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Updating nitrogen and sulphur fertiliser recommendations for spring barley

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1. Abstract

This project aimed to improve nitrogen (N) and sulphur (S) fertiliser management guidelines for modern spring barley varieties. The work was conducted to help farmers achieve grain N% targets and high (economically optimal) yields more reliably. Specific objectives were to:

1) Review data to understand how soil N supply, applied N and yield potential affect grain N%
2) Quantify the effect of timing of soil applied N and S fertiliser on grain N%
3) Quantify the effect of rate of soil applied N fertiliser on grain N%
4) Produce N and S fertiliser guidelines for achieving grain N% targets with maximum yield
5) Transfer guidelines to farmers and agronomists

Eleven N-response experiments resulted in an average optimum N rate (N_{opt}) of 118 kg N/ha, with an average yield of 7.4 t/ha and an average grain N% of 1.63%. Analysis of new experimental data and a UK review dataset confirmed that the crop N demand increased with yield, with an additional 20 kg N/ha for each additional tonne, equating to an additional fertiliser requirement of 33 kg N/ha per tonne. On average, the current RB209 recommendations over-estimated N requirement by over 40 kg N/ha, with an average error of +/- 48 kg N/ha. Two options are proposed that deal with this inaccuracy (both give similar N recommendations at expected yields of 7–8 t/ha):

i) Change the expected yield value from which N rate is adjusted from 5.5 t/ha to 7.5 t/ha.
ii) Adopt a method to calculate fertiliser N requirement based on crop N demand and fertiliser recovery.

Across the new experimental data and UK review dataset, reducing grain N% by 0.1% required a reduction in N rate of 29 kg N/ha, thus confirming the current RB209 recommendation of a reduction of 30 kg N/ha. The average grain N% at the N_{opt} was 1.72% and 67% of crops achieved a grain N% of <1.8% at the Nopt. A cost-benefit analysis indicated reducing the N rate recommended for optimum yield by 30 kg N/ha would maximise the reliability of achieving a grain N% of less than 1.8%. However, if historic grain N% data for the field indicates that grain N% is consistently below 1.8% with fertiliser rates optimised for yield then it may not be necessary to reduce the N rate.

Eleven N-timing experiments clearly indicated that all the N should be applied between the time of drilling and GS30, with at least 40 kg N/ha in the seedbed. However, to minimise the risk of nitrate leaching, no more than 40 kg N/ha should be applied in the seedbed, if the crop is sown before March, grown on a light-sand soil or if there is a likelihood of substantial rainfall soon after drilling.

The results indicated that there was no requirement to alter current recommendations for S fertiliser, with applications of 25–50 kg SO_3/ha, where a risk of S deficiency is identified.

2. Introduction

2.1. Spring Barley Production and Fertilisation on UK Farms

The area of spring barley grown in the UK increased to over 700k ha between 2017 and 2019, with over 1 million ha grown in 2020 as a result of fewer autumn sown crops sown in this season (Figure 2.1). The area of spring barley grown is likely to remain high to aid black grass control and as a replacement for oilseed rape especially in regions where cabbage stem flea beetle pressure is high. The increased demand for spring cropping has resulted in farmers growing spring barley who have less experience with this crop and may find it challenging to reliably achieve the grain quality targets. Furthermore, spring barley has traditionally been grown on light textured soil, but the area is now expanding to heavier textured soil too, which is likely to affect the optimum N strategy to achieve various grain N% targets.

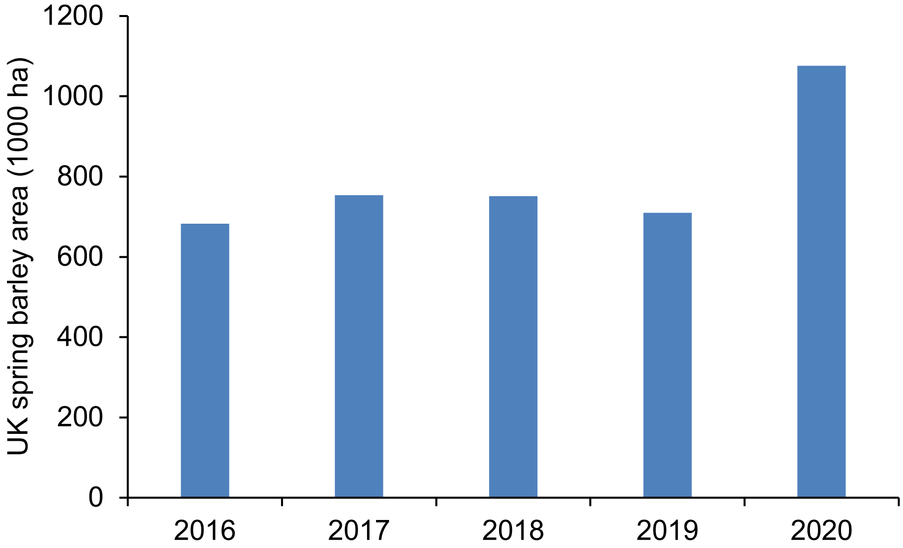

Figure 2.1 UK spring barley area (Defra statistics)

Spring barley is grown for different malting markets and for use as feed. Between 2015 and 2019, approximately 56% of spring barley was grown for malting, with the remainder used for feed (British Survey of Fertiliser Practice, 2020). There are three main malting markets which are differentiated primarily by the variety used and the grain N content: i) Grain N% of 1.65% and below is used for malt distilling, ii) Grain N% of 1.60% to 1.85% is used for brewing and iii) grain N% of above 1.85% is used for grain distilling. The N levels in distilling can affect the processibility of the grain and ultimately impact on the spirit level. In England, the majority of malting barley purchased by UK maltsters falls into the 1.56-1.65% grain nitrogen band, whereas in Scotland, there is greatest demand for spring barley with a grain N% of less than 1.55%. Traditionally, demand for malting barley with a grain N% of above 1.85% has been much less as this tends to represent specialist markets for grain distilling. However, more recently the size of market for higher grain N for grain distilling has been expanding. As well as grain N percentage there are several other grain quality requirements that must be met including; correct grain moisture, germination, specific weight, low screenings, low admixture and absence of ergot or pest infestation. The two most common reasons for grain to be rejected for quality markets are low germination and incorrect grain N percentage (https://www.ukmalt.com).

Financial premiums for growing grain which meets the quality specification for malting and brewing can be substantial and achieving them can make the difference between making a profit or loss. Growers are often cautious with their N fertiliser rates to avoid exceeding minimum thresholds for grain N percentage and as a result may 'miss out' on yield due to the use of sub-optimal N rates. Furthermore, there is uncertainty about how crops with a greater yield potential should be fertilised to achieve the target grain N percentage. New varieties yield more than 10% more than some traditional varieties (e.g. Concerto), and national spring barley yields have been increasing by an average of 0.4 t per decade (Figure 2.2) as a likely result of improvements to both varieties and crop management.

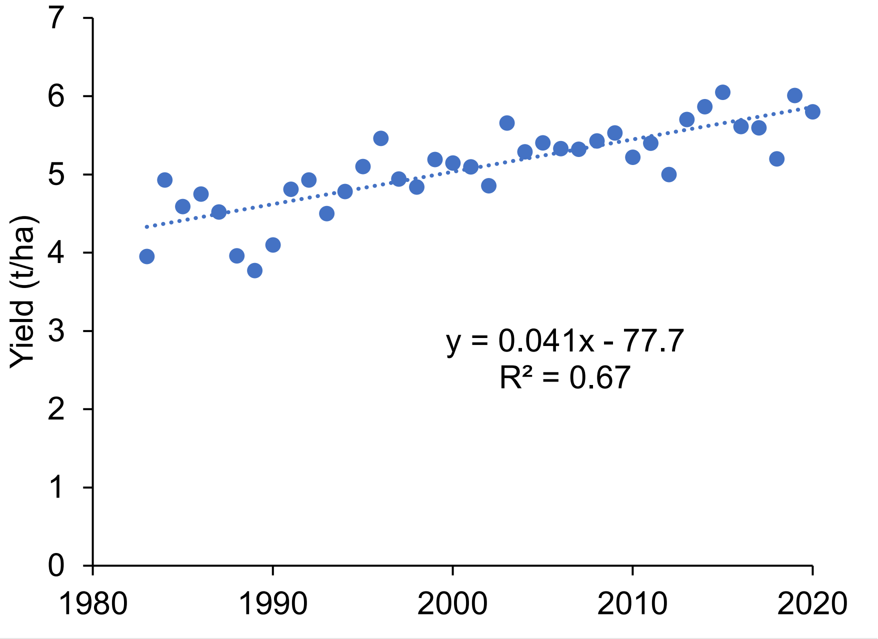

Figure 2.2 UK spring barley yields (Defra statistics)

The average N rate applied to spring barley between 2015 and 2019 was 101 kg N/ha, with no clear change in N rates over this period (BSFP, 2020). The average N rate applied to malting crops between 2015 and 2019 was 108 kg N/ha, with 98 kg N/ha applied to non-malting crops. It might be expected that non-malting crops would have a greater N rate because the AHDB Nutrient Management Guide recommends a higher N rate for non-malting crops compared with malting crops (for the same soil type and previous crop). This apparent anomaly may be explained by a greater proportion of spring barley crops grown for feed being grown in mixed rotations and on soil types with heavier textures, which have a greater soil N supply, which consequently reduces the crops demand for N fertiliser. Additionally, more non-malting crops received manure, with 39% of non-malting crops receiving manure compared with 22% of malting crops. Between 2015 and 2019 the average percentage of spring barley crops grown for malting markets was 56% (BSFP, 2020).

Approximately 73% of spring barley crops receive an N rate of less than 125 kg N/ha, with 19% receiving between 125 and 149 kg N/ha and 8% receiving 150 kg N/ha or more (Figure 2.3). More than 90% of spring barley crops receive the N in 1 or 2 splits. Nineteen percent of malting crops receive all N in one split which rises to 36% non-malting crops, reflecting the lower average N rate applied to non-malting crops (Figure 2.4).

The BSFP survey data can be used to indicate the proportion of the total N that is applied in the seed bed up to and including the day of drilling. In this context 'in the seed bed' means any N from straight N or compounded/blended fertiliser products applied by broadcasting before or at the time of drilling or by combined drilling. It should be recognised that this definition does not include N-containing product that is top dressed after the day of drilling. There were only modest differences in the percentage of N applied in the seedbed between malting and non-malting crops.

Spring barley grown in Scotland had a greater percentage of total N applied in the seed bed, either combined drilled or as a top dressing on or before the day of drilling, compared with England & Wales. On average between 2015 and 2019, 76% of Scottish crops had some N applied to the seed bed compared with 17% in England and Wales. Slightly more than 30% of Scottish crops received >50% of the total N in the seed bed compared with only 8% of crops grown in England & Wales. The large difference between England & Wales and Scotland may be due to the more frequent practice of combined drilling in Scotland. It may also be relevant that more N is applied as a compound fertiliser in Scotland compared with England & Wales. In Scotland, the BSFP reports that on average over the past five seasons 89% of the spring barley crop received N in a compound, providing 52% of the total N applied. In England & Wales, the equivalent values were 25% N provided to spring barley crops in compound products, providing 14% of the total N applied. The data indicates that most crops in England & Wales do not have N incorporated into the seed bed or broadcasted on, or before, the day of drilling.

The percentage of spring barley crops receiving sulphur fertiliser increased from 48% to 59% between 2015 and 2019 (BSFP, 2020). The average rate of sulphur applied to the crops which received sulphur fertiliser remained similar over this period at 43 kg SO_3/ha. The sulphur rate recommended by the AHDB Nutrient Management Guide for winter or spring sown cereals where sulphur deficiency is recognised or expected is 25 to 50 kg SO_3/ha.

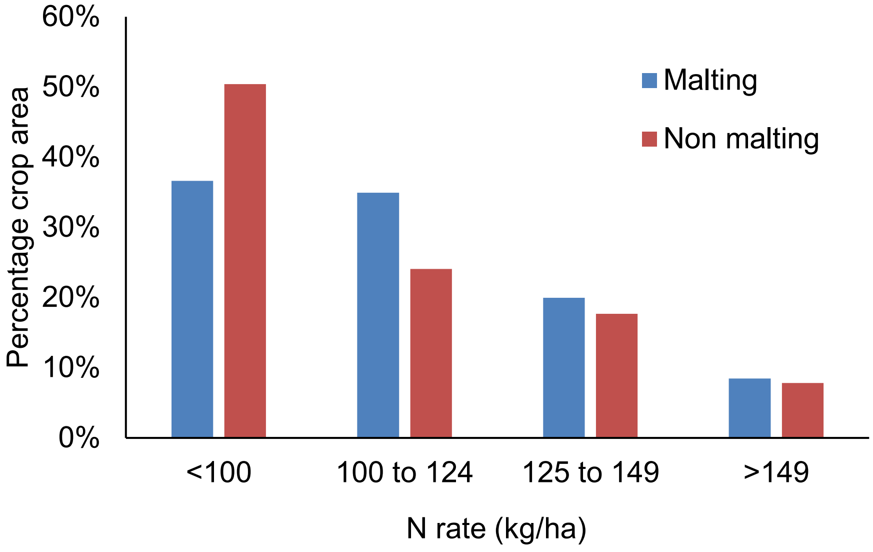

Figure 2.3 Total rates of N fertiliser applied to spring barley between 2015 and 2019 (BSFP, 2020)

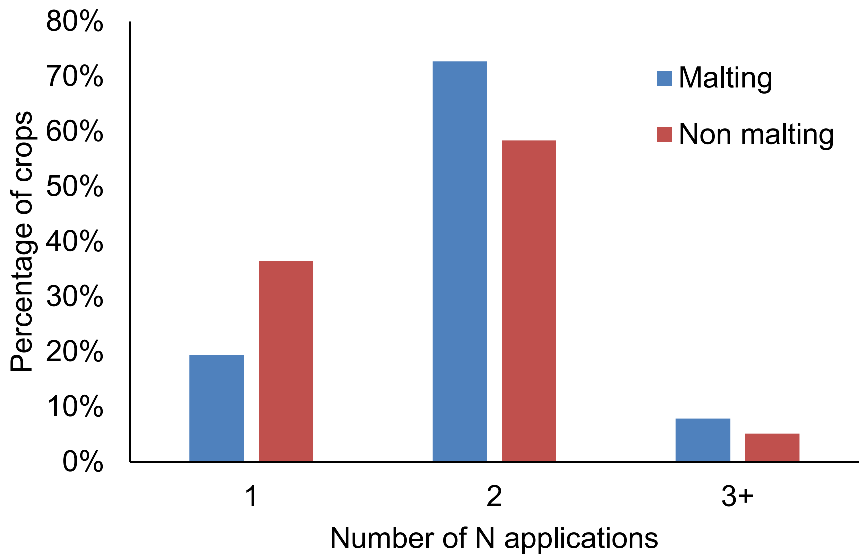

Figure 2.4 Number of N applications for spring barley between 2015 and 2019. (BSFP, 2020)

2.2. Experimental Evidence About Optimisation of N and S Fertiliser for Spring Barley

A review of RB209 recommendations was carried out by Roques et al, (2016) which concluded that recommended N rates described in the RB209 (8th edition) guidelines were suitable, except for crops grown on sandy soils for which an increase in N rate was recommended. In some experiments (e.g. Scottish trials from Gilchrist et al. (2012) AHDB Project Report No. 484), high levels of N optima were reported for spring barley. Many of these experimental sites were on sandy soil and the high N optima may have been a consequence of leaching of applied N following high spring rainfall or drought conditions later in the season.

Optimising N for a wide range of malting %N specifications on modern spring barley varieties was highlighted as a knowledge gap with high priority in the RB209 review (Roques *et al.*, 2016). Of the 39 spring malting barley site x treatment combinations which were included in the review for which sufficient %N data was available to allow curve fitting, 29 exceeded 1.8% grain N at the economically optimum N rate for yield, and seven of these exceeded 1.8% grain N even at nil applied fertiliser N. Using the N rates for spring barley recommended by the previous version of RB209 (8th Edition), 14 of the 39 sites exceeded 1.8% grain N. The review calculated that the guidance provided by RB209 would only achieve target grain N% in 60% of cases. For a grain N% target of 1.5%, only 23 out of the 39 site x treatment combinations had <1.5% grain N at nil N (i.e. less than 60% of cases).

AHDB Project 438 (carried out in 2005-7) (Sylvester-Bradley et al., 2008) showed that higher yielding spring barley varieties (malting and feed) had the same economic optimum N rate and lower grain N% at the optimum N rate than lower yielding varieties. This project compared old varieties such as Golden Promise and Triumph with then current varieties Spire and Troon. The current AHDB RL show that Laureate and RGT Planet yield 11-12% above Concerto, with grain N% reduced by 3-4%, but it is not known whether these high yielding varieties have a greater optimum N rate than Concerto. Roques et al (2016) found that across environments there was a strong positive relationship between N requirement (soil N supply and optimum fertiliser N rate) and yield at the optimum N rate, which showed that for each additional tonne of yield over 5.5 t/ha, an additional 28 kg N/ha extra fertiliser is required (compared with the recommendation provided with RB209 8th edition). The recommendation from the review was that the recommended N rate should be increased by 20 kg N/ha for each t/ha of expected yield above 5.5 t/ha, up to a maximum yield of 10 t/ha.

There are very few published experiments describing the effect of N timing on spring barley yield and quality. Field experiments carried out in Northern Ireland between 1978 and 1980 investigated N applied to spring barley either all in the seed bed or as a divided dressing with 10 or 25 kg/ha in the seed bed and 50 or 60 kg applied at emergence or 10, 20, 30, 40, 50, 60 or 70 days after emergence (Easson et al., 1984). Applying part of the N as a top dressing up to 30 days after emergence had no significant effects on the grain yield, compared with applying all the N in the seed bed. Grain yields were progressively reduced with top dressings from 40 days after emergence (first node stage) onwards. Top dressing at 40 days after emergence stimulated tiller survival but did not improve grain yield because there were fewer grains per ear. Thousand-grain weights were lowest with top dressings at 50 days after emergence and grain N increased progressively with delay in top dressings from 30 days after emergence onwards. A two-split N application approach was most beneficial in early sown crops for which it could improve yield and offsets leaching risk, especially if there is rainfall following sowing (Easson 1984).

More recently a study across 20 field experiments in Ireland showed that grain yield and grain N concentration of spring barley has provided more up to date information about the effects of N timing (Hackett 2019). Where the majority of N was applied before the end of tillering stage, the grain yield and grain N concentration were relatively insensitive to the timing of fertiliser N inputs. There was little consistent difference between applying the first N at sowing compared to applying the first N at emergence on either grain yield or grain N concentration. Similarly, altering the proportion of the total N dose that is applied at the first application, where the remaining N is applied before stem extension, had no consistent effect on either grain yield or grain N. The work also showed there is potential to delay a portion (0.2) of N for spring barley until the stem elongation phase without affecting grain yield or grain N (Hackett 2019). A study on spring barley grown in Canada has shown that if a proportion of the total N is applied after the start of stem extension then yield can be reduced and fertiliser recovery also reduced (Zebarth et al., 2007). This study also showed that 50% of the total N applied can be delayed until early tillering without reducing yield compared with applying all fertiliser N in the seed bed (Zebarth et al., 2007). More generally it has been concluded that a beneficial effect of splitting N applications on grain yield is most common in situations where wet conditions increased the risk of N loss early in the growing season (Roth and Marshall 1987; Gravelle et al. 1988).

Few experiments have been carried out to compare incorporating N in the soil, e.g. using combine drilling, with broadcasting at the same time. Widdowson et al. (1961) showed that combine-drilling ammonium sulphate produced higher mean yields than broadcasting across 15 spring barley crops. Placement of fertiliser can be a key factor in increasing the efficiency of N use. Banding, where fertiliser is placed to shallow depth into the seedbed soil or directly with the seed, or a separate band close to the seed, has been proposed as a method to minimise nutrient losses and optimise crop nutrient use (Grant et al. 2002; Malhi et al. 2001).

The review of Roques et al (2016) was unable to provide an update to the recommendations for timing advice because no new data was available. Current RB209 recommendations for N timing are as follows: “Apply all the nitrogen by early stem extension but not after end of March. Where the target grain %N is below 1.8%, the nitrogen rate should be adjusted as necessary for predicted yield, then reduced by approximately 30 kg N/ha to achieve 1.7% grain N or 60 kg N/ha to achieve 1.6% grain N. Grain N% may be diluted in high yielding crops. This N should all be applied by mid-March.”. The guidance for Scotland given in Technical Note TN731 is as follows: For crops sown up to the beginning of April apply half fertiliser N to seedbed and half at 2-3 leaf stage for low N malting and start of tillering for feed and high N malting crops. From beginning of April onwards, all may be applied to seedbed. Incorporation in the seed bed, or combine drilling reduces the risk of poor N uptake in dry weather conditions.

In 2005, AHDB Report 374 (Carver, 2005) showed that 15% of spring barley crops had an increased yield when S was applied, giving an average yield response of 0.7 t/ha. Sulphur depositions to the land from the atmosphere have declined since 2005 and are now very low (Webb et al., 2016). In 2019, 59% of spring barley received S fertiliser at an average rate of 41 kg SO_3/ha (BSFP, 2020). It is not known whether the increase in the proportion of spring barley crops that receive sulphur fertiliser has been sufficient to keep pace with the reduction in atmospheric S deposition. It is also not known how sulphur fertiliser affects the grain N% of modern spring barley varieties.

