breeding to improve NUE metrics, but this has not been realised at reduced N rates. Comparable findings were reported from multi-site and multi-year spring barley experiments assessing three modern varieties and one older variety (Kendall *et al.*, 2021). Here, modern varieties yielded significantly more than the older variety at similar optimum N rates and had a significantly higher NHI. However, variety did not affect NUpE, NutE, total crop N uptake, NUE, or apparent fertiliser recovery, possibly reflecting the small number of varieties tested. No consistent changes in yield or grain N content rankings were observed across sites and seasons and Kendall *et al.* (2021) concluded the yield differences between varieties at optimum N rates (~0.5 t ha^{-1}) were marginal compared with yield differences between sites (> 5 t ha^{-1}).

Overall, there is some evidence that breeders have improved different NUE metrics for barley which has increased yields and N fertiliser rates and decreased grain N content. There is little evidence to suggest different contemporary barley varieties can maintain productivity at lower N rates, or that yield ranking changes can be observed consistently across different sites and seasons.

4.2.3. Oilseed rape

The use of inorganic Nitrogen (N) led to a dramatic improvement in yields to the oilseed rape (Brassica napus) crop in the mid-twentieth century. Worldwide, the use of N fertilisers increased by 430 % from 1965 to 1998 (Mosier, 2002) and new varieties were selected for their ability to respond to high N inputs and in particular for their improved resistance to lodging. However, massive fertilisation has major environmental drawbacks, with nitrate leaching and greenhouse gas emissions.

In recent years, the concept of the efficiency of N use has become much more important as researchers have been looking at the complex issue of how oilseed rape plants deliver seed yield from available N.

Although less investigated in peer reviewed papers, it is widely accepted that the oilseed rape canopy in early spring will contain around 50 kg ha^{-1} N per unit of GAI which growers are encouraged to exploit. However, there is little information relating to any potential varietal differences.

NUE is an important target because it increases profitability, either through greater yields or reduced fertiliser costs. Improving NUE will also reduce the greenhouse gas (GHG) emissions associated with the production of each kg of yield as it has been estimated that N fertiliser accounts for 79% of the GHGs associated with the production of oilseed rape (Brassica napus L.) in the UK (Mahmuti *et al*., 2009). From a grower's perspective with the increased costs of applying fertiliser, an understanding of how best to exploit the genetic potential of different cultivars would be very useful.

This is because the process of turning available N into seed yield in oilseed rape is very complex and includes traits related to NUpE (e.g., rooting traits, duration of N uptake, total N accumulated during vegetative growth) as well as NUtE (e.g., N remobilisation during leaf senescence, increased harvest index). The final seed yield is also complex due to the potential of oilseed rape to branch after flowering which enables the crop to use one yield component to compensate for limitations in another one. As a consequence, a given final yield can result from different combinations of yield components (number of plants per m^2, number of pods per plant, seed weight, seed quality) (Diepenbrock 2000). All these components are impacted by developmental traits (flowering time, seed filling duration), and environmental conditions (climatic conditions, water and fertiliser availability).

Fabian and Hosrt (2016) carried out a detailed study of two varieties to assess N remobilisation in OSR. The two varieties tested were Capitol and Apex as these had been reported as differing in N efficiency. Fabian and Horst (2016) reported under no N application, Apex reached a significantly higher grain yield compared to Capitol leading to a significant cultivar * N interaction. In conclusion, the previously reported higher N efficiency of Apex compared to Capitol could be confirmed.

Ulas *et al.* (2013) assessed a broader range of varieties, including Apex and Capitol and reported the N-efficient cultivar Apex had a significantly higher yield than the other cultivars without N fertilisation. At an intermediate N supply (120 kg ha^{-1}) both Apex and Bristol had higher yields than Lirajet and Capitol. At the highest N rate (240 kg ha^{-1}) Bristol significantly out-yielded the other cultivars and can thus be designated as a N-responsive cultivar.