2.3. Prediction of grain N concentration

Grain N concentration is the quotient of the amount of N in the grain and the grain dry matter (yield) as such it depends on factors that affect both the deposition of protein and starch in the grain. Protein and starch deposition in cereal grains are independent processes. Under field conditions their rates are often asynchronous with the rate of protein deposition reaching a peak and then declining before that of starch (Jenner et al. 1991). This may be a response to a declining N supply to the grain during the second half of grain filling. The majority of N in the grain at harvest comes from remobilisation of N accumulated in leaves, stem and chaff before anthesis, but as roots remain physiologically active during grain filling, crop N uptake may continue after anthesis providing there is sufficient mineral N available in the soil (McTaggart and Smith, 1995; AHDB 2020). By contrast, starch deposition may be controlled by both the supply of carbon assimilates and the physiological capacity of the grain (Jenner et al. 1991). As a result of these asynchronous patterns of deposition, conditions that reduce the duration of starch deposition, such as drought or high temperature during grain filling, can lead to an increase in grain N% by reducing yield without affecting the amount of grain N (Morgan and Riggs, 1981). Conversely conditions that prolong N supply to the grain such as a large post-anthesis soil N availability can also lead to greater grain N concentrations by increasing the rate and duration of protein deposition without affecting yield (McTaggart and Smith, 1995).

When developing management strategies and fertiliser recommendations to achieve target grain N specifications it is, therefore, necessary to consider those site, season and husbandry factors that might influence pre- and post-anthesis N uptake, N remobilisation, the formation of grain sink capacity (grain number and potential size) and the duration of grain filling.

Several factors have been shown to affect the grain N concentration of spring and winter barley including: i) Supply of N from the soil and from fertiliser: an increase in N fertiliser rate of 25 to 30 kg N/ha has been estimated to be required to increase the grain N concentration of winter barley by

0.1% (Garstang et al., 1993). ii) Timing of N fertiliser: for winter barley, AHDB Report No 571 (Kendall et al., 2017) showed that applying the spring dressing of N 3-4 weeks earlier reduced grain N concentration by 0.1% and increased yield by up to 0.4 t/ha. Other work reports that either not applying any N in the seed bed or delaying a proportion of the N until GS32 increased grain N% (Zebarth et al., 2007). iii) Foliar N: Liquid N (50 kg N/ha) applied to spring barley in June increased the grain N% by 0.13% (Widdowson et al., 1982), iv) S fertiliser rate: sub-optimal S has been shown to increase grain N% in barley (AHDB Report 369, Zhao et al., 2005). v) Plant population density: AHDB project report 320 (Wade et al., 2003) provides evidence that low plant populations of spring barley have a higher grain N% than crops drilled at high seed rates.

Several studies have attempted to predict the grain N concentration of barley at a time when it is still possible to manipulate it using N fertiliser applications. Nolan (2016) investigated the processes contributing to variation in grain N% across several fertiliser rates, timings, sites and years in spring barley experiments in Ireland. Grain N concentration was related to both N content and grain yield at harvest, which in turn were strongly associated with crop N content and biomass, respectively, at ear emergence. Statistical models using measurements of crop N content and biomass at ear emergence accounted for up to 80% of the variation observed in grain N concentrations suggesting that the models could be useful practical tools for predicting grain N concentration. Although post-anthesis N uptake ranged from 0 to over 50 kg/ha in these experiments, it did not account for a significant amount of the variation in crop N content or grain N% observed at harvest between sites, years and N fertiliser treatments.

Other studies have demonstrated correlations between grain N% and crop measurements at anthesis. In Mediterranean conditions Molina-Cano et al., (2001) found it was possible to predict the N concentration of spring barley grain by analysing the N content of the whole plant at anthesis. However, the regression models used accounted for less than 50% of the variation in grain N%. In Sweden, Söderström et al., (2010) also reported some limited success for predicting grain N concentration of malting barley from spectral reflectance measurements of the crop at anthesis using a Yara N-Sensor and satellite imagery when data from a single region and year were used. However, the accuracy of the predictions fell when data from different regions and years were included in the models.

In Sweden, Pettersson and Eckersten (2007) showed it was possible to predict malting barley grain N concentrations for specific cultivars using the day number at sowing and a spectral reflectance vegetation index at early stem extension. The sowing date was included to account for variations in the duration of grain filling (shorter duration with later sowing) and the vegetation index provided an estimate of the crop N content). However, statistical models based on either a single measure of canopy reflectance at anthesis, or repeated measurements from tillering to booting, gave very poor predictions of grain N concentration in spring barley crops in Denmark (Hansen et al., 2002).

The research described above shows that whilst there may be potential to predict the grain N concentration of malting barley at harvest from estimates of crop N content and yield made at anthesis, the accuracy and reliability of predictions is highly variable. The accuracy and reliability tend to decline further when predictions are made across sites and years and from measurements taken earlier in the season when decisions about fertiliser N applications need to be made. It therefore appears that there is little scope to use existing grain N concentration prediction models to guide N fertiliser to increase the likelihood of achieving target grain N concentration in the UK.

2.4. **Effects of breeding on N requirement and grain N%**

To date, breeding of spring barley has focused largely on the improvement of grain yield and quality, but there is strong evidence that this has been accompanied by indirect improvements in nitrogen use efficiency (NUE). In an analysis of the effects of breeding for yield over a 75-year period on the NUE of West European spring barley, Bingham et al., (2012) grew a range of old and modern varieties with and without fertiliser N at three-site seasons in Scotland. Fertiliser N was applied at a single rate recommended for malting barley crops in the region. The study showed that breeding has increased yield and NUE (grain yield per kg of N supplied by fertiliser and soil) by an average of 1% and 1.2% per year respectively (Bingham et al., 2012). Indirect improvements in NUE have also been reported from barley breeding programmes in other parts of the world including Argentina (Abeledo et al., 2008) and Finland (Rajal et al., 2017) although the physiological basis of these improvements differ in some respects.

In West European varieties, including those widely grown in the UK, approximately two-thirds of the improvement in NUE was associated with an increase in the N utilisation efficiency (NUtE) whilst one-third was the result of an increase in N uptake efficiency (NUpE). The increase in NUtE (grain yield per kg of N captured) of modern varieties was almost entirely the result of their greater partitioning of dry matter to the grain as shown by their greater harvest index (HI). The improvements in HI were observed irrespective of whether the crop was supplied with N fertiliser or not (Bingham et al., 2012). By contrast, the improvements in NUpE (N uptake per kg available N from fertiliser and soil) were observed only with crops given fertiliser. There was no evidence to suggest that non-fertilised modern varieties were better able to capture soil N than old varieties. In fact, there was an indication that modern varieties were marginally less effective at some sites (Bingham et al., 2012). However, the relative contributions of NUtE and NUpE to gains in NUE differ between barley breeding programmes. In Argentina increases in NUE were associated with improvements in NUtE (also known as physiological efficiency) with no clear increase in uptake efficiency (Abeledo et al., 2008), whereas in Nordic barley breeding the greatest contribution (70%) came from NUpE (Rajala et al. 2017).

Whilst the above studies demonstrate that barley breeding has led to steady increases in the yield potential of new varieties and that indirect improvements in NUE have enabled greater yields to be achieved at the same level of fertiliser supply, because they are based on comparisons of crop growth at a limited number of fertiliser N rates, they do not indicate whether the breeding for higher yield has altered the crop's fertiliser N requirement. For that a comparison of varieties grown over a wide range of fertiliser rates is required so that their N optima can be determined. Using such an approach Sylvester-Bradley and Kindred (2009) demonstrated that there was no clear difference in N optima of a small selection of spring barley varieties popular in the UK in the mid-1980s and those being grown in the mid-2000s. Thus, the improvement in NUE appears to have largely kept pace with the improvement in yield potential of the varieties.

What effect has breeding had on grain N%? It would be expected that by partitioning more dry matter to the grain (increasing HI) modern varieties will have a lower grain N% compared to old varieties as a result of the N dilution effect. Several studies report a decrease in grain N% or protein concentration of spring barley associated with breeding gains in yield (Sylvester-Bradley and Kindred 2009; Bingham et al. 2012; Peltonen-Saino et al., 2012; Rajala et al., 2017). However, these decreases are minimised by the increases in N uptake and partitioning of N to the grain (N harvest index, NHI) that have accompanied the increase in dry matter harvest index (Bingham et al. 2012; Rajala et al., 2017). Thus, Bingham et al., (2012) reported a 15-18% reduction in grain N concentration for a corresponding 75% increase in yield over the breeding period and Rajala reported a 7-8% decrease in grain N concentration for 35-40% increase in yield.

2.5. **Aim**

The aim of this project is to provide nitrogen and sulphur fertiliser management guidelines for more reliably achieving grain N% targets with maximum yield for modern spring malting barley varieties.

2.6. **Specific Objectives**

1) Review existing data to understand how soil N supply, applied N and yield potential affect grain N%
2) Quantify the effect of timing of soil applied N fertiliser and S fertiliser on grain N%
3) Quantify the effect of rate of soil applied N fertiliser on grain N%
4) Produce N and S fertiliser guidelines for achieving grain N% targets with maximum yield
5) Transfer fertiliser management guidelines to farmers and agronomists

3. Materials and methods

3.1. Experimental information

Experiments were conducted over three seasons: 2018, 2019 and 2020 and included N rate experiments, N timing experiments and S rate experiments. In total, eleven N rate, N timing and S rate experiments were done. The experiments were carried out close to four regions located near ADAS Gleadthorpe in Nottinghamshire, near ADAS High Mowthorpe in North Yorkshire, Scotland's rural college (SRUC) in East Lothian and near ADAS Terrington in Norfolk (Table 3.1). In all but the Nottinghamshire experiments, the ground was ploughed before drilling. At the Nottinghamshire site, the ground was min-tilled before drilling. The previous crop residues were removed, with the exception of the Norfolk site where the previous crop residues were incorporated.

For all N rate experiments, three varieties were investigated at the Nottinghamshire, Norfolk and East Lothian sites (RGT Planet, Laureate and Concerto) and a single variety was investigated at the North Yorkshire site (KWS Irina in 2018, Laureate in 2019 and 2020). In the experiments at Nottinghamshire, Norfolk and East Lothian, a split plot design was used with six N rates (0-360 kg N/ha or 0-300 kg N/ha) as the main plots and the varieties were fully randomised as sub plots within each main plot. In the North Yorkshire experiments, a fully randomised design was used. The N timing splits were as described in Tables 3.2, 3.3 and 3.4. There were three replicates of each treatment combination. Seed rates were 350 seeds/m^2.

For the N timing experiments, four varieties were investigated at Nottinghamshire, Norfolk and East Lothian (RGT Planet, Laureate, Concerto and LG Diablo) and one variety was investigated at the North Yorkshire site (KWS Irina in 2018, Laureate in 2019 and 2020). A split plot design was used at Nottinghamshire, Norfolk and East Lothian sites with four N timing treatments as the main plots and the varieties fully randomised as sub plots within the main plots. In the North Yorkshire experiments, a fully randomised design was used. There were three replicates of each treatment combination. Seed rates were 350 seeds/m^2. The total amount of N applied to each N timing experiment was estimated from RB209. The four N timing treatments consisted of seedbed, RB209, Late and Little and Often (L&O). For the seedbed treatment, all N was applied to the seedbed. At the Nottinghamshire site and North Yorkshire site (2019 and 2020), N was incorporated using the drill just before the seed was drilled. At the Norfolk, East Lothian and North Yorkshire (2018 only) sites, the N was broadcast following drilling. For the RB209 N timing treatment, 40 kg N/ha was applied to the seedbed and the remaining amount of nitrogen was applied between GS14-30. For the Late treatment all N was applied between GS14-30. Finally, for the L&O treatment, N was approximately equally divided between seedbed, GS14-30 and GS37-39. The N splits were as described in Tables 3.6, 3.7, 3.8, 3.9 and 3.10 and application dates and growth stages are shown in Table 3.5.

S rate was also investigated in these experiments, with treatments as per indicated in Table 3.11. All S was applied as potassium sulphate and applied at the same time as the seedbed N treatment.

Table 3.1 Site details for experiments.

Identifier	**Year**	**Site**	**Grid Reference**	**Soil type**	**Previous crop**	**Sow date**
Nottinghamshire	2018	ADAS Gleadthorpe, Nottinghamshire	SK 685 635	Loam	Winter wheat	24/04/18
North Yorkshire	2018	ADAS High Mowthorpe, North Yorkshire	SE 900 625	Shallow silty clay loam over chalk	Spring barley	6/04/18
East Lothian	2018	SRUC, East Lothian	NT 473 656	Loam	Winter wheat	20/04/18
Norfolk	2018	ADAS Terrington, Norfolk	TF 722 383	Sandy clay loam	Sugar Beet	5/04/18
Nottinghamshire	2019	ADAS Gleadthorpe, Nottinghamshire	SK 678645	Sandy clay loam	Oilseed rape	27/02/19
North Yorkshire	2019	ADAS High Mowthorpe, North Yorkshire	SE 895710	Shallow silty clay loam over chalk	Winter wheat	21/02/19
East Lothian	2019	SRUC, East Lothian	NT 475662	Loam	Winter wheat	25/03/19
Norfolk	2019	ADAS Terrington, Norfolk	TF 641 112	Sandy loam	Spring Beans	21/02/19
Nottinghamshire	2020	ADAS Gleadthorpe, Nottinghamshire	SK 667 636	Sandy clay loam	Oilseed rape	26/03/20
North Yorkshire	2020	ADAS High Mowthorpe, North Yorkshire	SE 884 700	Shallow silty clay loam over chalk	Winter wheat	24/03/20
Norfolk	2020	ADAS Terrington, Norfolk	TF 628 121	Sandy loam	Sugar Beet	24/03/20

Table 3.2 Application timings for N rate experiments at North Yorkshire (2018 and 2020), Norfolk (2018 and 2019), Nottinghamshire (2020) and East Lothian (2018 and 2019)

1st split Seedbed	2nd split GS13	3rd split GS30	Total (kg N/ha)
0	0	0	0
40	0	0	40
60	0	40	100
60	60	60	180
100	80	80	260
120	120	120	360

Table 3.3 Application timings for N rate experiments at Nottinghamshire (2018 and 2019) and Terrington (2020).

1st split Seedbed	2nd split GS13	3rd split GS30	Total (kg N/ha)
0	0	0	0
40	0	0	40
40	0	40	80
60	0	60	120
60	70	70	200
80	110	110	300

Table 3.4 Application timings for N rate experiments at North Yorkshire (2019)

1st split Seedbed	2nd split GS13	3rd split GS30	Total (kg N/ha)
0	0	0	0
40	0	0	40
60	0	20	80
60	0	60	120
100	50	50	200
120	90	90	300

Table 3.5 Application dates and growth stages for the N timing experiments.

Site	Sow date	Seedbed application	2nd timing application	2nd timing application	3rd timing application	3rd timing application
Norfolk 18	5.4.18	5.4.18	GS15	17.5.18	GS39-41	19.6.18
Notts 18	24.4.18	24.4.18	GS 23/24	23.5.18	GS39	19.6.18
North Yorks 18	6.4.18	6.4.18	GS13/14	3.5.18	GS39	8.6.18
East Lothian 18	20.4.18	26.4.18	GS13	15.5.18	GS37	13.6.18
Norfolk 19	21.2.19	21.2.19	GS17	29.4.19	GS37	17.5.19
Notts 19	27.2.19	27.2.19	GS24/25	1.4.19	GS39	28.5.19
North Yorks 19	21.2.19	21.2.19	GS13 & GS30	18.4.19 5.5.19	GS37	31.5.19
East Lothian 19	25.3.19	28.3.19	GS13	19.4.19	GS37	7.6.19
Norfolk 20	24.3.20	24.3.20	GS23	6.5.20	GS39	1.6.20
Notts 20	26.3.20	26.3.20	GS23	6.5.20	GS37	29.5.20
North Yorks 20	24.3.20	24.3.20	GS13/22	30.4.20	GS32/37	29.5.20

Table 3.6 Application timings and N rate for N timing experiments at Nottinghamshire (2018 and 2019) and Norfolk (2019 and 2020).

Treatment	Rate (kg/ha) seedbed	Rate (kg/ha) GS14-30	Rate (kg/ha) GS37-39	Total (kg/ha)
Seedbed	110	0	0	110
RB209	40	70	0	110
Late	0	110	0	110
L&O	40	40	30	110

Table 3.7 Application timings and N rate for N timing experiments at North Yorkshire (2019 and 2020) and Nottinghamshire (2020).

Treatment	Rate (kg/ha) seedbed	Rate (kg/ha) GS14-30	Rate (kg/ha) GS37-39	Total (kg/ha)
Seedbed	140	0	0	140
RB209	40	100	0	140
Late	0	140	0	140
L&O	40	50	50	140

Table 3.8 Application timings and N rate for N timing experiment at Norfolk (2018).

Treatment	Rate (kg/ha) seedbed	Rate (kg/ha) GS14-30	Rate (kg/ha) GS37-39	Total (kg/ha)
Seedbed	150	0	0	150
RB209	40	110	0	150
Late	0	150	0	150
L&O	50	50	50	150

Table 3.9 Application timings and N rate for N timing experiments at North Yorkshire (2020).

Treatment	Rate (kg/ha) seedbed	Rate (kg/ha) GS14-30	Rate (kg/ha) GS30	Rate (kg/ha) GS37-39	Total (kg/ha)
Seedbed	170	0	0	0	170
RB209	40	130	0	0	170
Late	0	85	85	0	170
L&O	40	80	0	50	170

Table 3.10 Application timings and N rate for the N timing experiments at East Lothian (2018 and 2019)

Treatment	Rate (kg/ha) seedbed	Rate (kg/ha) GS14-30	Rate (kg/ha) GS37-39	Total (kg/ha)
Seedbed	120	0	0	120
RB209	40	80	0	120
Late	0	120	0	120
L&O	40	40	40	120

Table 3.11 Summary of sulphur rates used in the experiments.

	SO_3 Rate (kg/ha) applied to the seedbed				
Site	0	10	20	40	80
Notts 2018	✓	✓	✓	✓	✓
Norfolk 2018	✓	✓	✓	✓	✓
North Yorks 2018	✓			✓	
East Lothian 2018	✓	✓	✓	✓	✓
Notts 2019	✓			✓	
Norfolk 2019	✓	✓	✓	✓	✓
North Yorks 2019	✓	✓	✓	✓	✓
East Lothian 2019	✓	✓	✓	✓	✓
Notts 2020	✓			✓	
Norfolk 2020	✓	✓	✓	✓	✓
North Yorks 2020	✓	✓	✓	✓	✓

3.2. Assessments

Soil and Crop N and S Measurements

In Jan-Feb, soil samples were taken to 90 cm (or to the depth of soil for shallow soils) from the field experimental areas, care being taken to keep each 30 cm horizon separate. Soil cores were sent in a cool box to Hill Court Farm Research for measurement of soil mineral N (SMN) and Additionally Available N (AAN). Samples from the 0-30 cm horizon were tested for extractable sulphur as well.
To estimate crop N and S, leaf samples were taken from the zero S treatments at GS32 for malate-sulphur and total S and N analysis by Hill Court Farm Research.

Shoot number, Green area index and light interception

At the North Yorkshire site in 2018-2020 and Norfolk and Nottinghamshire sites in 2020 (on the Laureate variety only), additional measurements were made in the N timing experiment including shoot number, NDVI measurements and green area index (GAI). At GS33 a crop sample was taken from a 0.49 m^2 quadrat. The same number of rows were included in each quadrat by arranging the quadrat so that a plant row ran from one corner to the diagonally opposite corner. The plants were dug up and taken back to the lab for analysis.
The soil was washed away from the roots and the fresh weight of the sample was recorded. A 25% sub sample was taken and the fresh weight measured. The roots were removed at the point where

the stem changed from green to white and the sub sample was re-weighed. The number of fertile and dead/dying tillers in the sub sample was counted. The leaves were separated from the stem. A moving belt leaf area meter (Li-Cor Model 3100, Delta-T Devices, Burwell, Cambridge, UK) was used to determine the area of the leaves followed by the stems. Leaves and stems were placed in an oven tray and dried at 80 °C until there was no further reduction in weight (approximately 48 hours).

Before the crop samples were taken, spectral reflectance measurements were taken of the quadrat area using a CropScan instrument. Measurements were taken in uniformly sunny or light cloud conditions after 10 am and before 3.30 pm. Scanning measurements following heavy dew or rain were avoided. Three CropScan readings were taken per plot, about 1m above the region where the crop was then to be sampled.

Pre Harvest Sampling

At the Norfolk, Nottinghamshire and North Yorkshire sites, just before harvest, samples of about 20 shoots cut at ground level from five randomly chosen positions per plot were taken to give a total sample of around 100 shoots. The ears and straw were then separated. The ears and straw were dried and their weights recorded. The ears were threshed and the dry weight of the grain recorded. Sub-samples (300-500 g) of straw/chaff were sent to NRM labs for N concentration analysis.

Lodging at Harvest and Yield

The percentage areas affected by leaning (displaced by 9º and less than 45º from the vertical) and lodging (displaced by greater than 45º from the vertical) was recorded. The grain yield of all plots was recorded using a small plot combine. The moisture content and specific weight was determined using a Dickey John GAC 2000 grain analysis computer.

Screenings and TGW

A 100 g grain sample was passed over a stack of 2.5 mm and 2.25 mm sieves. The weight of grains that remained in each sieve and those that passed through all sieves was recorded. The TGW was measured on the same grain sample. Grain samples were sent to Adams and Howling for N concentration analysis. Grain samples from the zero S and 40 kg/ha SO_3 plots were also analysed for S concentration.

Agronomic Inputs

All ADAS experiments on N rate and N timing received 40 kg/ha of SO_3 applied to the seedbed in the spring as potassium sulphate (18% S). All other crop management inputs were according to commercial farm practice to ensure that other nutrients were not limiting, and to control weed, pest, disease and lodging incidence. All other inputs were applied as per standard farm practice, including a comprehensive PGR programme.

Micromalting

Following initial analysis of the data, a subset of samples was selected for micromalting. A 500g sample of the selected treatments were sent to participating maltsters where they were micromalted according to the Malting Barley Committee Protocol. A Laureate grain sample was sent to each maltster to act as a control.

Statistical Analysis

Analysis of Variance

Each experiment was analysed by ANOVA in Genstat 18th edition for grain yield and grain N concentration as well as other measures, as either a randomised block design (S-rate experiments and North Yorkshire experiments), or as a split-plot design with N rate or N timing as the main plot and variety as the sub-plot (Nottinghamshire, Norfolk and East Lothian experiments). The analyses tested for differences between varieties, differences between N rates or N timings and for any interaction between varieties and N rates or N timings, i.e. whether the response to N was different for each variety.

Linear Regression

A general linear regression was done in Genstat 18th edition where just one of the variables had associated error. For analyses where both variables had associated error, a Model 2 Regression was carried out using the Linear Functional Relationship analysis in Genstat 19th edition, adopting the coefficients of the Standard Major Axis.

The apparent recovery of fertiliser N and N utilisation efficiencies were calculated as follows for the N rate closest to the economically optimum N rate in each N experiment for each variety:

Fertiliser recovery (kg/kg) =

$$\frac{\text{N uptake (kg/ha)} - \text{N uptake (at NIL N) (kg/ha)}}{\text{Rate of fertiliser N applied (kg/ha)}} \qquad \text{(Equation 1)}$$

N uptake efficiency (kg/kg) =

$$\frac{\text{N uptake (kg/ha)}}{\text{N uptake at NIL N (kg/ha)} + \text{rate of fertiliser N applied (kg/ha)}} \qquad \text{(Equation 2)}$$

N utilisation efficiency (kg/kg) =

$$\frac{\text{Dry matter grain yield (kg/ha)}}{\text{N uptake (kg/ha)}} \quad \text{(Equation 3)}$$

N use efficiency (kg/kg) =

$$\frac{\text{Dry matter grain yield (kg/ha)}}{\text{N uptake at NIL N (kg/ha) + rate of fertiliser N applied (kg/ha)}} \quad \text{(Equation 4)}$$

Grain Yield Response Curves and Deriving Economic Optimum (N_{opt}) Rates

The N requirement or economically optimal N rate (N_{opt}) is the rate at which any further increase in N rate will result in greater N fertiliser costs than the value of the additional grain produced. This is therefore dependent on the relative price of the grain and N fertiliser, or the breakeven ratio (BER): the amount of grain (kg) required to pay for one kg of fertiliser. In order to calculate the optimum N rate it is necessary to mathematically describe the response of crop yield to N fertiliser. The relationship between applied N and yield is complex and usually typified by a rapid increase in yield at low N rates, followed by a levelling off of the yield response, and sometimes a reduction of yield at super-optimal N rates due to factors such as lodging. A linear plus exponential (LpE) function (Equation 5) was chosen as being best at describing the range of N responses of UK cereals (George, 1984) and it has remained the standard for 30 years. The LpE function has four fitted parameters a, b, c & r which approximately (because they are strongly correlated) describe respectively the asymptote, the effect of omitting N, the slope of the asymptote, and the curvature of the response. In order to fit an LpE function information about the effects of five to seven levels of N on grain yield is required.

$$Y = a + br^N + cN \quad \text{(Equation 5)}$$

The fitting process did not use common values of parameters between sites or seasons; thus it was assumed that responses were unique to a site. In order to determine N_{opt} for each variety at each site the LpE function was fitted using a 'Parallel curve' approach. This involved a four-stage procedure:

i) Fit a common curve to all varieties (i.e. keeping a, b, c and r constant for all varieties at a site).
ii) Fit separate curves for each variety, with a common response but different intercepts (i.e. varying a but keeping b, c and r constant).
iii) Fit separate curves for each variety allowing a, b and c all to vary (i.e. just keeping r constant).
iv) Fit separate curves for each variety, allowing all parameters to vary.

The sums of squares explained at each stage was calculated, and a test was made of the improvement in fit over the previous model. If there was no significant improvement between two stages, then the previous model was taken as the best description of the data.

Estimates of N_{opt} values were derived from the fitted LpE parameters as follows:

$$Nopt = \frac{[\ln(k/1000 - c) - \ln(b(\ln r))]}{\ln r} \quad \text{(Equation 6)}$$

Where k is the breakeven price ratio between fertiliser N (p/kg) and grain (p/kg). A breakeven ratio of 5 was used in this study because this is used as a standard for fertiliser recommendations in the UK for cereals. The yield at each N_{opt} rate (Y_{opt}) was calculated from the fitted parameters.

Grain N Response Curves

A response curve was fitted independently to each set of grain N data for each variety. A Normal Type curve with Depletion (NTD) function was used (with the exception of the East Lothian site in 2018 where an Exponential curve was fitted and the Nottinghamshire site in 2019 where a linear curve was fitted.

The function for the NTD curve is:

$$y = (d+c*EXP(a*(N-b)^2)) \quad \text{(Equation 7)}$$

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

The function for the Exponential curve is:

$$y= (a+b*(R^N)) \quad \text{(Equation 8)}$$

where y is grain N (%), a, b and R are fitted parameters determined by fitting, and N is applied N (kg/ha).

The function for the linear curve is:

$$y= (a+b^N) \quad \text{(Equation 9)}$$

where y is grain N (%), a and b are fitted parameters determined by fitting, and N is applied N (kg/ha).

Review Data

A previous UK experimental dataset was utilised in the project to provide opportunities for further data analysis and exploration. The majority of the data selected had been previously reviewed by Roques *et al.,* (2016), with the exception of one CF Fertiliser funded trial conducted by ADAS in 2017. This UK dataset was restricted to include 13 experiments carried out since 2005 for which N response curves explained at least 80% of variation and data for the most recently introduced varieties used in each experiment (Table 3.12). This dataset is referred to as the UK Review dataset from this point forward. Additionally, an extensive Danish dataset provided by Seges was analysed, which included 48 N response experiments carried out between 2005 and 2019. The Danish data was kept separate to the UK dataset for all analyses and was used to investigate whether similar effects to those found in the UK dataset also applied to Denmark. All experiments included in the database used between five and seven N rates (including a nil N treatment), to allow the fitting of linear plus exponential response curves to yield data and normal plus depletion response curves to grain N% data. The SNS (kg/ha) was estimated at each site from the N uptake by crops without N fertiliser using the following:

SNS= 10 * (Yield at Nil N) * (Grain N% / NHI) (Equation 10)

Where NHI is the N Harvest Index, taken as 0.75 for nil N treatments and 0.73 for all other N treatments (see justification in section 5).

Table 3.12 Data sources for review of spring barley N requirements

Year	Location	Soil type	Variety	Source
2005	Aberdeenshire	SZL	Cocktail/Troon	Sylvester-Bradley et al (2008)
2005	Aberdeenshire	SL	Cocktail/Doyen	Sylvester-Bradley et al (2008)
2006	Cambs	SCL	Cocktail/Doyen	Sylvester-Bradley et al (2008)
2006	Yorkshire	SZL chalk	Cocktail/Tocada	Sylvester-Bradley et al (2008)
2007	Aberdeenshire	SL	Westminster/Waggon	Sylvester-Bradley et al (2008)
2007	Cambs	SL	Waggon/Publican	Sylvester-Bradley et al (2008)
2007	Aberdeenshire	SZL	Publican/Doyen	Sylvester-Bradley et al (2008)
2007	Aberdeenshire	SL	Waggon/Optic	Gilchrist et al. (2012)
2007	Fife	SL	Waggon/Optic	Gilchrist et al. (2012)
2008	Aberdeenshire	SL	Waggon/Optic	Gilchrist et al. (2012)
2008	Borders	SL	Waggon/Optic	Gilchrist et al. (2012)
2008	Fife	SL	Waggon/Optic	Gilchrist et al. (2012)
2017	Norfolk	LS	RGT Planet	CF Fertilisers

4. Results

4.1. Environmental conditions

Soil N Supply

The soil N supply for each ADAS experimental site is shown in Table 4.1. SNS indices according to the Field Assessment Method were consistent at Index 1 or Index 2 across sites.

Table 4.1 SMN, AAN and the SNS index estimated from the AHDB Nutrient Management Guide for each ADAS experiment.

Site	SMN (kg/ha)	AAN (kg/ha)	SNS Index (FAM)
18 Norfolk	52	24	1
18 Notts	71	35	1
18 Yorks	45	35	1
18 East Lothian	96	43	1
19 Norfolk	50	28	1
19 Notts	53	30	2
19 Yorks	93	67	1/2
19 East Lothian	135	52	1
20 Norfolk	63	43	1
20 Notts	38	30	2
20 Yorks	48	40	1

Rainfall

Rainfall data for each site is shown in Figures 4.1 to 4.4. This information is relevant in providing context to the results that follow in this report. At the Nottinghamshire site, rainfall from 1st March to 30th June amounted to 229 mm in 2018, 212 mm in 2019 and 111 mm in 2020. Rainfall at the Norfolk site was 174 mm in 2018, 190 mm in 2019 and 117 mm in 2020. In North Yorkshire, rainfall in the period of 1st March to 30th June was 218 mm in 2018 and 160 mm in 2020. In 2019, rainfall from 1st March to 28th May came to 113 mm. Finally, in East Lothian, rainfall amounted to 166 mm in the March – June period in 2018 and 208 mm in 2018.

At the Norfolk site in 2019, only 4.2 mm rain fell between 18th March and 30th April. Conditions at this site was also relatively dry in 2020, with 1.9 mm falling between 1st and 27th April, which was then followed by 21 mm over three days.

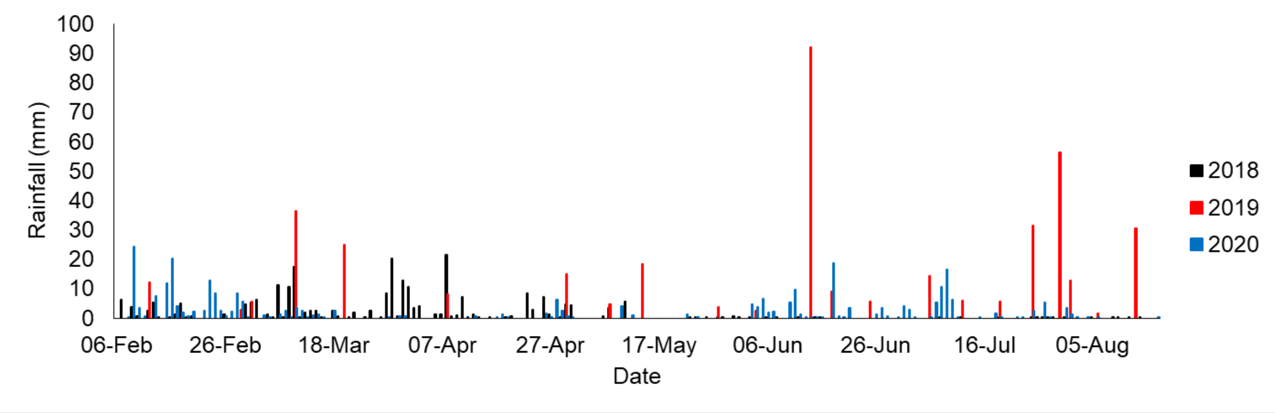

Figure 4.1 Rainfall data for the Nottinghamshire site in 2018, 19 and 2020. Data for 2019 is less frequent than 2018 and 2020.

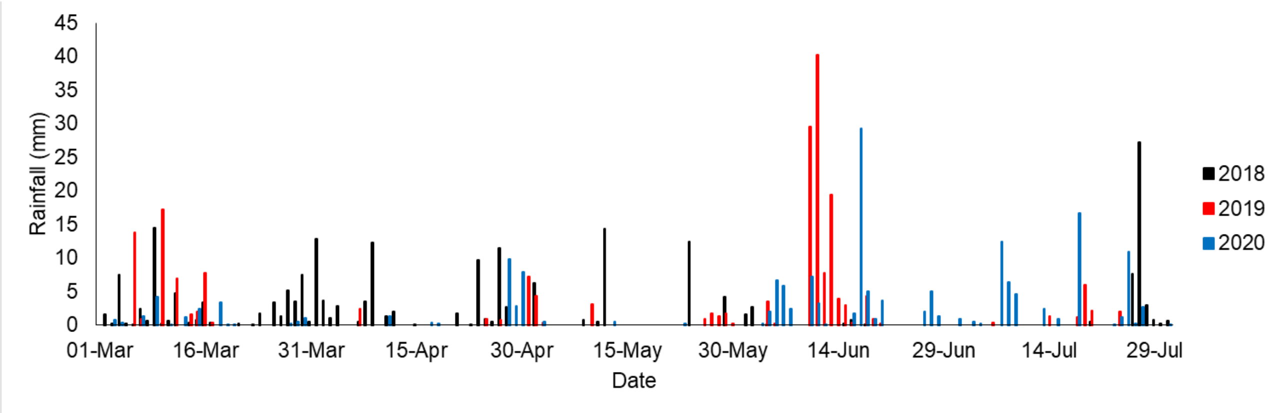

Figure 4.2 Rainfall data for the Norfolk site in 2018, 19 and 2020.

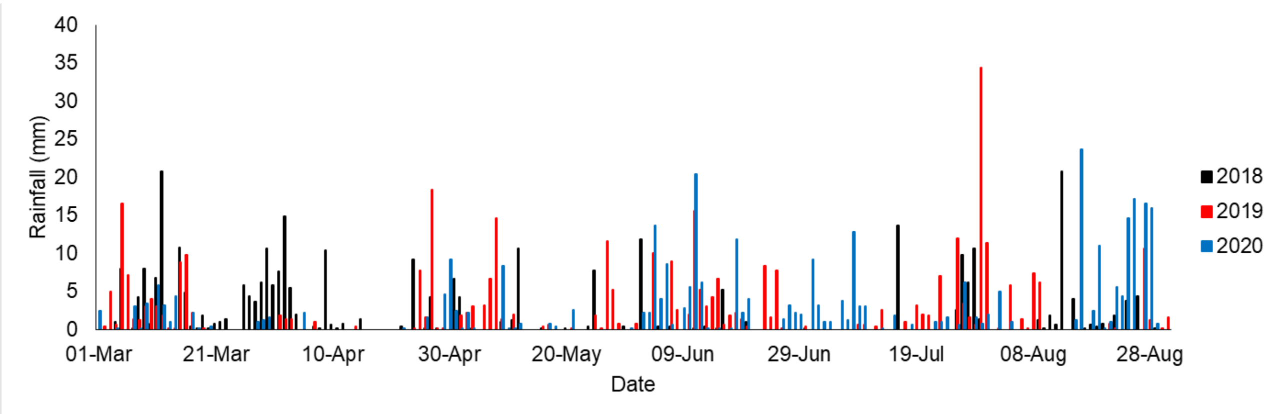

Figure 4.3 Rainfall data for the North Yorkshire site in 2018, 19 and 2020.

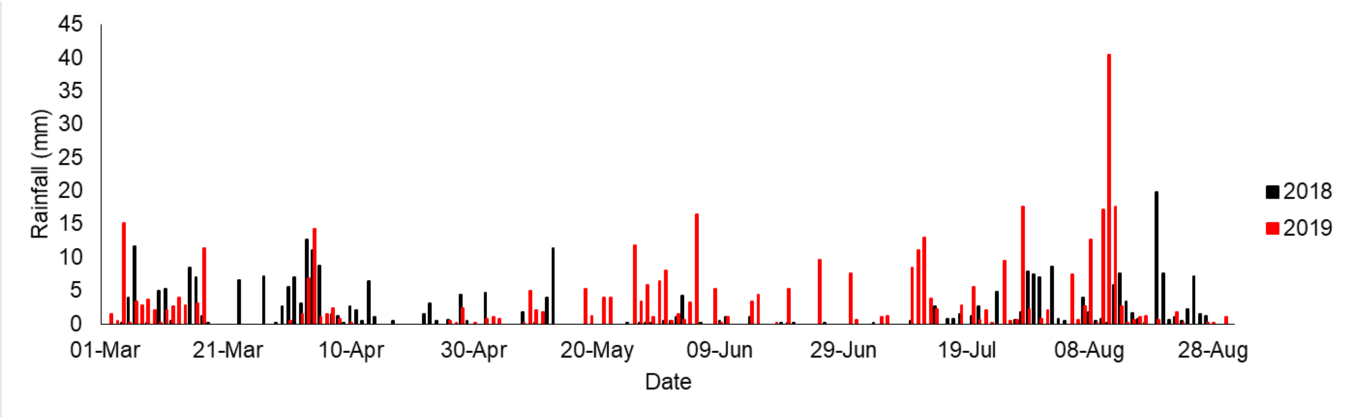

Figure 4.4 Rainfall data for the East Lothian site in 2018 and 2019.

4.2. Objective 3 Quantify the effect of rate of soil applied N fertiliser on grain N%

The primary objective of this section is to understand how N fertiliser rate affects grain N concentration and whether variety choice affects this relationship. In order to calculate the optimum N rate required to achieve specific grain N concentrations it is also necessary to understand the effect of N rate on grain yield and quality parameters, such as specific weight and screenings, so that any potential trade-offs between grain N concentration and yield/quality can be evaluated. Finally, the effect of N rate on yield components and lodging are reported to help explain the mechanism of effects of N rate on yield and grain N concentration which will help to develop wider management strategies for maximising crop productivity.

Grain N% and yield

Linear plus exponential curves were fitted to N response data obtained for each of the three varieties (Concerto, Laureate and RGT Planet) or single variety (KWS Irina or Laureate) from the eleven experiments performed in years 2018-2020 (Appendix 1). At the Norfolk, Nottinghamshire and East Lothian sites where more than one variety was assessed, statistical analysis showed that either the same response curve, or parallel response curves, were fitted to the different varieties which meant that all varieties in any given experiment had the same economically optimum N rate (N_{opt}). Note that at the North Yorkshire site, a single variety was tested in each year. Table 4.2. shows the N_{opt}, along with average yield and grain N% at the N_{opt} across varieties where multiple varieties were included. Figure 4.5 demonstrates the N response curves for each experiment. N_{opt} ranged from 30 kg N/ha at Norfolk in 2020 to 219 kg N/ha at North Yorkshire in 2018. Average yields at the N_{opt} ranged from 3.62 t/ha at Norfolk in 2020 to 9.36 t/ha at Nottinghamshire in 2019, with an overall average across all sites of 7.38 t/ha. Grain N% at the N_{opt} averaged 1.63%, with a range of 1.33% at North Yorkshire in 2020 to 1.97% at North Yorkshire in 2018 (Table 4.2 and Figure 4.6).

Table 4.2 Summary of average N_{opt}, yield (t/ha) at the N_{opt} and grain N% at the N_{opt}.