Berry and Spink (2009) compared two contemporary varieties at seven N rates in a three-year experiment and reported no interaction between variety and N rate for yield, oil content, crop N uptake or crop height. Another multi-site and season report comparing a standard height variety with a semi-dwarf variety also found no differences in N uptake, N offtake, total biomass or residual N (Berry *et al.*, 2012). Although the semi-dwarf variety produced significantly more seeds, a compensatory reduction in thousand seed weight resulted in overall similar yields between varieties and no consistent changes in yield ranking orders. A further report assessed a wide range of varieties to identify crop traits associated with high yield under low N fertilisation (Berry *et al*., 2011). Here, significant interactions were presented between variety and N supply for yield, suggesting yield ranking orders did change between N rates. Post-flowering N uptake was presented as the most important trait indicating high yield under low N rates, but other traits include seeds/m^2 low seed N content, tall stature, and high remobilisation of stem N to seeds and pods (Berry *et al*., 2011). Furthermore, optimum N rates were reported to vary by >100 kg ha^{-1} and NUE (measured as kg of seed yield per kg of N fertiliser) varied by 30% between elite UK varieties, suggesting there is scope to select varieties to perform well under reduced N fertilisation.

However, a subsequent report that assessed 21 varieties to identify ‘HYLO’ oilseed rape varieties reported no consistent interaction between variety and N rates across four sites (Sylvester-Bradley *et al*., 2015). Similar to wheat and barley, gross output was positively correlated with year of introduction and a significant effect was reported with variety, but no differences were found across sites for optimum N rates or gross output between modern and old varieties, or open pollinated and hybrid varieties. This suggests OSR breeding has improved NUE in modern varieties, but yield losses are still expected when sub-optimal N rates are applied. Therefore, no varieties were identified as conforming to the 'HYLO' type and no consistent differences in gross output ranking orders were observed across sites and seasons.

Varieties that can maintain “high yield” whilst requiring “low” N rates are generally known as ‘HYLO’ varieties. As described above, the fact that the reasons for the difference in behaviour are so complex, much of the work on this subject has been targeted at identifying the reasons for this difference and much of the work has involved the use of small numbers of varieties known as “N efficient” or “N inefficient” with a view to study where or when the differences occur. Much of this work was carried out in Germany around 2010-12. There are cultivars with the capacity to increase yield when N supply is increased, which are called N responders (Gerloff 1977). Since N responsive cultivars are not necessarily N-efficient, N efficiency and N responsiveness should be investigated separately.

Stahl *et al. (*2017) argued that direct selection for yield and seed oil concentration leads not only to a yield gain in highly fertilised environments, but also to a selection of genotypes with superior performance in low N-input systems. Thus, genetic improvement increases NUE in oilseed rape and reduces the reliance on fertiliser inputs per unit seed produced. Therefore, yield improvement should play a predominant role in strategies toward GHG emission, as the new higher yielding varieties do not demand more N than is currently considered the optimal. However, much of the peer reviewed literature looks at the possibilities of reducing the N inputs whilst maintaining a suitable gross margin.

In OSR, it is generally accepted that the interaction between variety and N supply for yield demonstrates that variety rankings for yield measured under high N supply, as used in RL trials, are not necessarily a good predictor of yield rankings under low N supply.

Storer *et al*. (2018) suggest that methods of rapidly identifying breeding lines with lower N requirement are required. One solution would be to include a low N environment within the breeding programmes as it has been illustrated that varieties with a greater yield at low N are likely to have a greater NUE at the economic N fertiliser application rate through achieving a similar yield with a lower economic N rate (Sylvester Bradley and Kindred, 2009). Another solution is to identify traits which indicate high yield performance in a low N environment, but which are exhibited in higher N environments typically used within breeding and testing systems which clearly are complicated.

The work went on to conclude: Yield must be measured at sub-optimal and super-optimal N rates in order to identify HYLO type varieties. Yield measurements at low N are insufficient to identify HYLO varieties because this measurement does not explain the rate of yield response to applied N fertiliser or the yield at high N rate. Thus, the aim of identifying HYLO varieties necessitates the assessment of optimum N rate at a range of N levels. It therefore seems likely that the best approach for measuring varietal differences in Optimum N regime's (Nopt) will be to develop new experimental approaches for measuring yield at more than one N level.