Year	Site	N_{opt} (kg/ha)	Yield at N_{opt} (t/ha)	Grain N% at N_{opt}
2018	E.Lothian	171	9.05	1.77
2018	Norfolk	74	5.34	1.40
2018	Nottinghamshire	104	7.79	1.56
2018	North Yorks	219	7.84	1.97
2019	E.Lothian	116	8.88	1.58
2019	Norfolk	83	4.48	1.56
2019	Nottinghamshire	151	9.36	1.63
2019	North Yorks	124	9.01	1.40
2020	Norfolk	30	3.62	1.74
2020	Nottinghamshire	169	8.24	1.95
2020	North Yorks	60	7.57	1.33

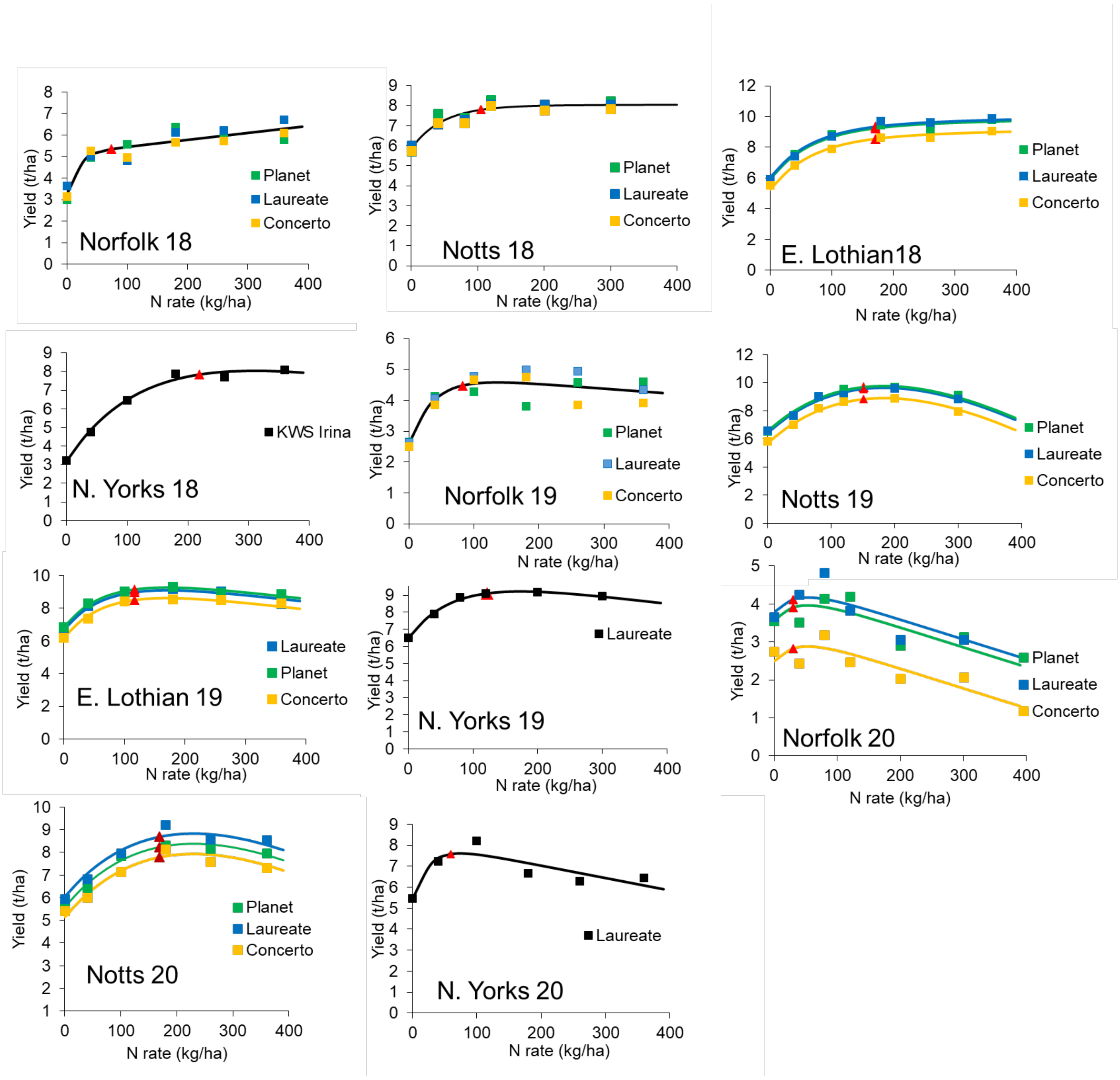

Figure 4.5 Linear plus exponential curves fitted to yield response data. Solid squares indicate experimental data. Red triangles represent the economic optimum N rate.

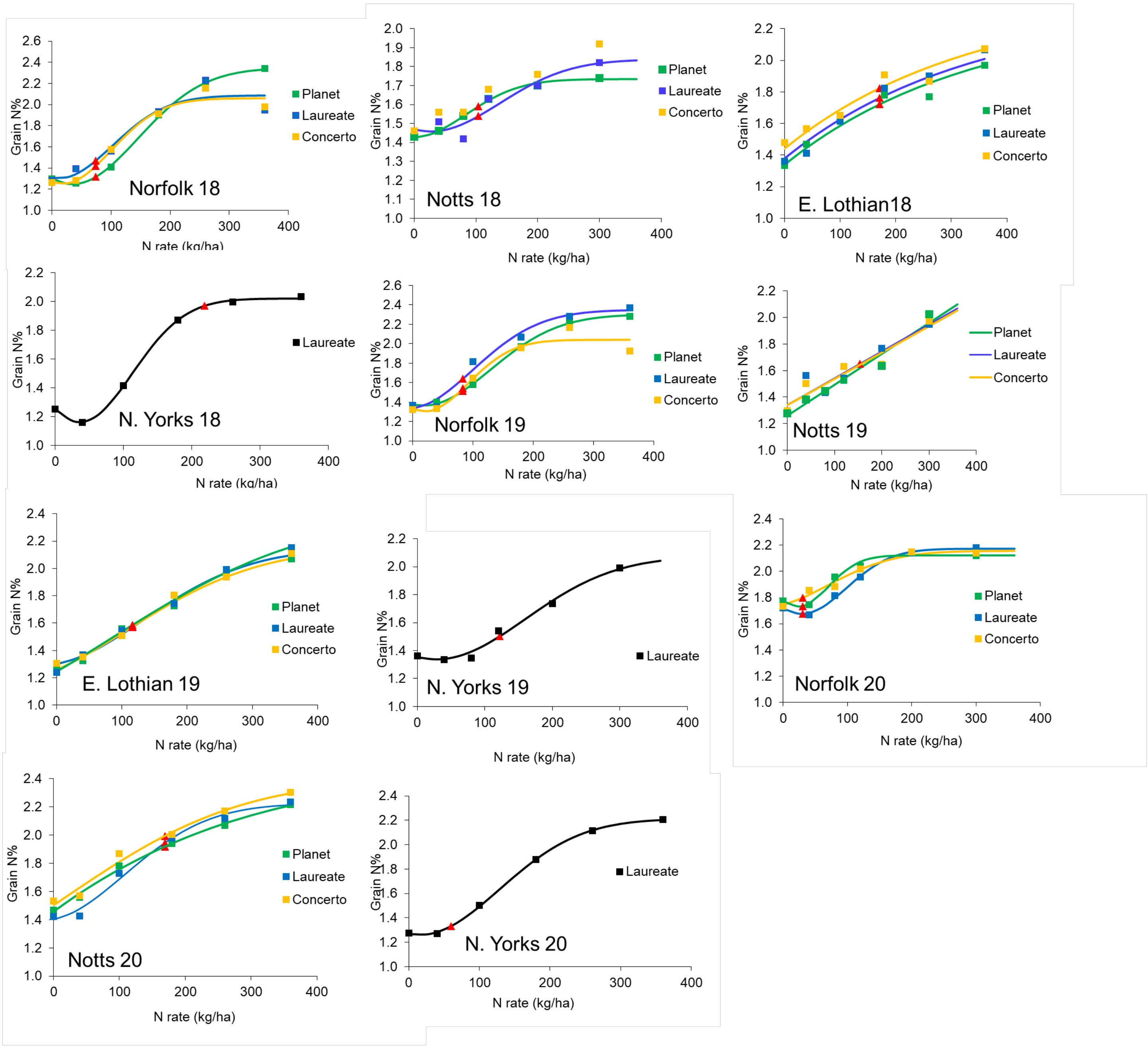

Figure 4.6 Normal plus depletion curves fitted to grain N% data, with the exception of the East Lothian 2018 site where an exponential curve was fitted and Notts 2019 where a linear curve was fitted. Solid squares indicate experimental data. Red triangles indicate the economic optimum N rate.

Does variety affect the responses to N rate?

Across the eight experiments where Concerto, RGT Planet and Laureate were included, variety had a significant effect on yield in six cases, with Concerto yielding lower than the two modern varieties across the six different N rates included in each experiment (Appendix 1). When the data was grouped together and a cross site analysis performed, variety was shown to significantly affect yield with Concerto yielding 0.6 t/ha less than RGT Planet, and 0.7 t/ha less than Laureate. Focusing on yield at the N_{opt}, there was also a significant effect of variety (P=0.023), and in this scenario, Concerto yielded 0.6t/ha less than Laureate and 0.7 t/ha less than RGT Planet.

Notably, across the same eight sites and all N rates, there was no significant effect of variety on grain N%, with average grain N% measuring 1.74%, 1.74% and 1.72% for Concerto, Laureate and RGT Planet respectively (Appendix 1). Additionally, when focusing on grain N% at the N_{opt} only, there was no significant impact on grain N% (P=0.388). Across these sites, the average grain N% at the N_{opt} was 1.65%, 1.64% and 1.58% for Concerto, Laureate and RGT Planet respectively. Across the eight experiments, there was only one experiment (Norfolk 2019) where there was a significant interaction between N rate and variety on grain N%. In this experiment, the grain N% for Concerto at higher N rates fell between 260 and 360 kg N/ha, with the modelled values showing a plateauing for grain N% between 180 and 360 kg N/ha. This was in contrast to the results for Laureate and RGT Planet, which continued to increase.

Therefore, the results indicate that whilst yield is affected by variety, with modern varieties yielding more than the older variety Concerto, variety does not significantly affect grain N%.

Explaining varietal effects on yield

To understand the reduced yield of Concerto in more detail, the effect of variety on a number of physiological parameters was investigated (Appendix 1). Focusing on the Nottinghamshire and Norfolk sites, where a crop sample were taken before harvest, a significant impact of variety on dry matter harvest index (DMHI) was observed, with Concerto displaying a significantly reduced DMHI in comparison to Laureate (Figure 4.7a). Nitrogen Harvest Index (NHI) was also significantly reduced for Concerto in comparison to both Laureate and RGT Planet (Figure 4.7b). Together this data indicates that Concerto partitioned less dry matter and N to the grain compared with the more modern varieties. There was no significant effect of variety on Total N uptake across the six N rates (Figure 4.7c). However, notably, when the dataset was restricted to the Nil N rate only, Concerto exhibited a significantly lower Total N uptake (P=0.049), with 69 kg N/ha compared to 75 kg N/ha for Laureate and 72 kg/ha for RGT Planet (Figure 4.7d).

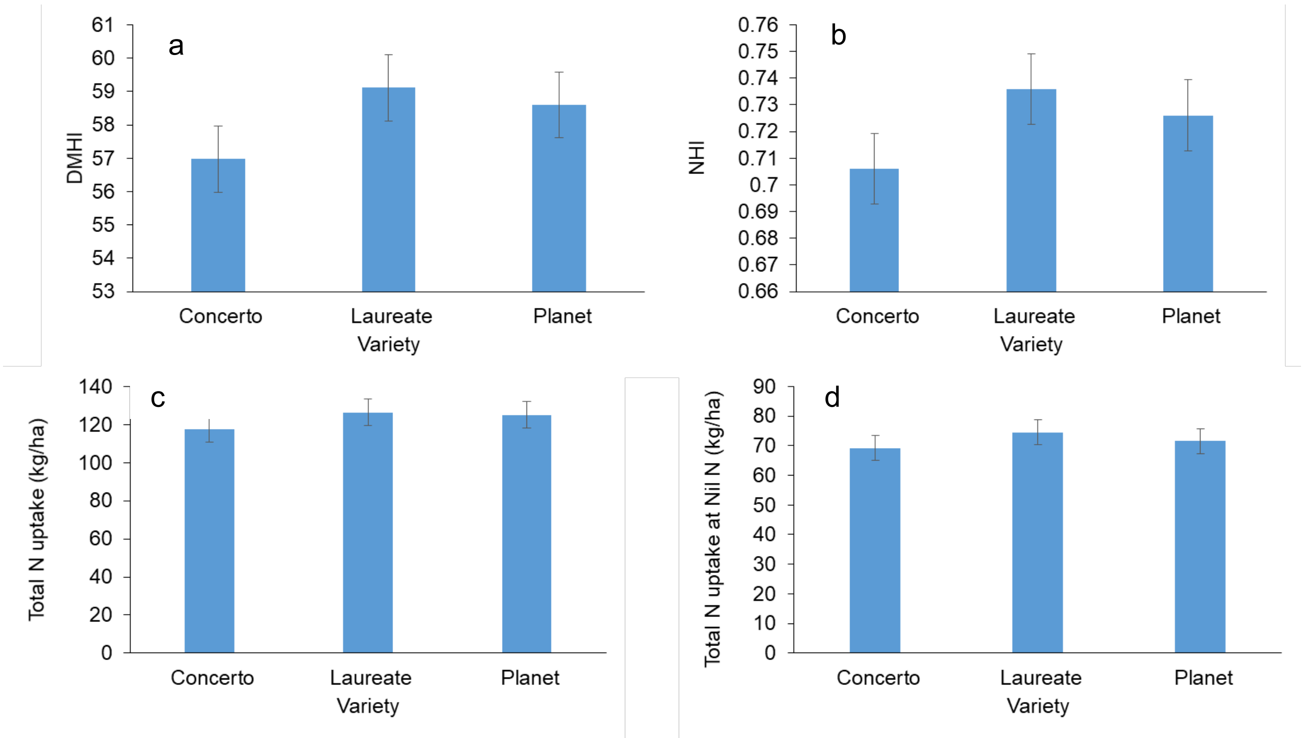

Figure 4.7 Effect of variety on dry matter harvest index (DMHI) (a), nitrogen harvest index (NHI) (b), Total N uptake (kg/ha) (c) and Total N uptake at Nil N (kg/ha) (d). Error bars represent the LSD.

To further the understanding of the difference in yield between Concerto and the modern high yielding varieties, effects on components of yield was investigated (Figure 4.8). The results indicated that variety had a significant effect on ears/m^2 (P=0.015), grains/ear (P<0.001) and TGW (0.018). As shown in Figure 4.8a, Concerto displayed significantly fewer ears/m^2 compared to Laureate, whilst Laureate had significantly fewer grains/ear in comparison to both Concerto and RGT Planet. These differences resulted in no significant effect on grains/m^2. The TGW of Concerto was significantly lower than both Laureate and RGT Planet. Therefore overall, it appears that Concerto yielded less than the modern varieties because it produced fewer ears and had lighter grains.

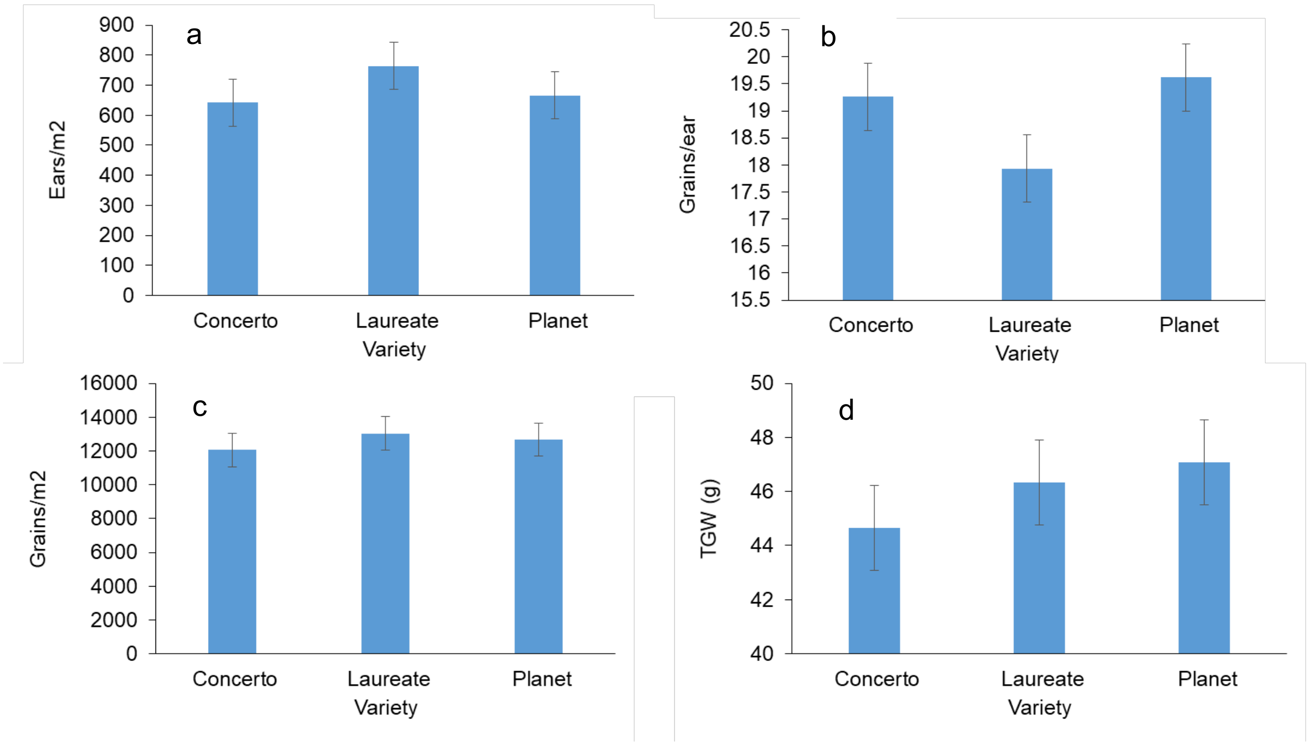

Figure 4.8 Effect of variety on Ears/m^2 (a), Grains/ear (b), Grains/m^2 (c) and TGW (d). Error bars represent the LSD.

Specific Weight and Screenings

Across the eleven experiments performed, there were few instances of a significant effect of N rate on specific weight (Appendix 1). In the Norfolk 2018 experiment, average specific weight across the experiment was 67.9 kg/hl and the Nil N treatment led to a significantly lower specific weight than the five other N rates, whereas N rates of 180, 260 and 360 kg N/ha resulted in significantly higher specific weights than 40 kg N/ha. Additionally, in the Yorkshire trial in 2019, again the Nil N treatment resulted in significantly lower specific weight than the other N rate treatments. N rates of 200 and 300 kg N/ha significantly increased specific weight in comparison to 40 and 80 kg N/ha. In contrast in the East Lothian experiment in 2019, it was the higher N rates which produced poorer specific weights. Finally, in the Norfolk 2020 experiment, specific weights were generally poor, with an average specific weight of 53.2 kg/hl. In this experiment, specific weight was reduced by increasing N rate.

Across the eight experiments where RGT Planet, Laureate and Concerto were all included, variety had inconsistent effects on specific weight (Appendix 1). In the Nottinghamshire experiment in 2018, on average specific weight was significantly lower for Laureate than RGT Planet and Concerto, and this result was also demonstrated in the Nottinghamshire trial in 2020. In the East Lothian and Norfolk trials in 2018, Laureate also exhibited a significantly lower specific weight in comparison to Concerto and RGT Planet (East Lothian) and RGT Planet (Norfolk). In the East Lothian trial and Nottinghamshire trials in 2019, specific weight was significantly lower for both RGT Planet and

Laureate in comparison to Concerto. Whilst in contrast, specific weight was significantly lower for RGT Planet than Laureate in the Norfolk 2020 experiment.

Lodging

In each experiment, leaning, lodging and brackling was assessed at harvest (Appendix 1). Generally low amounts of lodging and brackling were observed which are summarised in Appendix 1. In the Nottinghamshire trial in 2018, small amounts of leaning were measured in the crop, with a significant effect of both N rate and variety on the percentage of leaning. The amount of leaning was significantly greater at the 200 and 300 kg N/ha treatments than for the lower N rates. In the North Yorkshire trial in 2019, significant effects of N rate on leaning, lodging, brackling and necking were observed. There was significantly more lodging in the 360 kg N/ha treatment than the other N rate treatments. Plots which received 180 and 260 kg N/ha exhibited significantly more brackling than the 0 and 40 kg N/ha treatments.

There were small levels of brackling in the Nottinghamshire trial in 2020, with N rate significantly affecting the amount detected. N rates of 180, 260 and 360 kg N/ha showed significantly greater levels of brackling than N rates of 0 and 40 kg N/ha. In this trial, N rate and variety also had a significant effect on the percentage of the crop displaying leaning. Overall, the levels of leaning were low. The North Yorkshire trial in 2020 also displayed significant effects of N rate on lodging and brackling. N rates of 180, 260 and 360 kg N/ha resulted in 95% lodging. It is likely that at this site, the high amounts of lodging in the trial may have contributed to the lower N_{opt}.

4.3. Objective 2. Quantify the effect of timing of soil applied N fertiliser on grain N%

The primary objective of this section is to understand how the timing of N fertiliser application affects grain N concentration. In order to deduce the optimum application timings to achieve specific grain N concentrations it is also necessary to understand the effect of N timing on grain yield and quality parameters, so that any potential trade-offs can be evaluated. Finally, the effect of N timing on shoot number, yield components and lodging are reported to help explain the mechanism by which N timing affects yield and grain N concentration which will help to develop wider management strategies for maximising crop productivity.

Grain N% and yield

To determine the effect of N timing on yield, experiments were performed which consisted of four N timing treatments: Seedbed, RB209, Late and L&O, along with four varieties: RGT Planet, Laureate, LG Diablo and Concerto (see section 3 for details) (Appendix 2). At the North Yorkshire site, only one variety was tested and this was KWS Irina in 2018 and then Laureate in 2019 and 2020. A summary of application growth stages and dates is summarised in Table 3.5. At all sites, with the exception of East Lothian, the seedbed N application was applied on the same day as drilling. This was top dressed at the Norfolk, East Lothian & North Yorkshire (2018 only) sites and incorporated at the Nottinghamshire site and North Yorkshire site (2019 & 2020) just before drilling the seed. For the East Lothian site, N was applied 6 days after drilling in the 2018 experiment and 3 days after drilling in the 2019 experiment.

Table 4.4 summarises the effects of N timing across the four varieties. A cross site analysis showed that yield was significantly reduced when zero N was applied in the seedbed (Late N), with an average yield reduction of 0.38 t/ha compared to 100% of N applied in the Seedbed (Seedbed N). Across the eleven experiments, there were four experiments where N timing had a statistically significant effect on yield. At Nottinghamshire in 2018 and North Yorkshire in 2020, the Late N timing treatment resulted in a significantly lower yield than the other treatments. In the Nottinghamshire experiment, the L&O treatment also resulted in an almost significantly lower yield than the seedbed treatment. In the Norfolk experiment in 2019, the Late N treatment yielded significantly less than the L&O treatment, with no other significant differences detected. At the Scottish site in 2018 there were a range of effects of N timing on yield – with the Late N treatment yielding significantly less than the RB209 and L&O treatments. Interestingly the RB209 treatment yielded significantly more compared to the seedbed treatment in this experiment.
There was no evidence to suggest that the four varieties tested responded differently to the N timing treatments.

Rainfall measurements indicated that at the Nottinghamshire site in 2018, conditions were extremely dry following the second and final N applications at GS 23/24 and GS39, whereas 16 mm was received following the seedbed N application on 24th April. At the East Lothian site in 2018, 10 mm, 0 mm and 1.2 mm was received by the crop during the 7 days following the first, second and third applications respectively. At Norfolk in 2019, interestingly, 12 mm was received in the seven days following the second N application, with no rainfall in the seven days following the first or third applications. Finally, at the North Yorkshire site in 2020, the second N application in this trial was followed with 19 mm of rain, whilst conditions following the first and third applications were much drier.
It is important that the implications of rainfall are fully considered when interpreting the effects of the N timing treatments. There were three experiments where there was less than 1 mm of rainfall during the 14 days following an N application. At the Nottinghamshire site in 2018, less than 1 mm of rainfall was received following the N application at GS39. At the East Lothian site in 2018, following the 2nd application at GS13, less than 1 mm was received, and finally at the Norfolk site in 2020, following the 2nd application at GS23, there was also a significant lack of rainfall.

At both the Nottinghamshire and East Lothian experiments in 2018, there were significant effects of the N timing treatment on yield. The L&O treatment in the Nottinghamshire experiment yielded 0.43 t/ha less than the seedbed treatment and this was almost statistically significant. It is notable that the second N application at the East Lothian site was compromised by a lack of rainfall, at this site the Late N timing yielded significantly less than the RB209 and L&O treatments.

Table 4.4 Yield (t/ha) in response to N timing treatments.

Site	Seedbed	RB209	Late	L&O	*P*	LSD
Norfolk 18	5.86	6.15	5.36	6.22	0.183	0.910
Notts 18	6.89	6.57	5.70	6.46	0.003	0.440
North Yorks 18	6.89	7.32	6.99	6.97	0.253	0.446
East Lothian 18	7.83	8.94	7.16	8.40	0.029	1.065
Norfolk 19	4.63	4.09	3.87	4.79	0.021	0.910
Notts 19	9.15	8.84	9.15	9.43	0.150	0.520
North Yorks 19	9.06	8.97	8.94	8.86	0.830	0.510
East Lothian 19	8.41	8.49	8.30	8.38	0.100	0.150
Norfolk 20	3.62	3.58	3.90	3.96	0.536	0.748
Notts 20	6.68	5.96	6.26	6.67	0.323	1.011
North Yorks 20	7.87	8.07	7.07	7.94	0.029	0.627
Mean	6.99	7.00	6.61	7.10	0.01	0.294

Across the eleven sites, there was no significant effect of N timing treatment on grain N% (Table 4.5) (Appendix 2). On a site by site basis, grain N% was significantly impacted by N timing in four of the eleven experiments, with inconsistent treatment effects between the sites. At the Nottinghamshire site in 2018, grain N% was significantly higher for the Seedbed treatment compared to the three other N timing treatments. The grain N% for the Late N treatment was significantly lower than that obtained from the L&O treatment. In contrast, in the Scottish experiment in 2018 the Late N treatment had a significantly higher grain N% compared to the other treatments. This was also found in the Nottinghamshire site in 2019, whereby the grain N% for the Late N treatment was significantly higher than for the Seedbed N treatment. Finally, at the North Yorkshire site in 2020, grain N% for the Late N treatment was significantly higher than the Seedbed and RB209 treatments. In this experiment, the L&O treatment also showed significantly higher grain N% than the RB209 treatment. There was no evidence that the varieties responded differently to the N timing treatments in terms of their grain N concentration, with no experiments showing a significant interaction between variety and N timing treatment on grain N%.

Table 4.5. Grain N% in response to N timing treatments.

Site	Seedbed	RB209	Late	L&O	*P*	LSD
Norfolk 18	1.83	1.73	1.89	1.63	0.121	0.230
Notts 18	2.32	1.80	1.75	1.96	0.002	0.209
North Yorks 18	1.42	1.75	1.67	1.59	0.062	0.236
East Lothian 18	1.65	1.67	1.71	1.67	0.012	0.030
Norfolk 19	1.73	1.86	1.81	1.81	0.270	0.240
Notts 19	1.53	1.57	1.61	1.57	0.030	0.050
North Yorks 19	1.53	1.61	1.54	1.46	0.120	0.110
East Lothian 19	1.62	1.68	1.63	1.61	0.270	0.080
Norfolk 20	1.9	1.97	1.93	1.96	0.137	0.065
Notts 20	1.98	1.88	1.99	1.97	0.332	0.152
North Yorks 20	1.77	1.72	1.87	1.83	0.021	0.085
Mean	1.75	1.75	1.76	1.73	0.924	0.093

Components of yield

To understand the mechanism by which N timing affects yield, the components of yield were assessed across nine of the experiments (Table 4.9). Results for individual sites are presented in Tables 1.23 to 1.50 in appendix 2. The Late N treatment (zero seedbed N) reduced yield because it produced shoots with fewer grains per ear (P=0.002; LSD= 0.808). Additionally, the Seedbed N treatment resulted in significantly more grains/ear than the RB209 treatment. Numerically, the Late N timing treatment had the lowest number of grains/m^2, and the impact of N timing on grains/m^2 was statistically significant (P=0.025; LSD= 699.8), whereby the L&O treatment resulted in a significantly higher number of grains/m^2 than the Late treatment. There was no significant difference in the number of grains/m^2 between the Seedbed, RB209 and L&O treatments. There was no significant effect of the N timing treatment on ears/m^2 across all the experiments (P=0.254; LSD = 65.6). However, at one of the sites where yield was significantly reduced by the Late N timing treatment (Nottinghamshire 2018), this treatment did exhibit a significantly lower number of ears/m^2. In contrast, at the North Yorkshire site in 2020, where yield was also significantly reduced by applying no N in the seedbed, the Late N treatment resulted in a significantly higher number of ears/m^2 than the Seedbed N and L&O treatments. This was coupled with a significantly lower number of grains/ear, and a significantly lower TGW too. Across the eleven experiments there was no significant effect of N timing treatment on thousand grain weight (TGW) (P=0.672; LSD=1.011). On average, TGWs ranged from 46.4 g for the L&O treatment to 47.0g for the Seedbed treatment.

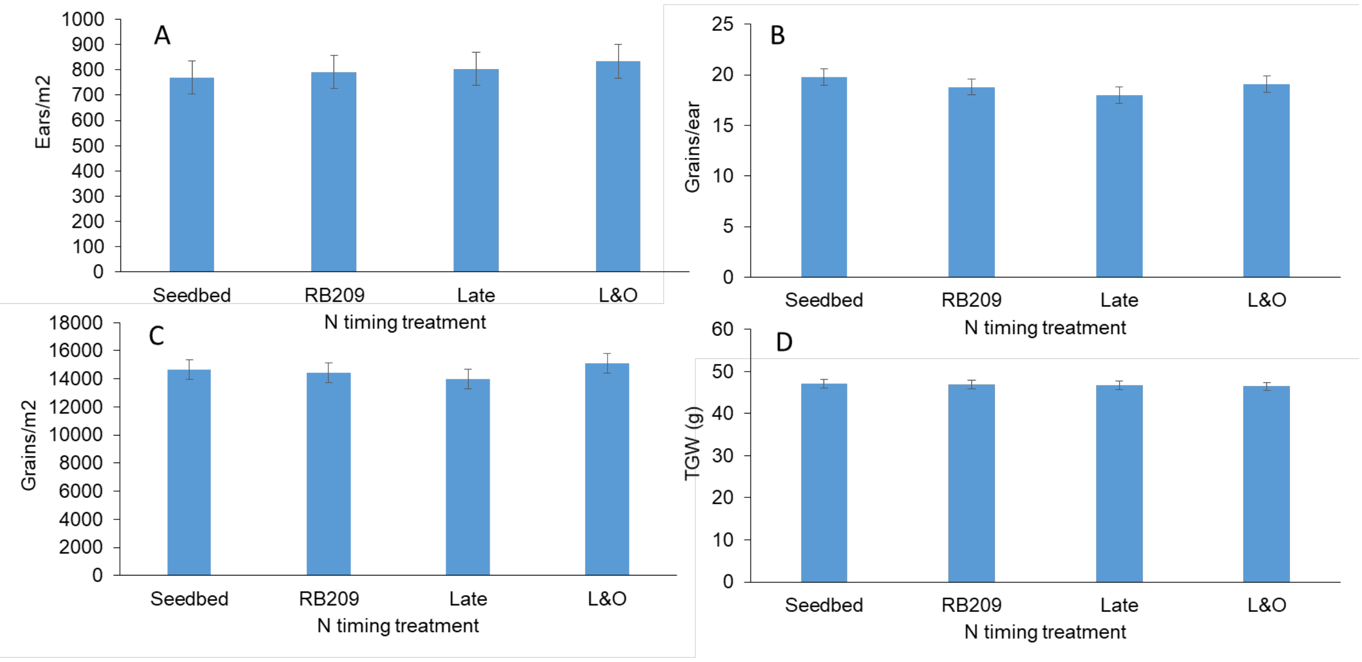

Table 4.9 Effect of N timing on ears/m^2 (A), grains/ear (B), grains/m^2 (C) and TGW (D). Error bars represent the LSD.

Specific weight and screenings

Across the eleven experiments we found no consistent effect of N timing on specific weight (P=0.7) (Table 4.6) (Appendix 2). However, in the Norfolk experiment in 2019, the N timing treatment significantly affected specific weight, with the Late treatment resulting in a greater specific weight than the three other treatments (P=0.007). There was also a significant interaction between N timing treatment and variety in this experiment. Specific weight was also significantly affected by N timing in the North Yorkshire experiment in 2020, with the L&O treatment resulting in a significantly lower specific weight than the other treatments (P=0.006).

Table 4.6. Specific weight (kg/hl) in response to N timing treatments.

Site	Seedbed	RB209	Late	L&O	*P*	LSD
Norfolk 18	68.3	68.8	66.7	68.4	0.001	4.947
Notts 18	63.3	65.4	63.5	63.4	0.393	3.150
North Yorks 18	64.4	64.5	64.2	64.2	0.958	1.631
East Lothian 18	65.5	66.6	65.4	66.0	0.182	1.274
Norfolk 19	60.8	60.7	62.8	60.6	0.007	1.097
Notts 19	63.6	63.2	63.0	63.2	0.235	0.602
North Yorks 19	63.6	63.0	63.0	63.6	0.071	1.720
East Lothian 19	62.8	61.9	62.2	61.9	0.222	1.100
Norfolk 20	53.2	54.5	53.8	54.2	0.145	1.145
Notts 20	60.9	59.1	62.1	61.7	0.214	3.209
North Yorks 20	60.4	59.8	59.9	58.7	0.006	0.701
Mean	62.3	62.4	62.3	62.01	0.700	0.711

The percentage of grains greater than 2.5 mm, between 2.25 mm and 2.5 mm and less than 2.25 mm were measured in each experiment. In the 2018 experiments, N timing significantly affected screenings at the Nottinghamshire site only. At this site, the percentage of grains greater than 2.5 mm was significantly lower for the seedbed treatment in comparison to the RB209 and late timing treatments. The seedbed N treatment showed a significantly greater percentage of grains that were 2.25 mm to 2.5 mm in comparison to the RB209 and late timing treatments. Finally, this treatment also resulted in a significantly higher percentage of grains that were less than 2.5 mm in size in comparison to the RB209 and late timing treatments. On average, this treatment resulted in 8% of grains which were less than 2.25 mm, which would be likely to fall below malting requirements. The proportion of grains that were greater than 2.5 mm was also significantly lower for the L&O timing treatment in comparison to the RB209 treatment.

Similarly, in 2019, it was the Nottinghamshire site which displayed significant effects of N timing on screenings. In this experiment, the L&O treatment produced a significantly lower proportion of grains greater than 2.5 mm in comparison to the three other N timing treatments, but with 92% of grains greater than 2.5 mm this would not have caused issues. This treatment also resulted in a significantly greater percentage of grains that were less than 2.25 mm, although this was still at an acceptable level of 3.1%.

In the 2020 experiments, screenings were significantly affected by N timing treatment in two of the experiments, at Norfolk and North Yorkshire. In the North Yorkshire experiment, the Late treatment resulted in a significantly lower percentage of grains which were greater than 2.5 mm in comparison to the seedbed, RB209 and L&O treatments, which averaged 84%. The seedbed treatment also produced significantly more grains that were greater than 2.5 mm in comparison to the L&O treatment. In this experiment, all treatments resulted in more than 4% of grains which were less than 2.25 mm. Here the late treatment resulted in the highest percentage of grains that were less than 2.25 mm and the L&O treatment also caused significantly more grains which were less than 2.25 mm in comparison to the seedbed and RB209 treatments. Finally, at the Norfolk site in 2020 the seedbed N treatment resulted in a significantly lower proportion of grains that were greater than 2.5 mm in comparison to the RB209 and late treatments. The proportion of grains between 2.25 mm and 2.5 mm was also significantly lower for the seedbed treatment when compared to the RB209 and late treatments. Levels of screenings in this experiment would not have resulted in rejections.

Lodging

In the 2018 experiments, no leaning, lodging or brackling was recorded. In 2019, at the Nottinghamshire site, brackling was present and this was significantly affected by the N timing treatment, with average levels of brackling of 15%. In this trial, the seedbed N treatment resulted in significantly less brackling than the other treatments (Appendix 2). Both the late and L&O treatments resulted in significantly more brackling than the RB209 treatment. Interestingly, in this trial, there was a significant interaction between variety and N timing treatment, with Concerto behaving differently to the three other varieties.

In 2020, very low levels of leaning and brackling were found in the Nottinghamshire trial, but there was no significant effect of N timing. High levels of brackling were measured in the Norfolk trial in 2020, with an average of 28% brackling. However, there was no significant effect of N timing on brackling in this experiment. Finally, at the North Yorkshire site, levels of lodging in the trial were significant, with an average across all treatments of 86% and an average amount of brackling of 9%. In this trial, there was an almost significant effect of N timing on lodging and brackling (P=0.062 and P=0.063 respectively). The seedbed N treatment resulted in considerably less lodging, but more brackling. Despite the high levels of lodging in this trial, there was no significant difference in yield between the seedbed N treatment with 67% lodging and 27% brackling and the L&O treatment which had 93% lodging and 1.7% brackling.

Shoot and ear numbers

To understand the physiological effect of N timing, several assessments were performed at GS31 or GS33 in the variety Laureate, at the North Yorkshire site in each year and at Nottinghamshire and Norfolk in 2020 only. The assessments included measuring GAI, NDVI and the number of shoots. Final ear number data is also shown, and the percentage of shoots lost to allow an understanding of the dynamics of shoots through the season. It should be noted that the L&O treatment would not have had the final N application at the timing of this assessment. For this reason, the treatment was omitted from the analysis in 2018. Across the experiments, NDVI was significantly affected by the N timing treatment in three of the five experiments, with the seedbed N treatment displaying a greater NDVI. There was only one example where shoots/m^2 was significantly affected by N timing, in the North Yorkshire experiment in 2018 the seedbed N treatment displayed more shoots/m^2 than the RB209 treatment. The late N timing treatment also exhibited a lower number of shoots/m^2 but this effect was not significant. Additionally, there were some significant effects of N timing on GAI. In the North Yorkshire experiment in 2018 (Table 4.7), both the RB209 and the Late treatments displayed a reduced GAI in comparison to the seedbed treatment, with the Late treatment also significantly lower than the RB209 treatment. It is notable that in this experiment, despite the significant effects on growth early in the season, the pattern was quite different at harvest, with more shoots lost in the seedbed treatment. There was no significant effect of the N timing treatments on yield, despite the differences in ear numbers. In the North Yorkshire experiment in 2019, GAI was also significantly affected by N timing, with the late and L&O treatments showing a lower GAI than the seedbed and RB209 treatments (Tables 4.8, 4.9, 4.10, 4.11).

In no cases did the Late N timing treatment result in a significant reduction in shoots/m^2 measured at GS31 or GS33. In the North Yorkshire 2020 experiment, the late treatment produced a significantly higher number of ears/m^2, and a significant increase in the proportion of shoots retained. In fact, at this site, the number of ears/m^2 exceeded the number of shoots/m^2 measured at GS33, suggesting secondary tillering occurred in this crop, which resulted in unproductive shoots. This is confirmed by the significant increase in screenings for this treatment (Appendix 2).

Table 4.7 Physiological assessments performed at GS33 & harvest at North Yorkshire in 2018

	Timing			
	Seedbed	RB209	Late	Grand mean
GAI	2.90	2.21	1.15	2.09
NDVI	0.89	0.84	0.67	0.80
Shoots/m^2	1013	920	953	962
Ears/m^2	676	798	823	766
% shoots lost	32.8	15.2	9.5	19.2
	P	SED	LSD	
GAI	<.001	0.265	0.563	
NDVI	<.001	0.013	0.028	
Shoots/m^2	0.002	41.7	88.4	
Ears/m2	<.001	45.5	95.7	
% shoots lost	0.055	6.27	13.28	

Table 4.8 Physiological assessments performed at GS31 & harvest at North Yorkshire in 2019

	Timing				
	Seedbed	RB209	Late	L&O	Grand mean
GAI	5.28	5.04	3.6	3.94	4.47
NDVI	0.91	0.90	0.87	0.90	0.89
Shoots/m^2	1754	1584	1773	1450	1640
Ears/m^2	659	672	794	885	753
% shoots lost	60.5	57.6	54.5	39.2	52.9
	P	SED	LSD		
GAI	0.021	0.434	1.063		
NDVI	0.077	0.010	0.026		
Shoots/m^2	0.355	189	461		
Ears/m^2	0.127	89.6	219.3		
% shoots lost	0.103	7.49	18.32		

Table 4.9 Physiological assessments performed at GS33 & harvest at Norfolk in 2020

	Timing				
	Seedbed	RB209	Late	L&O	Grand mean
GAI	0.35	0.40	0.33	0.40	0.37
NDVI	0.73	0.72	0.57	0.66	0.67
Shoots/m^2	508	542	508	551	527
Ears/m^2	489	509	570	525	523
% shoots lost	4.7	1.9	-1.1	1	1.6
	P	SED	LSD		
GAI	0.668	0.0686	0.1678		
NDVI	0.004	0.0268	0.0656		
Shoots/m^2	0.921	80.5	197		
Ears/m^2	0.776	79.6	204.7		
% shoots lost	0.992	19.62	50.44		

Table 4.10 Physiological assessments performed at GS33 & harvest at Nottinghamshire in 2020

	Timing				
	Seedbed	RB209	Late	L&O	Grand mean
GAI	2.64	2.37	1.70	2.37	2.27
NDVI	0.34	0.31	3.24	0.31	0.299
Shoots/m^2	886	935	830	1047	925
Ears/m^2	1018	1041	915	1150	1031
% shoots lost	-20	-15	-11	-18	-16
	P	SED	LSD		
GAI	0.214	0.400	0.979		
NDVI	0.049	0.0255	0.0624		
Shoots/m^2	0.68	180	441		
Ears/m2	0.237	100.2	245.2		
% shoots lost	0.992	32.1	78.5		

Table 4.11 Physiological assessments performed at GS33 & harvest at North Yorkshire in 2020

	Timing				
	Seedbed	RB209	Late	L&O	Grand mean
GAI	3.48	3.64	3.03	4.05	3.55
NDVI	0.88	0.88	0.86	0.88	0.87
Shoots/m^2	1363	1221	1183	1312	1270
Ears/m^2	989	1178	1308	1123	1149
% shoots lost	24.5	3.3	-12.4	13.6	7.2
	P	SED	LSD		
GAI	0.152	0.371	0.908		
NDVI	0.298	0.0136	0.0332		
Shoots/m^2	0.335	99.2	242.7		
Ears/m2	0.028	75.0	183.4		
% shoots lost	0.042	9.73	23.81		

Crop N uptake

In order to understand the impact of the N timing treatments on yield further, the effect of N timing on total N uptake was investigated. Across the nine experiments where Total N uptake was measured, there was no significant effect of N timing (P=0.772) (Table 4.12). There were, however, two trials in which total N uptake was significantly affected by N timing. At Nottinghamshire in 2018, the seedbed N timing treatment resulted in a significantly higher Total N uptake in comparison to the other three timing treatments. In this experiment, the Late timing treatment also had a significantly lower total N uptake than the L&O treatment. In the same year, at the North Yorkshire site, the RB209 and Late treatments resulted in a significantly higher total N uptake than the seedbed N treatment. The late timing treatment also exhibited a significantly greater total N uptake than the L&O treatment.