It is again noted here that much of the work carried out has been on a limited number of N rates (Schulte auf'm Erley *et al.*, 2007; Bouchet *et al.*, 2014), and thus the optimum N rate cannot be calculated and identification of HYLO varieties is not possible.

Schulte auf'm Erley *et al.* (2011) appears to be the first to measure NUE at the optimum N rate for a substantial number of oilseed rape varieties. The results illustrate that elite variety yield rankings commonly change between N fertiliser rates, and it is therefore important if reporting NUE, to measure NUE at the relevant optimum N regime for that variety. It was noted that given the prospects for substantially reducing the N requirement of high yielding oilseed rape varieties, the next step is to consider how plant breeders and variety testers can efficiently develop these types of variety.

Greatest progress will be made by developing varieties with high yield and low Nopt (HYLO) (Kindred and Sylvester-Bradley, 2010). This accounts for both economically optimum fertiliser N rate and yield at the optimum N rate, which are likely to be key drivers of variety uptake by industry. The identification of HYLO varieties cannot be made solely on the basis of NUE as it is possible to get a high NUE with a low yielding crop which may not be economic. In order to identify HYLO varieties, each variety must be grown at several N fertiliser rates in order to measure the Nopt. Generally, there are differences in the NUE of oilseed rape varieties which is demonstrated when varieties are grown in sub optimal N conditions. However, these differences are generally masked when the N supply is not limiting.

4.2.4. Oats

This review evaluated five peer reviewed papers and two AHDB reports assessing N response experiments for winter and spring oat varieties. Givens *et al.* (2003) reported on the effect of variety, N fertiliser and various agronomic factors in winter oats over two seasons and three sites across England in 1994 and 1995. At each site, crops were sown on two dates, one in September and one in October, and all crops were grown with the application of either zero or optimum fertiliser N (80 to 140 kg ha^{-1}). The results indicated that variety and factors contained within the site and year effect had the greatest influence on the chemical analysis and nutritive value of oats, followed by N fertiliser treatment. This study did not directly look at yield response to N and therefore no comment can be made on whether genotype is responsive to N rates in oats.

A further study on N response in two winter oat varieties was reported by Chalmers *et al.* (1998) which investigated N doses between 80 and 240 kg ha^{-1}. There was no mention in the report to differences in yield or grain N response between varieties tested at their respective N doses. However, grain N concentrations increased significantly with applied N (Chalmers *et al*., 1998).

Six spring oat varieties were studied across three consecutive growing seasons (2012 to 2014) by Chappell *et al*. (2017), using a randomised block design with five replicates. Fertiliser was applied at planting at a rate of 50-60 kg N ha^{-1}. Data was analysed by two-way ANOVA with variety and year as treatment factors. Chappell *et a*l. (2017) concluded that there were significant interactions ($p < 0.001$) in yield between variety and year for oats showing that some varieties performed better in some years than others suggesting that variations in yield between varieties may result from varietal differences in ability to adapt to seasonal variations.

Buerstmayr *et al*. (2007) carried out a series of four field trials in Austria and Germany in 2002 evaluating 120 oat genotypes of global origin for agronomic and grain quality characters. Analysis of variance for all traits indicated highly significant variation among genotypes within each environment and for mean performance across environments. The highest yielding entries were cultivars from European breeding programs. It is not clear from this study whether cultivars released in a similar time period do differ in metrics of NUE or yield ranking orders.

Muurinen *et al*. (2006) studied 18 cultivars of spring oats released from 1922 to 2002. Cultivars were sown in 2003 and 2004 in a split-plot arrangement in a randomized complete block design with three replicates. N dose was 70 kg ha^{-1} and applied as ammonium nitrate. There were no clear differences in NUE among modern spring oat cultivars. However, there were significant NUE improvements in oat cultivars across time. The study revealed that most breeding effects on NUE were associated with changes in N uptake efficiency (Muurinen *et al.*, 2006).