Table 4.12 Effect of N timing on Total N uptake (kg/ha)

Site	Seedbed	RB209	Late	L&O	*P*	LSD
Norfolk 18	120	116	109	113	0.617	19.4
Notts 18	174	127	110	138	0.001	20.2
North Yorks 18	109	142	148	117	0.041	28.8
Norfolk 19	104	97.8	93.4	109.3	0.176	15.8
Notts 19	171	171	187	180	0.046	15.4
North Yorks 19	180	167	173	161	0.588	34.5
Norfolk 20	81.5	83.5	89.7	92	0.467	17.5
Notts 20	148	123	156	143	0.113	21.4
North Yorks 20	212	212	209	216	0.937	29.8
Mean	144	138	142	141	0.772	13.1

4.4. Objective 2: Quantify the effect of S fertiliser on grain N%

In each of the eleven experiments S rate was investigated, either as a full S response experiment where five rates of SO_3 were applied, or where a Nil S treatment was included (North Yorkshire in 2018; Nottinghamshire in 2019 and 2020). Across the eight experiments which tested the full five rates, there was no significant effect of S rate on yield (Table 4.13) (Appendix 3). On an individual experiment basis, a significant yield response was obtained at the Norfolk site in 2018, where yield was significantly increased by 10 kg/ha SO_3, with no further increases in yield obtained in response to further increases in sulphur. In this experiment, there was a significant effect of S on ears/m^2 and grains/m^2. SO_3 rates of 20 kg/ha or more resulted in significantly greater number of ears/m^2 and grains/m^2 in comparison to the nil s treatment. There was no significant effect of S rate on grains/ear or TGW(g).

Across the eleven experiments where a Nil S and a 40 kg/ha SO_3 treatment were included there were mixed responses to the S application, ranging from a yield increase of 1.9 t/ha through to a 1.9 t/ha yield reduction. In the three experiments where only a Nil S and a 40 kg/ha SO_3 treatment were included, the only significant yield effect detected was the 1.9 t/ha reduction in response to 40 kg/ha

SO_3 at the Nottinghamshire site in 2020 (P=0.032, LSD: 1.5 t/ha). In this experiment, the 40 kg/ha SO_3 resulted in a significantly lower number of ears/m^2 and a significantly lower number of grains/m^2. There was no significant effect of S rate on grains/ear or TGW. It should be noted that there is a possibility that underlying field variation may have influenced this result so it should be treated with caution.

To help to understand more about the risk of deficiency at each site, a soil, malate: sulphate ratio and grain S analyses were used (Table 4.14). These results show numerous scenarios in which the soil analysis and malate:sulphate test indicate S deficiency. Additionally, seven of the nine experiments in which grain S concentration of the Nil S treatment were measured indicated a sulphur deficiency.

Across the eight experiments where five S rates were included, there was no significant effect of SO_3 rate on grain N%, with a maximum difference of 0.03% between the five rates (Table 4.15). It is notable that grain N% was significantly affected by SO_3 rate in two experiments (East Lothian 2018 and North Yorkshire 2020). At the East Lothian site in 2018, the 20 kg/ha SO_3 treatment had significantly higher grain N% than the Nil S treatment. The 80 kg/ha SO_3 treatment displayed significantly higher grain N% than both the Nil S and the 10 kg/ha SO_3 treatments. In the North Yorkshire experiment in 2020, the three highest SO_3 rates all displayed significantly greater grain N% that the Nil and 10 kg/ha SO_3 treatments. Across all experiments, this was not a trend that was replicated with no indication that increasing SO_3 rate resulted in higher grain N%.

Table 4.13 Yield (t/ha) in response to different rates of SO_3.

	SO_3 rate (kg/ha)						
Site	0	10	20	40	80	*P*	LSD
Norfolk 18	4.03	5.87	7.14	5.93	6.85	0.003	1.864
Notts 18	6.16	6.18	6.16	6.6	6.36	0.167	0.425
East Lothian 18	8.79	8.97	8.58	9.11	8.54	0.442	0.789
Norfolk 19	4.27	4.46	4.91	4.89	5.22	0.123	0.808
North Yorks 19	9.00	8.84	9.19	9.29	9.32	0.612	0.806
East Lothian 19	8.77	8.61	8.77	8.52	8.56	0.780	0.633
Norfolk 20	4.83	4.25	3.97	4.05	4.27	0.729	1.533
North Yorks 20	7.88	7.92	7.82	8.47	8.27	0.237	0.703
Mean	6.72	6.89	7.07	7.11	7.17	0.354	0.504

Table 4.14 Explanatory analyses to accompany S response results. Def refers to where the chemical analysis indicated a deficiency and suf indicates sufficiency.

Site	Sulphur risk matrix	Available Soil S (mg/kg)	Malate-sulphate tissue test ratio	Grain S concentration Nil S (mg/kg) Critical 1150	Grain S concentration 40kg/ha SO_3 (mg/kg)	Yield response to 40kg/ha SO_3
Norfolk 18	High	3.6 (Def)	11.4 (Def)	977 (Def)	1118 (Def)	1.9t/ha
Notts 18	High	4.0 (Def)	1.9 - 2.9 (Def)	1019 (Def)	1006 (Def)	0.4t/ha
North Yorks 18	High	4.1 (Def)	14.9 (Def)	856 (Def)	1019 (Def)	0.3t/ha
East Lothian 18	Intermediate	-	-	-	-	0.3t/ha
Norfolk 19	High	3.3 (Def)	25.7 (Def)	1082 (Def)	1320 (Suf)	0.6t/ha
Notts 19	High	4.0 (Def)	1.9 (Suf)	1120 (Def)	-	-0.9t/ha
North Yorks 19	High	4.0 (Def)	12.0 (Def)	1072 (Def)	1089 (Def)	0.3t/ha
East Lothian 19	Intermediate	-	-	-	-	-0.3t/ha
Norfolk 20	High	0.9 (Def)	1.2 (Suf)	1153 (Suf)	1280 (Suf)	-0.7t/ha
Notts 20	High	4.0 (Def)	3.1 (Def)	1207 (Suf)	-	-1.9t/ha
North Yorks 20	High	1.3 (Def)	8.15 (Def)	933 (Def)	1033 (Def)	0.6t/ha

Table 4.15 Grain N% in response to different rates of SO_3.

	SO_3 rate (kg/ha)						
Site	0	10	20	40	80	*P*	LSD
Norfolk 18	2.00	2.00	1.84	1.72	1.93	0.31	0.322
Notts 18	1.74	1.69	1.73	1.66	1.63	0.805	0.237
East Lothian 18	1.61	1.62	1.67	1.64	1.69	0.04	0.054
Norfolk 19	1.94	1.88	1.82	1.82	1.75	0.867	0.092
North Yorks 19	1.44	1.49	1.48	1.43	1.46	0.583	0.093
East Lothian 19	1.62	1.65	1.69	1.75	1.65	0.261	0.079
Norfolk 20	1.89	1.92	1.89	1.91	1.91	0.985	0.150
North Yorks 20	1.59	1.56	1.80	1.77	1.76	0.005	0.065
Mean	1.73	1.73	1.74	1.71	1.72	0.962	0.075

4.5. Micromalting results

Results for friability, homogeneity, total malt N%, total soluble N, soluble N ratio, diastatic power (DP), wort β-glucan and hot water extract (HWE) are presented from representative sites and treatments. There were three malting analyses from harvest 2018, five from 2019 and three from 2020.

Each analysis includes a project control against which modification characteristics (friability and homogeneity) can be compared. Overall, friability ranged from good, above 90% indicating good modification during malting, to poor a value below 80% or 70%, indicating a potential problem, or under-modification. There was no evidence for systematic treatment effects on friability or homogeneity, and all data were retained for analysis of N timing and S rate on malting characteristics. Summary analyses of N rate on malting was carried out for a quality check on expected change in malting characters.

Data from harvest 2018 indicated good modification, intermediate malt N content, wort β-glucan content and hot water extract from a variety and N timing trial, an S rate trial and a N rate trial (Appendix 4). Overall, malting quality in terms of modification and hot water extract ranged from better than to poorer than the controls.

Data from harvest 2019 were from two variety and N rate trials, variety and N rate plus N timing, variety and N rate and S rate trials from multiple sites (Appendix 4). The sites and treatments provided a good range of low, medium and high malt N contents from which to compare other malting characteristics. Among all trials, modification ranged from good to poor or intermediate or variable (Appendix 4). Overall, malting quality in terms of soluble N, DP, wort β-glucan content and HWE ranged from better than or as good as, or poorer than the controls.

Data from harvest 2020 included two S rate trials, a variety and N timing trial and a variety and N rate trial (Appendix 4). Sites and treatments provided moderate to high malt N content, modification ranged from good to highly variable (Appendix 4). In most malted samples, HWE was poorer than the control, though this would have been expected from the relatively high malt N content compared to the control.

With the exception of seedbed applied N reducing malt N content, there was no significant effect of N timing on the main malting characters (Table 4.16). We conclude that N timing had no significant effect on malt modification, HWE or predicted sprit yield (PSY). The lower total malt N with seedbed N treatment was associated with reduced DP, which would be expected. Both seedbed N and RB209 treatments had slightly increased HWE and PSY compared to other treatments (Table 4.16).

For samples from N timing trials, HWE generally increased with total malt N% in samples from four out of six sites (Figure 4.10a), whilst at two low N sites, HWE expressed a wide range that was associated with different extract levels among varieties about the same malt N. DP increased with an increase in total malt N (Figure 4.10b). HWE generally increased with either across-site and within site variation in friability (Figure 4.10c), though some differential levels in either homogeneity or extract among varieties at two sites was evident.

Malting characters were affected by S rate in a limited way (Table 4.17). There was a weakly significant effect of S rate on malt modification, with nil S or 10 kg/ha S samples having reduced friability and homogeneity. Sulphur rates at 40 to 80 kg/ha significantly increased DP, but not malt N. Sulphur rates from 20 to 80 kg/ha resulted in small increase in HWE or PSY compared to nil and 10 kg/ha S, but this difference was not significant. We conclude that S application may have some positive effects on malt modification, DP, HWE and PSY.

For samples from S rate trials, within each site there was the expected association with HWE increasing with malt total N% (Figure 4.11a), data clusters represent a range of acceptable malt N and HWE. Within three trials, DP increased with total malt N%, whilst at a fourth site with high N% malt there was increased DP (Figure 4.11b); this indicates expected positive relationship between malt N content and malt enzyme levels. In samples from S rate trials there was a positive association between HWE and friability (Figure 4.11c), highlighting an expected change in grain modification and the level of extract produced.

Malting data from N rate trials were used a quality check on malting characters. The following observations were made. As expected, total malt N and total soluble N increased with increasing N rate; friability was reduced at high rates (>120 kg N/ha), DP was least at low N rates (<100 kg N/ha); HWE was greatest at low N rates (<80 kg N/ha) and least at high N rates (>120 kg N/ha).

Table 4.16 Main effect of N timing on malting characteristics. Data comprised of six year-site combinations, or 18 year-site-variety combinations. * = significant at 10%, ** = significant at 5%.

Analysis					Timing treatment					
	Wald Stat	F Stat	F Pr		Seedbed	RB209	Late	L&O	SED	LSD
Friability	0.46	0.15	0.928		86.7	85.3	87.1	86.1	2.846	5.812
Homogeniety	2.10	0.70	0.557		94.1	94.1	96.4	93.6	2.264	4.621
Total N	9.94	3.31	0.026	*	1.51	1.57	1.59	1.58	0.026	0.053
Soluble N	2.50	0.83	0.482		0.62	0.63	0.62	0.64	0.015	0.031
SNR	5.63	1.88	0.144		41.0	40.3	39.0	40.6	0.897	1.833
DP	3.35	1.12	0.350		99.1	104.0	105.0	107.2	4.275	8.732
Wort β-glucan	0.58	0.19	0.900		168.4	151.0	164.7	148.9	30.78	62.83
HWE	1.47	0.49	0.690		309.6	308.6	307.4	307.7	1.903	3.881
PSY	0.42	0.14	0.934		405.5	404.6	403.6	401.8	5.818	11.87

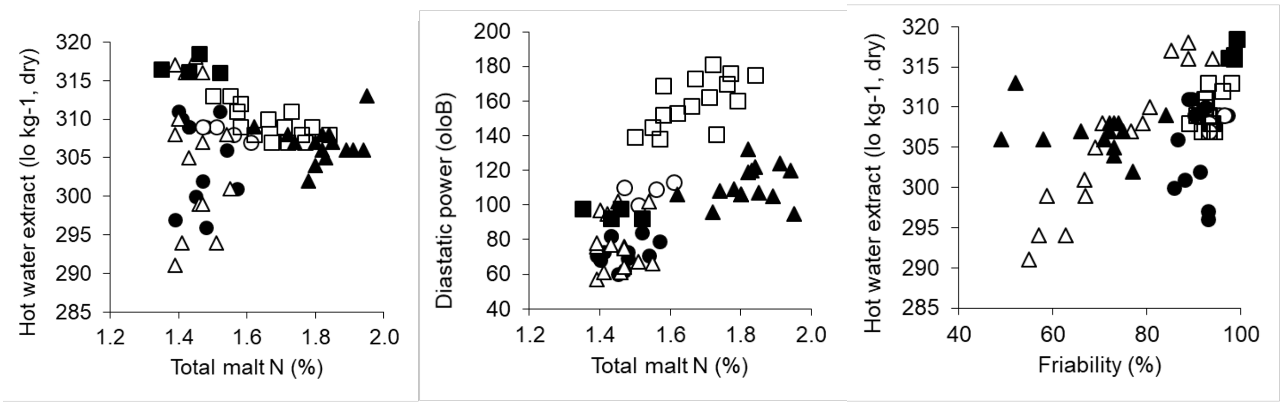

Figure 4.10 Change among different malting characteristics as influenced by N timing at six crop trials. (a) Hot water extract on total malt N, (b) Diastatic power on malt N and (c) Hot water extract on friability.

Table 4.17 Main effect of S rate on malting characteristics. Data comprised of six year-site combinations, or 18 year-site-variety combinations.

Analysis				SO_3 rate (kg/ha)						
	Wald Stat	F Stat	F Pr	0	10	20	40	80	SED	LSD
Friability	10.87	2.72	0.059 *	77.2	79.0	81.9	82.2	79.7	1.789	3.731
Homogeniety	9.07	2.27	0.098 *	86.9	87.3	89.6	89.7	87.0	1.356	2.829
Total N	4.86	1.22	0.354	1.55	1.56	1.51	1.58	1.52	0.039	0.087
Soluble N	4.97	1.24	0.345	0.63	0.63	0.63	0.60	0.55	0.045	0.101
SNR	6.51	1.63	0.231	40.8	40.2	42.2	37.6	36.2	2.689	5.859
DP	20.55	5.14	0.012 **	78.4	81.7	84.3	93.1	87.6	3.523	7.676
Wort β-glucan	4.17	1.04	0.426	273.3	214.3	200.8	209.0	224.5	39.71	86.52
HWE	6.84	1.71	0.187	303.8	303.3	306.4	306.5	304.4	1.62	3.378
PSY	8.00	2.00	0.146	387.5	391.5	392.6	396.1	392.7	3.188	6.596

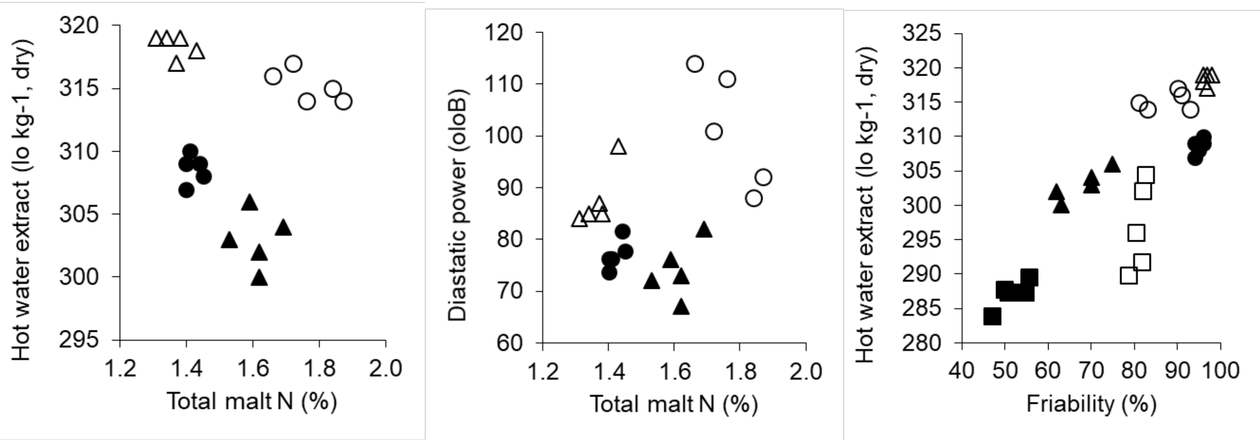

Figure 4.11 Change among different malting characteristics as influenced by S rate at different crop trials. (a) Hot water extract on total malt N at four sites, (b) Diastatic power on malt N at four sites and (c) Hot water extract on friability at six sites.

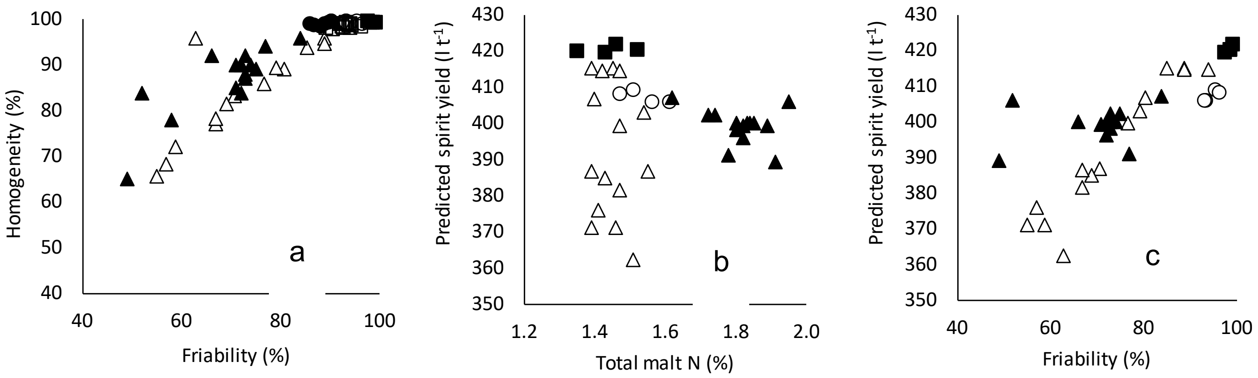

Figure 4.12. Change among different malting characteristics as influenced by N timing at six crop trials for (a) homogeneity on friability and at four sites for (b) predicted spirit yield on total malt N% and (c) predicted spirit yield on friability.

For samples from N timing trials, homogeneity and friability were positively associated (Figure 4.12, a). Some sites produced grain samples that were relatively low in both friability and homogeneity, compared to what might be expected from commercial samples i.e. <80%. This indicates lower modification of grain samples sourced from some sites, though there was no evidence to suggest that N timing itself had any negative impact on either friability or homogeneity. Predicted spirit yield decreased with an increase in total malt N% (Figure 4.12, b); this was as expected. Furthermore, predicted spirit yield was positively associated with friability (Figure 4.12, c); indicating that across sites and treatments spirit yield increased with an increased in modification.

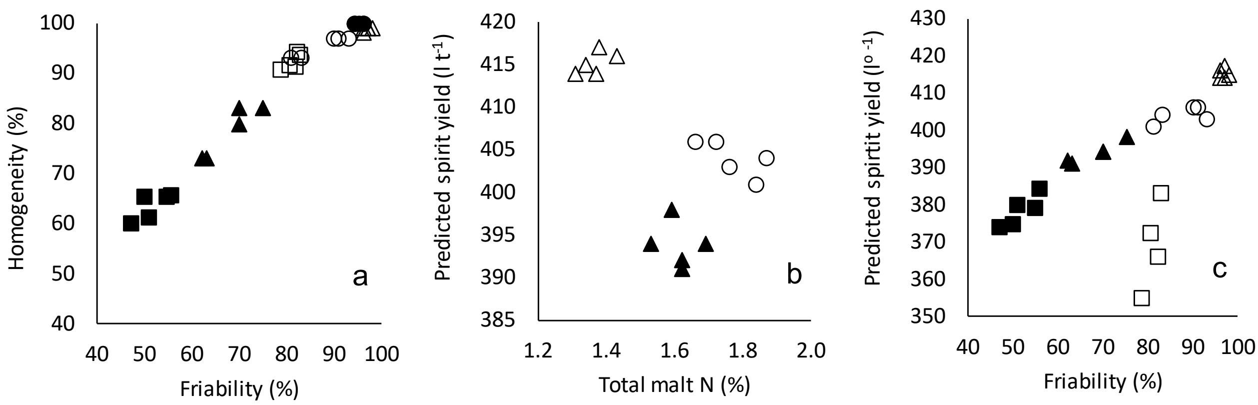

Figure 4.13. Change among different malting characteristics as influenced by N timing at six crop trials for (a) homogeneity on friability, at three sites for (b) predicted spirit yield on total malt N% and at four sites for (c) predicted spirit yield on friability.