Howarth *et al.* (2020) reported varietal responses from a single site in 2014 and 2016 assessing six N rates. Although the 2014 experiment reported significant interactions between N rate and variety for yield, total N uptake, NUE, and NUtE, these findings were predominantly caused by the presence of an older variety. Whilst the older variety performed relatively worse at higher N rates, performance of contemporary varieties was consistent across N rates (Howarth *et al*., 2020). The 2016 experiment assessed three modern varieties and reported no interaction between varieties and N rate for yield or NUE, but did report a significant effect on NUtE due to varietal performance variation within the 0-60 kg ha^{-1} range of N fertiliser. A 2022 report compared three spring and three winter oat modern varieties separately in experiments from 2019 to 2021 across multiple sites and found significant variation in responses between sites (Clarke *et al*., 2022.). Although some sites reported significant interactions between N rate and variety for yield, no consistent effects or changes in yield ranking orders were present across sites. Similarly, effects on NUE metrics including apparent fertiliser recovery, crop N uptake and NHI, were inconsistent between replicates.

Overall, this analysis suggests modern oat varieties do not consistently change in yield ranking orders and effects on NUE metrics are negligible or inconsistent between sites. However, as with wheat, barley and OSR there is some evidence that modern varieties have improved NUE at higher N rates, compared with older varieties, which has increased yields.

4.3. Summary findings from NIAB's unpublished trial data

NIAB (NIAB, 2014) carried out a series of winter wheat experiments run over three sites across England between 2011 and 2013 assessed the relative yields of sixteen winter wheat varieties grown under standard and reduced N doses (ranging between 100 and 213 kg N ha^{-1}).

There were a number of varieties that performed relatively well under the reduced N input (Figure 1). Varieties twelve to sixteen, all consistently outperformed the trial average. Variety 16, on average (over the nine trials in the series) outperformed the overall trial average by nearly 0.5 t ha^{-1}. Conversely varieties one to four, underperformed the trial average by over 0.25 t ha^{-1} over the nine trial series.

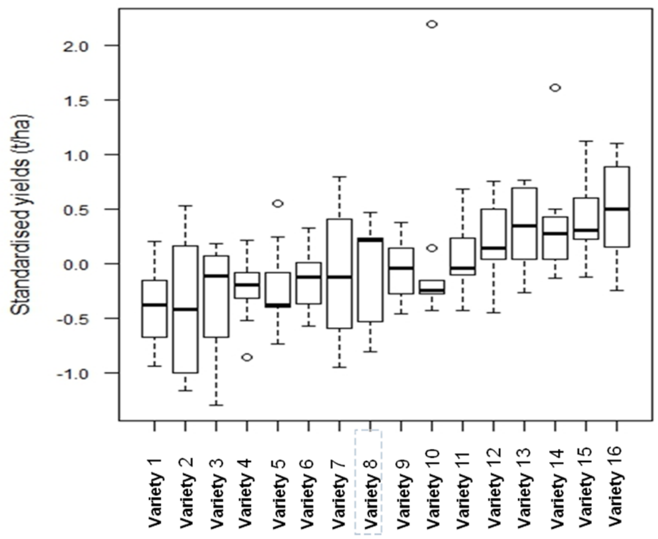

Figure 1: A series of box-plots summarising the relative performance of 16 wheat varieties under reduced N fertiliser input (NIAB, 2014). The yield for each variety is 'standardised' and shown as the deviation from the trial average (a value of Zero represents the trial average yield). Varieties are arranged in order of increased mean standardised yield.

A series of box-plots summarising the increases in crop yield observed in response to additional N fertiliser application is shown in Figure 2. The bars represent the range of responses observed for each variety over all nine trials in the series. Varieties are arranged in ascending order of the median percentage yield response.