For samples from S rate trials, homogeneity and friability were positively associated (Figure 4.13, a). As with the N timing trials, some sites produced grain samples that were relatively low in both friability and homogeneity, compared to what might be expected from commercial samples i.e. <80%. There was no evidence to suggest that S rate itself had any negative impact on either friability or homogeneity. Predicted spirit yield tended to decrease with an increase in total malt N% (Figure 4.13, b); this was as expected. Predicted spirit yield was strongly and positively associated with friability (Figure 4.13, c). As with the N timing trials, spirit yield increased with an increased in modification across sites and treatments.

5. The relationship between yield and N fertiliser requirement

This chapter investigates if crop yield affects the crop's N fertiliser requirement. Several factors must be considered including how environment (weather, soil, agronomy) and variety cause variation in yield, together with relationships between crop yield and crop N content and efficiency of N uptake. Data from 24 UK experiments have been used to test the performance of the current N fertiliser recommendations. These include eleven new experiments carried out in this project (2018 to 2020) (referred to as the UK Experiment dataset) and a further thirteen experiments carried out between 2005 and 2017 which are referred to as the UK Review dataset. Combining the results from new experiments conducted in the current study with review (extant) data provides a data set covering a wider range of sites and seasons than either alone, thus allowing for a more robust analysis of crop responses to fertiliser N. Conclusions drawn from the UK datasets are compared with similar experimental data from Denmark over the same time period.

5.1. Effects of yield variation caused by environment

Crop demand for N

The data from previous work does not include measurements of straw biomass and N concentration and so direct measurements of total N uptake cannot be made. However, estimates of N uptake can be derived in two ways; firstly, from measured values of grain N offtake (N_{off}) using assumed values of N harvest index (NHI; grain N offtake/total above ground N) and secondly from estimates of N uptake without fertiliser plus rate of fertiliser N adjusted by the apparent fertiliser recovery. For these approaches to be used, it is first necessary to investigate how NHI and apparent fertiliser recovery vary with N fertiliser rate so that appropriate values can be selected. The UK Experimental dataset have been used for this analysis.

NHI was averaged across replicates and varieties for each N fertiliser rate at each site-year. The relationship between NHI and N fertiliser rate was then investigated using linear regression with groups. Fitting regression models with separate slopes and constants for each site-year significantly increased the percentage variance accounted for (Table 5.1). For all site-years except North Yorkshire in 2018 there was a slight negative relationship between NHI and fertiliser rate. The constant represents the NHI in non-fertilised plots. The models were used to estimate the NHI at the N_{opt} for each site-year. Within a given year NHI with zero fertiliser and at the N_{opt} were remarkably similar between sites. Values of NHI tended to be lower in 2019 compared to 2018 and 2020. Averaged across sites and years NHI at the N_{opt} was 0.731 and 0.753 at zero fertiliser N. Moreover, there was no relationship between the NHI at N_{opt} and the yield at N_{opt} (Figure 5.1). Thus, NHI did not appear to vary with yield of crops across sites under optimum N nutrition.

Table 5.1 Outputs from linear of regression of NHI (dependant variable) against N rate (kg/ha; explanatory variable) for different site-years.

Site year	Slope	Constant	N_{opt}, kg N/ha	NHI @ N_{opt}
Notts 2018	-7E-05	0.775	104	0.768
Notts 2019	-0.0007	0.796	151	0.690
Notts 2020	-0.0002	0.791	169	0.755
North Yorks 2018	0.0001	0.741	219	0.764
Noth Yorks 2019	-0.0003	0.702	124	0.670
North Yorks 2020	-0.0003	0.796	60	0.778
Norfolk 2018	-4E-05	0.755	74	0.752
Norfolk 2019	-0.0002	0.678	83	0.663
Norfolk 2020	-0.0003	0.746	30	0.736
Mean		0.753		0.731
P <0.001	Variance accounted for, 82.4%			

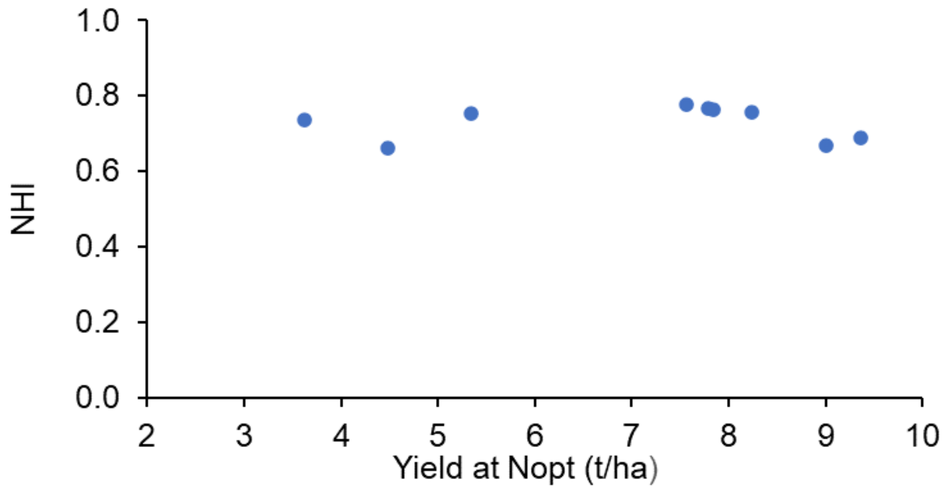

Figure 5.1 Nitrogen harvest index (NHI) at the optimum N fertiliser rate (N_{opt}) as a function of the yield at N_{opt}. Data are from measured values of NHI interpolated to the value at N_{opt} averaged across varieties for Nottinghamshire, North Yorkshire and Norfolk in 2018, 2019 and 2020. No measurements of total N uptake were made at East Lothian.

N uptake efficiency

The relationship between apparent fertiliser recovery and the rate of fertiliser applied varied widely between site-years (Figure 5.2). At six of the nine site-years fertiliser recovery declined as the rate of N application increased, but at the North Yorkshire site in 2018 and 2019 there was no apparent relationship. Moreover, at Norfolk in 2020 the recovery was extremely and atypically low ranging from 0.03 to 0.27 possibly as a result of the drought conditions that year. This site-year has, therefore, been excluded from further analysis of fertiliser recoveries. Linear regression models were fitted to the data for individual site-years (excluding Norfolk 2020) to estimate the fertiliser recovery at N_{opt}. The R^2 differed widely between models. Fertiliser recoveries ranged from 0.40-0.63 at N_{opt} across sites, with a mean of 0.53 (Table 5.2). Taking the mean fertiliser recovery from measured values at the N rate closest to the N_{opt}, rather than interpolating from regression models, resulted in a very similar mean value across site-years of 0.54.

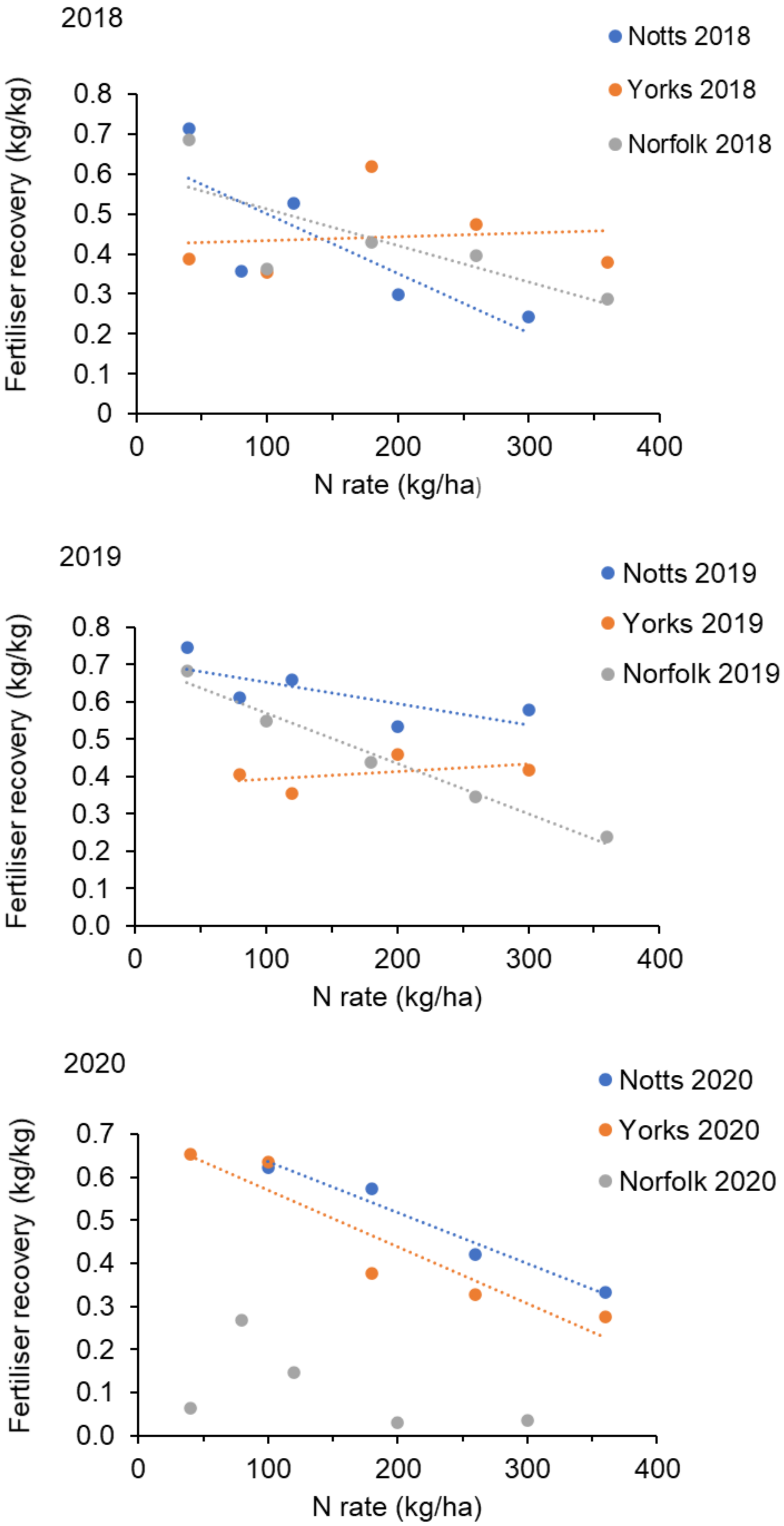

Figure 5.2. Apparent N fertiliser recovery rates plotted against the rate of fertiliser applied for sites where total N uptake was measured at harvest. Trend lines fitted by least squares regression. Each point is the mean for a given N rate across varieties and replicate plots.

Table 5.2 Linear regression models of apparent fertiliser recovery against rate of applied N and estimated recovery at the optimum N rate (N_{opt}).

Year	Site	Slope	Constant	R^2	N_{opt}, kg/ha	Fert recovery @ N_{opt}
2018	Notts	-0.0015	0.65	0.64	104	0.49
	Yorks	0.00009	0.43	0.01	219	0.45
	Norfolk	-0.0009	0.61	0.59	74	0.54
2019	Notts	-0.0006	0.71	0.54	151	0.62
	Yorks	0.0002	0.37	0.20	124	0.40
	Norfolk	-0.0014	0.70	0.98	83	0.59
2020	Notts	-0.0012	0.75	0.97	169	0.55
	Yorks	-0.0013	0.70	0.88	60	0.63
	Norfolk				30	
	Mean					0.53
	Mean using measured values closest to N_{opt}					0.54

Fertiliser recovery for sites in the UK Review data set were calculated from estimated values of N uptake at N_{opt} and zero N fertiliser. These were estimated from values of grain N offtake in the review data and the mean NHI values for N_{opt} and non-fertilised crops derived from the UK Experimental dataset reported above. This gave a mean recovery across site-years in the UK Review dataset of 0.67. The mean value for the UK Experimental dataset, when calculated in the same way, was 0.54; almost identical to the values derived by interpolation from measurements of crop N uptake described above. Thus, the average fertiliser recovery at N_{opt} for the combined UK Review and UK Experimental dataset was 0.61 kg/kg applied N.

Do fertiliser N requirements vary according to site yield potential?

There was a positive linear relationship between the yield observed at N_{opt} and the fertiliser rate required to achieve it (i.e. N_{opt}). Thus, higher yielding crops had a higher N fertiliser requirement (Figure 5.3a). The slope of the relationship was 33.4 (CI 25.90 - 46.95) indicating an increase in fertiliser N requirement of 33 kg N/t increase in yield. The R^2 of 0.36 shows that there was a considerable amount of variation in N requirement (N_{opt}) that was not explained by variation in yield across sites. Some of this unexplained variation was the result of differences in the amount of N supplied by the soil between site-years because when yield was plotted against soil N supply (SNS) plus N_{opt} (Figure 5.3b), a greater proportion of the total variation was accounted for (R^2 0.64). This had little effect on the slope of the relationship but reduced its confidence interval. The amount of N captured from non-fertiliser sources can be estimated as the N content of crops grown without N fertiliser. Thus SNS + N_{opt} is the amount of N captured by the crop in the absence of fertiliser plus the amount of N fertiliser applied at the optimum rate, not all of which is captured by the crop because the uptake efficiency of fertiliser was on average 61%.

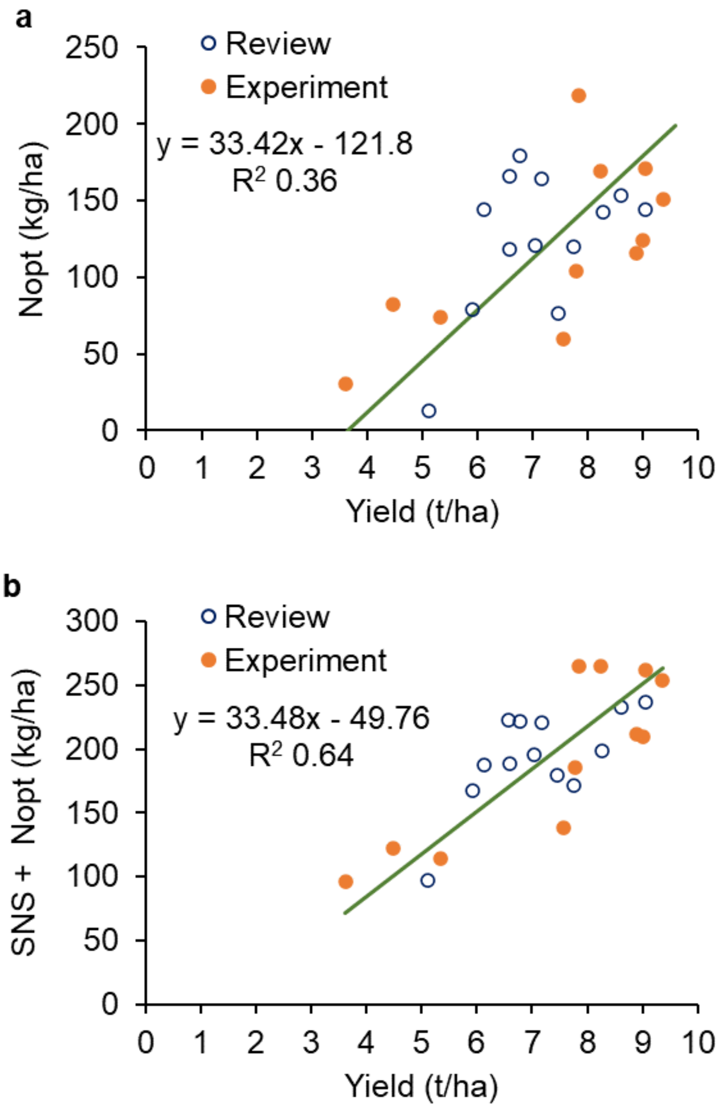

Figure 5.3 Relationship between yield measured at the optimum N rate (N_{opt}) and a) the N_{opt} and b) the N_{opt} plus the soil N supply estimated as the N uptake by non-fertilised crops. Lines were fitted by model II regression to combined UK Review and UK Experimental data. Each point is the average for an individual site-year. 95% confidence intervals for the slopes were a) 25.90 – 46.95 and b) 27.67 – 40.68.

The total N content of a crop determined at the N_{opt} is a measure of its demand for N. There was a strong positive relationship between the N content at N_{opt} and yield indicating that crops in environments with higher yield potential have a greater demand for N. Yield accounted for 78% of the observed variation in N content (Figure 5.4). The slope of the relationship was 22.19 (CI 19.60 – 26.10).

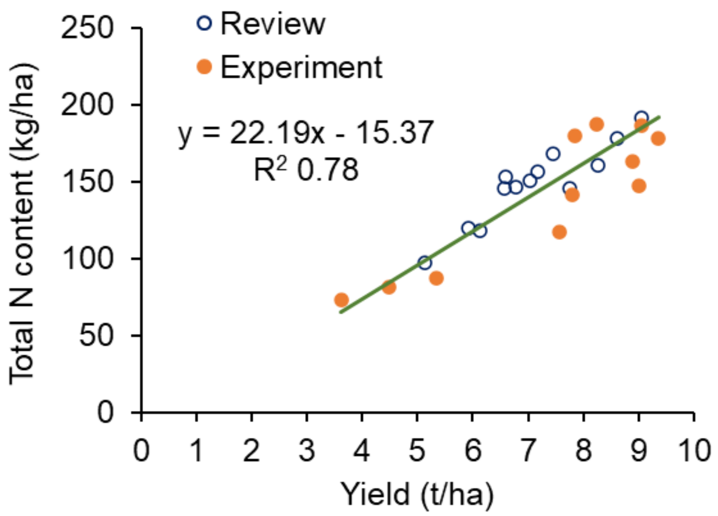

Figure 5.4 Relationship between yield measured at the optimum N rate (N_{opt}) and the total above ground N content of the crop at N_{opt}. Lines were fitted by model II regression to combined UK Review and UK Experimental data. Each point is the average for an individual site-year. 95% confidence interval for the slope was 19.60 - 26.10.

Does grain N% at the optimum N rate vary with site yield potential?

Current N fertiliser RB209 recommendations start by setting the N_{opt} for crops with an expected yield of 5.5 t/ha. Adjustments are then made to the recommendation for variations in N demand according to the expected yield at the site. This adjustment assumes that the grain N% at N_{opt} does not change with expected yield, is this true?

When grain N% was plotted against yield at N_{opt} there was no clear relationship (Figure 5.5). Grain N% was similar across a wide range of yields (3.6 to 9.4 t/ha) with an average of 1.72%. However, at any given yield or narrow range of yield, there was appreciable variation in grain N% between site-years (from 1.33 to 1.99%). Thus, we conclude that grain N% at N_{Opt} does not vary with site yield potential. Additionally, an analysis was done to determine if it was possible to use grain N% at a standard N fertiliser rate of 120kg N/ha as an indicator of whether the crop was under- or over-fertilised compared with the N_{opt}. A weak negative trend was found between grain N% and the difference in N rate between 120 kg N/ha and N_{opt}, suggesting that grain N% is not a good indicator of under- or over-fertilisation.

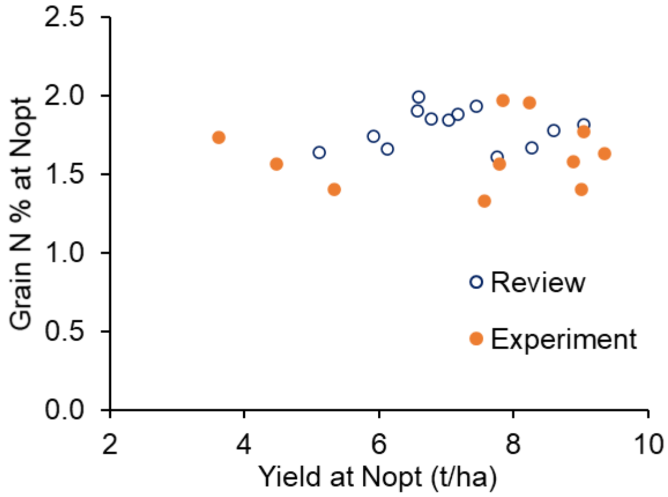

Figure 5.5 Grain N% at N_{opt} plotted against yield at N_{opt}. Each point is the average for an individual site-year.

Comparison of UK and Danish data

Analysis of 48 N fertiliser response experiments in Denmark conducted from 2005 to 2017 revealed responses similar to those described above for UK trials (Figure 5.6). Thus, N fertiliser requirement (N_{opt}) increased positively with the yield at N_{opt}. However, the relationship was weak (R^2 0.18) and a large proportion of the variation in N_{opt} (82%) was not explained by the yield (Figure 5.6a). As with the UK data, an appreciable amount of this was the result of variation in SNS between site-years and R^2 was improved when SNS plus N_{opt} was plotted against yield at N_{opt} (Figure 5.6b). There was a strong relationship between crop N content at N_{opt} and yield at N_{opt} indicating that crop N demand increased with yield under optimum N nutrition (Figure 5.6c). The slope of the relationship was a little lower for the Danish trials compared to the UK. A model II regression with groups to compare slopes and intercepts of Danish and UK crops indicated that they were significantly different at $P<0.05$.