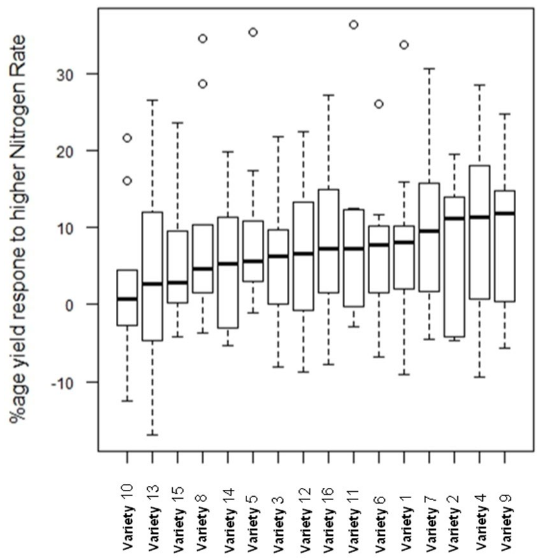

Figure 2: A series of box-plots summarising the increases in crop yield observed in response to additional N fertiliser application (NIAB, 2014). The bars represent the range of responses observed for each variety over all 9 trials in the series. Varieties are arranged in ascending order of the median percentage yield response.

It is interesting to note that those varieties that performed relatively well under the lower N fertiliser input were not necessarily those with the highest yields at the standard (higher) N fertiliser input, and hence the different rank order. There is, however, a broad pattern that the best response to increased N fertiliser rate was observed where the yield under low N was lowest.

There was some consistency across the sites and years in the varieties that appear at the top or bottom of the responses; Varieties ten and fifteen tended to show little response to higher N, whilst variety seven showed a higher response. The responsiveness to the higher fertiliser application was subject to considerable variation across the nine trials of the series. It appeared that the performance of the varieties was more variable, and therefore, the choice of variety for cultivation under reduced N input would become more important.

Table 4 shows the percentage yield response to higher nitrogen dose, across three sites. Overall, differences amongst varieties were apparent with a mean yield response of 3-4% increase in yield under high N (e.g. varieties 12 and 14) whilst for others the increase in yield under high N it is closer to 10% e.g. varieties 1, 3, 5, 6.7 and 11). The data also suggest that site (soil type) would affect the responsiveness under higher nitrogen dose; with site 2 typically showing a higher response compared to site 1 and 3. Of the varieties, variety 7 stands out as showing a large response to, and therefore requirement for,higher N doses across all sites. Conversely, variety 13 and variety 15 were fairly consistent in showing a smaller response to extra N.

Table 4: Percentage yield response to higher N dose, 16 varieties, three sites, three-year mean.

Variety	Site 1	Site 2	Site 3	Mean
Variety 1	2.8	13.6	6.5	9.5
Variety 2	7.0	9.8	6.6	7.7
Variety 3	4.0	13.0	2.6	7.6
Variety 4	5.9	15.6	7.1	9.3
Variety 5	3.2	18.6	6.6	9.5
Variety 6	5.5	10.3	5.7	9.9
Variety 7	7.3	14.0	11.1	10.8
Variety 8	4.9	19.9	4.8	8.9
Variety 9	5.4	15.4	7.0	5.8
Variety 10	-2.8	11.5	0.3	7.8
Variety 11	6.5	15.3	4.9	9.5
Variety 12	3.0	9.8	6.4	3.7
Variety 13	3.3	9.2	-1.4	6.2
Variety 14	0.8	10.8	5.8	3.0
Variety 15	1.6	14.3	2.8	7.2
Variety 16	9.6	11.5	2.0	6.4

Previous data from field trials carried out by The Arable Group (TAG) between 1999 and 2009 looked at a total of 23 winter wheat varieties across 18 sites. N rates applied ranged from zero to 340 kg ha^{-1}, although this varied between sites. Data was used in an HGCA research review looking at better estimation of soil N use efficiency by cereals and oilseed rape. It therefore did not include detail on the variety component except for a statement in the conclusion reporting that a comparison of N uptake for past and recent winter cereal trials did not reveal a difference in efficiency of SMN use between older and more modern cereal cultivars (Knight et al, 2008).

4.4. Analysis of compiled data

Datasets were identified as being suitable for a meta-analysis. These included: (1) the WGIN dataset (already mentioned above) where a total of 45 winter wheat varieties as well as breeding lines were tested under 4 N rates (0, 100, 200 and 350 kg N ha^{-1}, with 50 kg N ha^{-1} tested in 2004 only) from 2004 and 2019; (2) the CINTRIN dataset where 52 winter wheat varieties as well as breeding lines and 3 triticale varieties were tested under 6 N rates (0, 70, 140, 210, 280 and 350 kg N ha^{-1}) for 2 seasons (harvest 2017 and 2018); and (3) a NIAB dataset where 21 commercial varieties were tested between 1999 and 2009 in a series of field trials with a range of N rate (from 0 to 380 kg N ha^{-1}). Each dataset was analysed separately (CINTRIN 2017 and CINTRIN 2018 were also analysed separately) using REML. The mean yield value was obtained for each variety, year and N treatment combination. Results were then combined, with each result weighted using the inverse of the standard error for each trial (this enabled to weight the result of each trial based on the variability of these). A second REML analysis was then conducted using the weighted mean. Overall, there was a significant interaction between varieties and N ($p < 0.01$).

5. Discussion

In this report, we set out **to provide evidence to inform AHDB's RL review by assessing whether there are significant varietal differences in cereal and oilseed performance under varied N scenarios using available literature and datasets.** To achieve this, we discussed the different NUE indices used, including indices that relate to the N response or tolerance rather than N processes. We reviewed the grey and academic literature for wheat, barley, oilseed rape and oats but found no peer-reviewed reports for triticale, rye and linseed.

There were many NUE metrics identified, differing in their suitability to answer contrasting questions. However, the most commonly used NUE metric (kg grain / kg N available) is often of limited use as it reflects yield measured at a specific N rate. The best way to assess varietal differences in this NUE measure is to calculate NUE at the optimum N rate. This is rarely done, but the method was used in the HYLO project (Sylvester-Bradley *et al*., 2015).

The evidence for interactions between modern varieties and N rate for yield was mixed. Evidence from the grey literature found NUE metrics, yield and grain protein ranking orders did not consistently change for UK cereal crops when experiments were run across multiple seasons/sites and varieties were from similar time periods and variety groupings. However, unpublished NIAB winter wheat field trials, completed over three seasons suggested varietal responses to N fertiliser change the rank order under lower N doses compared to high N doses. There was more evidence of significant variety x N rate interactions in the peer-reviewed literature, but this was often driven by the inclusion of older varieties or landraces.

Historical assessments have shown modern varieties perform better at higher rates of N than older varieties, due to improvements in various NUE metrics, which has driven higher optimum N rates to support increased yields. Attempts to identify 'HYLO' varieties, capable of achieving high yields at low optimum rates, have been largely unsuccessful in the current pool of varieties available to the UK market, but HYLO traits have been identified in varieties originating from countries such as Denmark, where breeders and farmers are working in a regulated low N environment. These varieties also had low grain protein, suggesting this is an important trait for breeders to target to reduce N requirements. In France, there is also a consistent body of work demonstrating a genotype x N-rate interaction in winter wheat. This work has led to the testing of new wheat varieties under different N levels (X and X-80 kg ha^{-1}, X being the optimal N level) as part of the national testing of varieties and a 'tolerance to N deficiency' index published. This approach was tested in the HYLO project but was unsuccessful.

Although there is limited evidence that testing current varieties under low N inputs would give additional insights into performance of current varieties bred under standard N regimes. There is an argument that RL trials including low N treatment would, in the short-term, aid levy payers in selecting current varieties suited to lower N input. In the longer term, this would stimulate breeders to start selecting in a low N environment or to submit varieties that have demonstrated NUE traits into the RL system where they might not previously have been tested. It is apparent from conversations with OSR breeders undertaken as part of this project that some are already doing this. From the review of literature there does appear to be potential for breeders to improve NUE metrics. Przystalski *et al.* (2007) advocated that breeders select for varieties that will show adaptation to a broad range of environments and Mini *et al.* (2023) were able to show that stacking favourable alleles led to increased tolerance to low N environments.

For OSR, trials in these crops are already challenged by weather and pest issues. Additionally, because of the nature of OSR, varieties often need differential and careful management and it has been raised by breeders that the nuances in management required if NUE information was included may not be easy for levy payers to take on board. Overall, it is concluded that OSR RL trials should not include differential N rates.

It is possible that early breeding lines may show greater variation, that could be beneficial. One of the arguments sometimes put forward is that it is important to evaluate varieties in conditions where they can display their full genetic potential (generally optimal or high N), so we are more likely to see high heritability. Though in some cases this was reported (Brancourt-Hulmel *et al*. 2005; Laperche *et al.* 2006), it is not always the case as Cormier *et al.* (2013) could measure similar heritabilities under low and high N with grain yield showing a heritability of 0.74 (LN) and 0.78 (HN). This could also depend on the N rate applied at LN. Quite strikingly, Mini *et al.* (2023) were able to show that stacking favourable alleles leading to increased tolerance to low N environment. If anything, driving for selecting varieties under lower N may enable a greater improvement under optimal N because it would allow for specific component of NUE (especially the capacity to extract N from the soil rather than from fertiliser) to be improved upon. Another option to drive an increase in N efficiency of feed varieties is for breeders to actively select for low grain protein concentration. From the review it was apparent that Danish varieties exhibited HYLO traits, although caution should be applied to this approach; in Denmark they found they needed to import more protein to make up for the low protein concentrations in grain.

There is clearly a demand from levy-payers to understand how RL varieties may perform at lower N rates. This review has shown that generally the relative performance of cereal varieties is similar whether a standard or low rate of N is applied. Although it may be beneficial to conduct some RL trials at a lower N rate to stimulate the entry of different varieties to the RL system, it is likely to be most valuable for AHDB to produce clear messaging to levy payers on this subject.

5.1. Knowledge gaps and horizon scanning

Most reports evaluated in this review used a methodology involving N dose response experiments. While some methodology such as 15-N tracer, are not optimal for assessing varietal differences in NUE metrics, due to cost and accuracy limitations, they can offer a means to measure some specific aspects of NUE in defined experiments. However, N-balance is a cheap alternative methodology which could be investigated further. Generally, measurements are conducted above ground and no measurements of root N content are reported. Although there are differences in root N content amongst wheat varieties, the amount is very low compared to the total plant N so it has very little influence.

Similarly, almost all N rate and variety interactions were analysed by ANOVA, with some using REML. Consistent methodologies can be beneficial when determining conclusions across reports and further projects could include a meta-analysis of recent data to analyse NUE metrics and yield ranking order changes.

Critically, a stakeholder meeting held for the purpose of gaining industry experience for the present review enabled industry partners to highlight various knowledge gaps relevant for further research. These included: the interaction between N rate and fungicide applications; interactions between N rates and biostimulants and other novel products; impacts of reduced N rates on soil parameters, in particular soil microbial processes; and interactions and confounding synergies with other agronomic changes, such as direct drilling and variable seeding rates.

Most of the reports and papers mentioned here included a N rate achieved by application of prill ammonium nitrate. However, other forms of N fertilisers including organic fertiliser (material) and biofertilisers (containing particular types of fungi and bacteria) are available to growers in the UK (Barnett and Wentworth, 2024). Foliar N fertilisers are becoming more relevant and targeted in crops for specific end markets.

None of the literature reviewed in this report specifically mentioned the interaction between root morphology and grain yield. However, research reported by White *et al*. (2013) measured root length densities (RLD) for seventeen commercial crops of winter wheat between 2004 and 2017 and reported that the critical RLD was inadequate for full water capture below a depth of 0.32 m for winter wheat and 0.45 m for OSR that could lead to a shortfall in grain yields under water-limited conditions. Whilst this study did not specifically look at the effect of wheat or OSR genotypes a study in north-western Australia, in relatively dry conditions, significant variation in all root traits was observed among fifteen wheat genotypes (Atta, *et al*., 2013) Atta *et al*. (2013) concluded that root traits collectively contributed between 31 and 45% of total variance in improved water-use-efficiency (WUE) and grain yield, respectively, under water stress and genotypes were identified that extracted water more efficiently under drought resulting in improved WUE and grain yield. White *et al*. (2013) mentioned that measurement difficulties have been a major factor contributing to the relatively small amount of data available on crop roots, methods generally being time consuming and destructive. However, understanding the drivers in NUE between varieties and root morphology would be pertinent to consider in future studies to understand optimising nitrogen uptake and utilisation.

On going research at NIAB funded by The Morley Agricultural Foundation (TMAF) and the JC Mann Trust, a multi-disciplinary six-year research project encompassing agronomy, genetics and molecular plant physiology is assessing novel wheat genotypes in regenerative agriculture conditions, including under low soil disturbance and lower N input. Following a rotation based on winter wheat, trials will rotate across well-characterised experimental sites in East Anglia, with a known history of management. Fully replicated plot trials will evaluate the performance of new wheat genetic material (including synthetic hexaploid wheat (SHW) derivative lines), under regenerative agricultural practices and lower nitrogen inputs.

5.2. Recommendations for further action

From the review, not all crops mentioned in the original call could be considered for the review. For some, there is little evidence that the subject has been investigated (e.g. linseed and rye), and therefore it may be valuable to look further into this.

Although the N rate is recorded as part of the meta-data obtained during trials conducted for the recommended list, this information was not easily accessible to us and therefore not used as part of this review. Handling the data acquired as part of the RL trials so that it can be easily mined may be beneficial.

The current set of criteria on the RL has a huge influence on the traits that are being selected for. The lack of testing for the NL under lower N level was mentioned in the stakeholder meeting as a reason why breeders don't select for this trait. While there have been some increases in NUE over time, this has been linked to increased yield per se. The evidence that NUE under low N availability is much higher than NUE under high N availability suggest that much progress can be made. The RL can act as a driving force pushing the development of commercial varieties that are more sustainable, i.e. lower N requirement, hence the recommendation to test winter wheat varieties under two N levels: current RL protocol and a reduced N rate**.** It was also noted at the stakeholder meeting that breeders need time to adapt and that a phased-approach may be more beneficial.

One possible route to achieving improved NUE traits in feed wheat varieties is for breeders to actively select for low grain protein concentrations (i.e. high-energy grain). Danish breeders, selecting in a low-N environment, have produced HYLO varieties as a consequence, and a similar strategy could be investigated in the UK.

Other cereals have limited data at this stage to warrant the expenditure and as described above. Indeed, the oats and barley 'grey' literature showed a lack of variety x N interaction. There is enough evidence and interest from levy payers to suggest that sub optimal N trials in winter wheat with full a fungicide programme (to reduce the risk of any other interaction) would be well received. This type of change would need to be telegraphed to the breeders as they would need to bring forward varieties that they think will suit, or in the longer term (breeding wise this is decades) they can look to breed from varieties that respond in lower N conditions. In the short term, engagement with the breeders to understand what they may have available and how those varieties may be best portrayed may help structure any future trial plans.

5.3. Key messages

- There are many NUE metrics that may be useful to measure in experiments testing varieties, including N Utilisation and Uptake efficiency. The most used NUE metric (kg grain / kg N available) should be treated with caution as it reflects yield measured at a specific N rate.
- Evidence for differing relative variety performance at low N rates (variety x N rate interaction) was mixed and particularly limited in reports from UK trials. There was evidence that varieties bred in low input environments, older varieties and landraces did perform relatively better at lower N inputs.
- There was little information available for spring-sown and more minor crops e.g. rye, triticale, linseed.
- Although there was not conclusive evidence for current cereal varieties, it would be beneficial to levy payers for AHDB to include low N rates in variety testing.

- We therefore recommend that some RL trials should include winter wheat varieties tested under two N levels: current RL protocol and a reduced N rate. In the short-term, this would aid levy payers in selecting current varieties suited to lower N input. In the longer term, this would stimulate breeders to start selecting in a low N environment, or to submit varieties that have demonstrated NUE (and HYLO High Yield Low Optimum) traits into the RL system where they might not previously have been tested.
- For OSR, trials in these crops are already challenged by weather and pest issues. Additionally, because of the nature of OSR, varieties often need differential and careful management, and it has been raised by breeders that the nuances in management required if NUE information was included may not be easy for levy payers to take on board. Overall, it is concluded that OSR RL trials should not include differential N rates.

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