As found with the UK data, there was no relationship between grain N% at N_{opt} and yield at the optimum. The mean N% at N_{opt} across trials was 1.52, significantly ($P<0.001$) lower than the 1.72 found for UK sites (Table 5.3). The SNS and apparent fertiliser recovery were also lower ($P = 0.009$ and 0.001 respectively) for sites in Denmark compared to the UK. Based on the increase in crop N demand per tonne increase in yield of 16.02 kg N and an average fertiliser recovery of 0.50 across sites in Denmark, the increase in fertiliser N requirement per tonne of additional yield is estimated to be 32 kg N/t. This value is comparable to the 36 kg N/t estimated from the UK data (Figure 5.4).

No relationship was observed between the apparent fertiliser recovery or SNS and yield at optimum N for either Danish or UK sites. Thus, there is no evidence from these data that the efficiency of fertiliser recovery was greater in higher yielding crops or that crops at higher yielding sites acquired more N from soil in the absence of fertiliser.

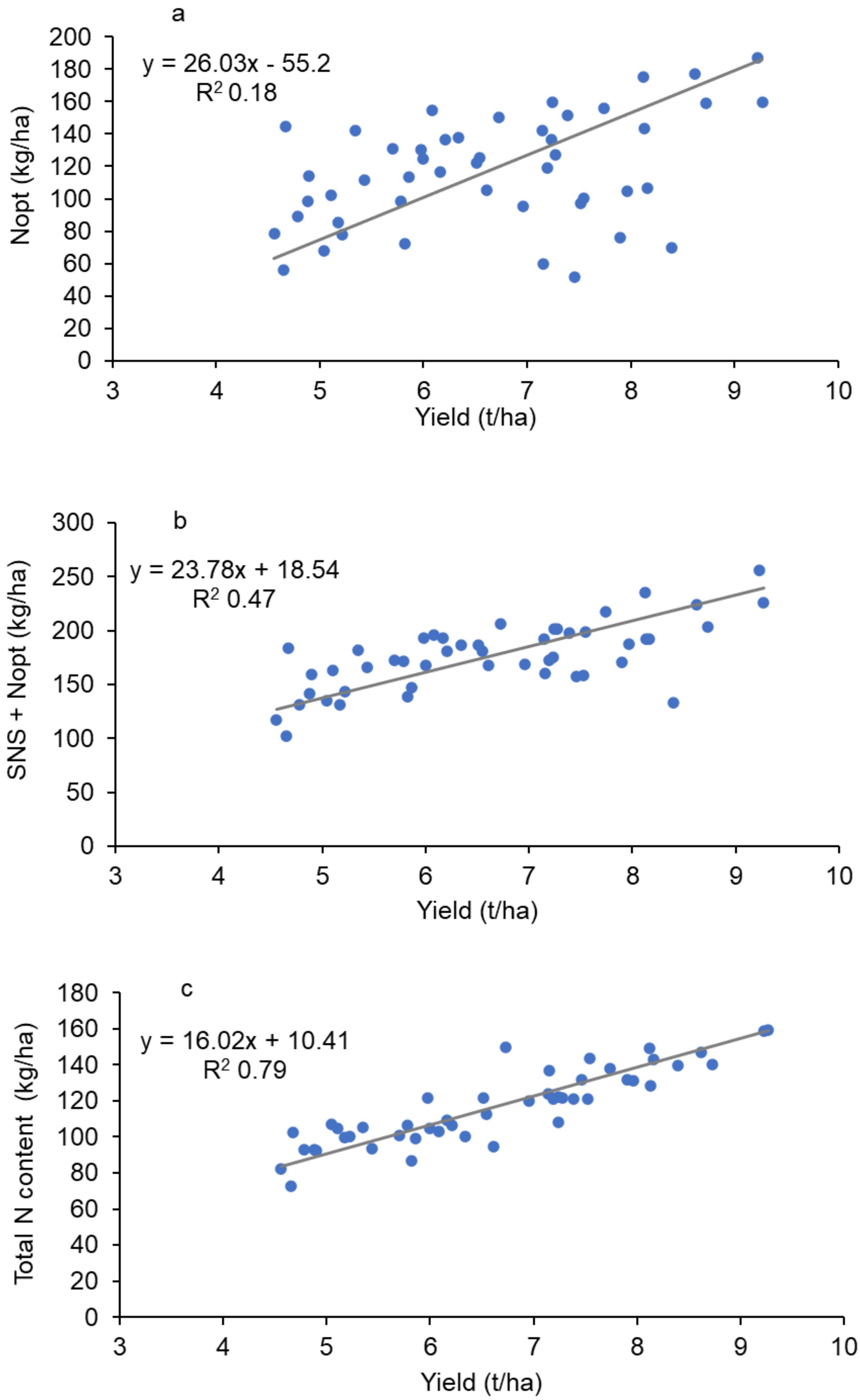

Figure 5.6 a) Fertiliser N optimum (N_{opt}); b) SNS + N_{opt}; and c) total crop N content at N_{opt} as a function of the yield at N_{opt} for 48 fertiliser trials conducted on spring barley in Denmark. Lines fitted by model II regression. Each point represents a single trial site-year. 95% confidence intervals for slopes are a) 22.06 – 30.79; b) 19.94 – 27.16 c) 14.12 – 18.27

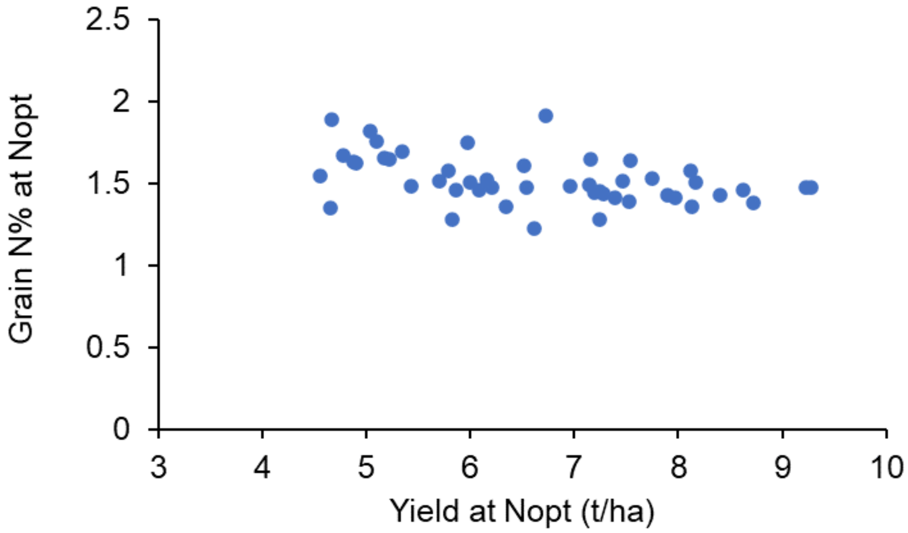

Figure 5.6 Grain N% at N_{opt} in relation to the grain yield at N_{opt} for 48 trials in Denmark. Each point is the value for an individual site-year.

Table 5.3 Mean grain N%, SNS (estimated as the crop N content from non-fertilised plots) and apparent fertiliser recovery at N_{opt} for trials in Denmark and the UK (combined review and current experiments). Data analysed by two sample t-test. SED is the standard error of the difference.

	Denmark	UK	SED	P
Grain N%	1.52	1.72	0.041	<0.001
SNS (kg N/ha)	58.8	71.7	4.74	0.009
Fertiliser recovery (kg/kg N)	0.50	0.61	0.034	0.001
Sample size	48	24		

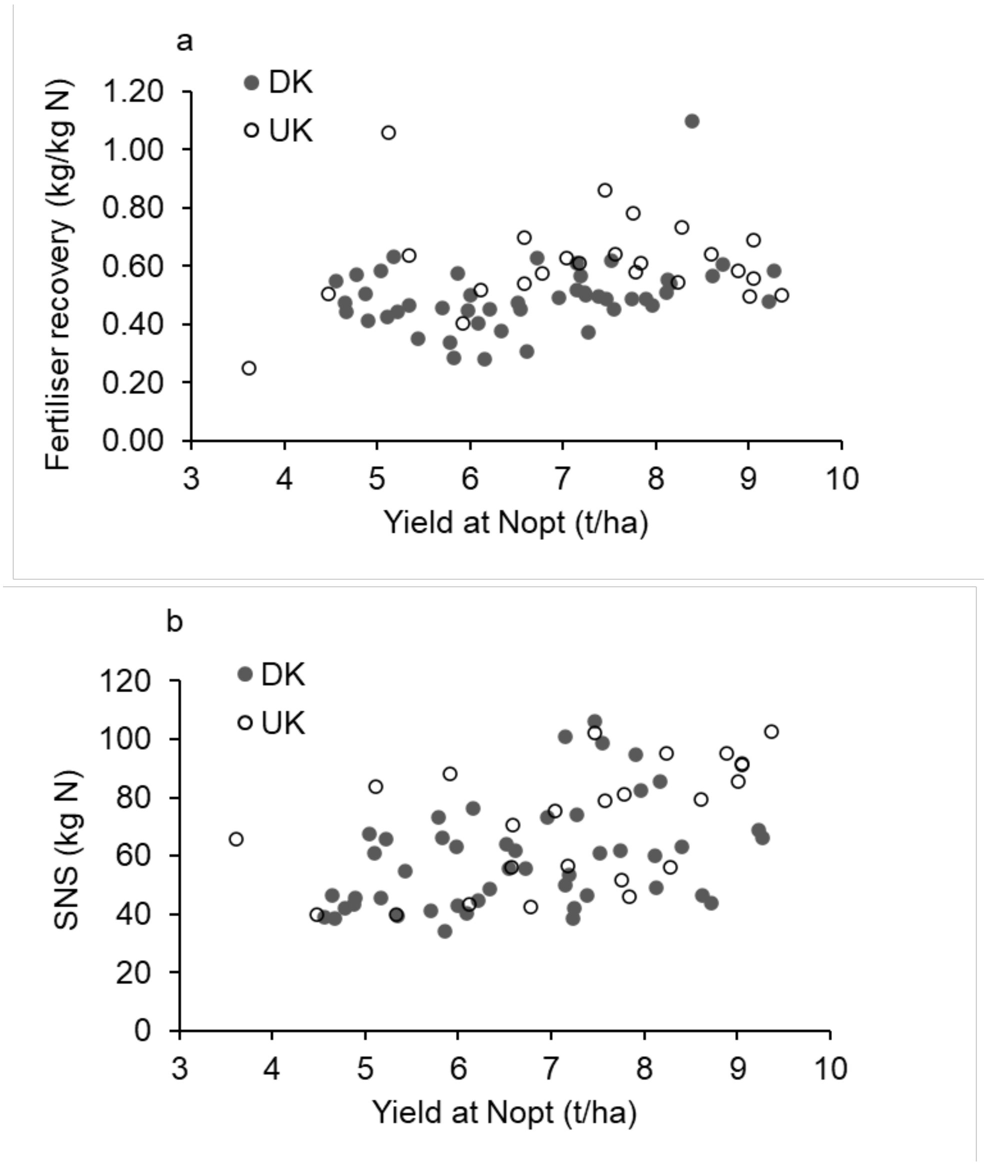

Figure 5.7 Relationship between a) fertiliser recovery at N_{opt} and yield at N_{opt} and b) SNS and yield at N_{opt} for trials in Denmark (DK) and the UK (combined UK Review and UK Experimental data).

5.2. Effects of yield variation caused by variety

Six experiments each investigating three varieties (Concerto, Laureate and RGT Planet) at multiple N rates showed there were no differences between the varieties in the N_{opt}. On average Concerto yielded 0.6 t/ha less than RGT Planet and Laureate. Across all six experiments, the average grain N% at the N_{opt} was 1.65%, 1.64% and 1.58% for Concerto, Laureate and RGT Planet respectively.

Effects of variety on N fertiliser uptake efficiency (kg/kg), N utilisation efficiency (kg of grain yield per kg of crop N uptake), N uptake efficiency (kg of crop N uptake per kg of soil N and fertiliser N) and Nitrogen Use Efficiency (NUE) (kg of grain yield per kg of fertiliser N) were calculated at the N rate closest to the N_{opt} (Table 5.4). In this analysis, the Norfolk 2020 data was removed as this showed extremely low fertiliser recovery at the N rate closest to the N_{opt} due to drought. Across the parameters there was no significant impact of variety, so the increased yield of RGT Planet and Laureate relative to Concerto could not be explained by improvements in efficiency.

It is probable that the yield difference between Concerto and more modern varieties (RGT Planet and Laureate) of 0.6 t/ha is not large enough to statistically test whether yield variation caused by variety affects N fertiliser requirement. There is no evidence that yield differences of this magnitude affect the uptake efficiency of fertiliser N or fertiliser N requirement. In the current AHDB Recommended List the difference in yield between the highest and lowest yielding variety is almost 1 t/ha, with a difference of about 0.5 t/ha for varieties introduced since 2018. This compares with yield variation between environments of up to 5 t/ha.

Table 5.4 Summary of fertiliser N uptake efficiency, N utilisation efficiency, total N uptake efficiency and NUE at the N rate closest to the N_{opt}.

Variety	Fertiliser recovery (%)	N utilisation efficiency (kg/kg)	N uptake efficiency (kg/kg)	NUE (kg/kg)	N uptake at Nil N (kg/ha)	Total N uptake (kg N/ha)	NHI (%)	Grain N%
Concerto	54.0	45.0	0.70	32.4	70.9	138	72.9	1.68
Laureate	50.1	46.0	0.69	32.4	75.7	140	74.3	1.68
RGT Planet	56.2	47.1	0.71	33.7	71.7	142	71.8	1.59
Grand Mean	53.4	46.0	0.70	32.8	72.8	140	73.0	1.65
P	0.744	0.616	0.872	0.658	0.074	0.884	0.615	0.029
LSD	18.21	5.036	0.1053	3.712	4.439	18.66	5.68	0.0752

6. Implications for N & S fertiliser recommendations

This chapter considers how evidence from the new experiments carried out between 2018 and 2020 (UK Experimental dataset), data from previous experiments done since 2005 (UK Review dataset) and relevant published information justifies any changes to the N and S fertiliser guidelines described in the AHDB Nutrient Management Guide 2021. This chapter considers i) the optimum N rate, ii) optimum N timing and iii) optimum S rate needed to achieve target grain N concentration together with the greatest economic yield.

6.1. Optimum N rate

Data from the 24 experiments that make up the UK Experiment dataset (2018-2020) and UK Review dataset (2005-2017) have been used to test the performance of the current N fertiliser recommendations. Combining the results from new experiments conducted in the current study with review (extant) data provides a data set covering a wider range of sites and seasons than either alone, thus allowing for a more robust analysis of crop responses to fertiliser N. The following approach has been taken:

i) Compare the current RB209 recommended N rate against the economically optimum N rate measured in the experiments
ii) Evaluate a new method of estimating N fertiliser requirement from SNS, crop demand and N fertiliser recovery using the analysis described in Chapter 5
iii) Quantify the grain N concentration achieved when a crop is fertilised at the economically optimum rate for yield and the trade-off with yield that results from reducing N fertiliser rate to achieve lower grain N concentrations

Comparison of the recommended N rate against experimental data

The N rates for feed quality spring barley recommended by the current RB209 have been estimated for the 24 experiments described above based on the SNS index estimated using the Field Assessment method (FAM), soil type and the yield measured in the experiment to retrospectively estimate the adjustment in N fertiliser required for expected yield. For the UK Experiment dataset (2018 to 2020), the average recommended N rate was 164 kg N/ha (range 70 to 210 kg N/ha). This compares with the measured economic optimum N rate which averaged 118 kg N/ha (range 30 to 219 kg N/ha). The average deviation between the recommended and measured N rate was +/- 52 kg N/ha. The average yield at the economic optimum was 7.4 t/ha and the average grain N concentration was 1.63%.

A similar pattern was found for the UK Review dataset of 13 experiments (2005 to 2017). The average recommended N rate was 167 kg N/ha (range 100 to 210 kg N/ha). This compares with the measured economic optimum N rate which averaged 125 kg N/ha (range 13 to 179 kg N/ha). The average deviation between the recommended and measured N rate was +/- 44 kg N/ha. The average yield at the economic optimum was 7.1 t/ha and the average grain N concentration was 1.79%.

Across both the UK Experiment and Review datasets, the average recommended N rate was 165 kg N/ha (range 100 to 210 kg N/ha). This compares with the measured economic optimum N rate which averaged 122 kg N/ha (range 13 to 179 kg N/ha). The average deviation between the recommended and measured N rate was +/- 48 kg N/ha. The average yield at the economic optimum was 7.2 t/ha and the average grain N concentration was 1.72%.

It is clear that the current RB209 approach overestimates the fertiliser N requirement. This may be because the current RB209 recommendations are based on a typical yield of 5.5 t/ha, whereas the yield of the experiments was 7.2 t/ha (or 7.4 t/ha if the droughted Norfolk 2020 site is not included). If the N rates are adjusted from a baseline yield of 7.5 t/ha, rather than 5.5 t/ha, then the recommended N rates are much closer to the measured N_{opt}. The average recommended N rate is 125 kg N/ha, compared with a measured N_{opt} of 122 kg N/ha, and the average deviation is +/- 31 kg N/ha. These results suggest that modern spring barley crops achieve higher yields than would be expected for the N rates used. The likely consequence of this is the dilution of grain N concentration. It is likely that this evolution has occurred over 20-30 years as a result of both breeding and agronomic improvements. It is consistent with the observed average grain N% of 1.72 at N_{opt} compared to the N% of 1.9% assumed for feed crops in the current RB209 recommendations.

Evaluate a new method for estimating N fertiliser requirement

Chapter 5 showed that crop yield was strongly and positively related to crop N content, but had no relationship with grain N concentration, NHI or the uptake efficiencies of either soil N or fertiliser N. This information can be used to estimate the Crop N demand (kg/ha) using Equation 11, where Expected Grain Yield is measured in t/ha at 15% MC, Grain N Concentration = 1.72% and NHI = 0.73, and the Fertiliser N Requirement using Equation 12 where SNS is the soil N supply (kg/ha) and Fertiliser Recovery = 0.61 (kg/kg).

*Crop N demand = 8.5 * (Expected Grain Yield) * (Grain N Concentration) / NHI* (Equation 11)

Fertiliser N Requirement = (Crop N Demand – SNS) / Fertiliser Recovery (Equation 12)

Applying Equations 11 and 12 gives N fertiliser requirements described in Table 6.1, where the SNS was assumed to be 50, 70, 90, 110 and 130 kg N/ha for soil indices 0, 1, 2, 3 and 4 respectively.

Across both the UK Experiment and Review datasets, the average recommended N rate using this method was 126 kg N/ha (range 0 to 214 kg N/ha). This compares with the measured economic optimum N rate which averaged 122 kg N/ha (range 13 to 179 kg N/ha). The average deviation between the recommended and measured N rate was +/- 38 kg N/ha. This exercise does not represent an independent test because the equations used to calculate the fertiliser N requirement have been calibrated using the same dataset used to evaluate its performance. So, it would be expected that the average recommended N rate is similar to the measured Opt N. It is worth noting that the average deviation between the recommended rate and the measured N_{opt} is about 10 kg N/ha smaller than the average deviation of the current RB209 recommendation. It is also worth noting that this approach is more mechanistic than the current RB209 system, which means that if crop characteristics of new varieties change by having a different grain N concentration, NHI or N fertiliser uptake efficiency, then it would be possible to account for these changes and re-calculate the N fertiliser recommendations using this approach. It should be emphasised this approach is not asking growers and advisors to calculate their N rates using equations 11 and 12 above, but to use the N rates summarised in Table 6.1 below.

Table 6.1. N fertiliser requirement (kg N/ha)

		SNS Index and range in kg N/ha				
Expected Yield (t/ha)	**Crop N demand**	**0 <60**	**1 61-80**	**2 81-100**	**3 101-120**	**4 121-140**
4	80	49	17			
5	100	82	49	17		
5.5	110	99	66	33		
6	120	115	82	49	17	
7	140	148	115	82	49	17
8	160	181	148	115	82	50
9	180	214	181	148	115	82

The current RB209 recommendations have separate recommendations for Light sands, Other mineral soils, Organic soils and Peats. The N recommendations for Other mineral soils, Organic soils and Peats are identical. We propose that there is no need to have separate N recommendations for Light sands and Other mineral soils because the SNS index accounts for any difference in soil N supply resulting from the different soil types and the yield adjustment accounts for any difference in expected yield. Across the UK Experiment and Review datasets there were 10 Light sand sites and 14 Other mineral soil sites. On average the Light Sand sites had a similar N_{opt}, which can be accounted for by Light Sand sites having a lower SNS and lower yield (Table 6.2).

Table 6.2. SNS, N_{opt} and Y_{opt} for Light sand and Other mineral soil sites

	Number of sites	SNS (kg/ha)	N_{opt} (kg/ha)	Y_{opt} (t/ha)
Light Sands	10	63	120	6.8
Other Mineral Soils	14	77	124	7.6

Managing N rate to achieve grain N% targets

In order for farmers to target specific grain N% markets with confidence, it is important that the relationship between N rate and grain N% is understood. Current RB209 recommendations are for a 30 kg N/ha reduction in N rate in order to achieve a grain N% reduction of 0.1%. Figure 6.1 shows the average N rate from the UK Experiment dataset to achieve different grain N% targets. Across the four grain N%, there was an average reduction in N rate of 29 kg N/ha to reduce grain N% by 0.1%, confirming that current RB209 recommendations are sensible.

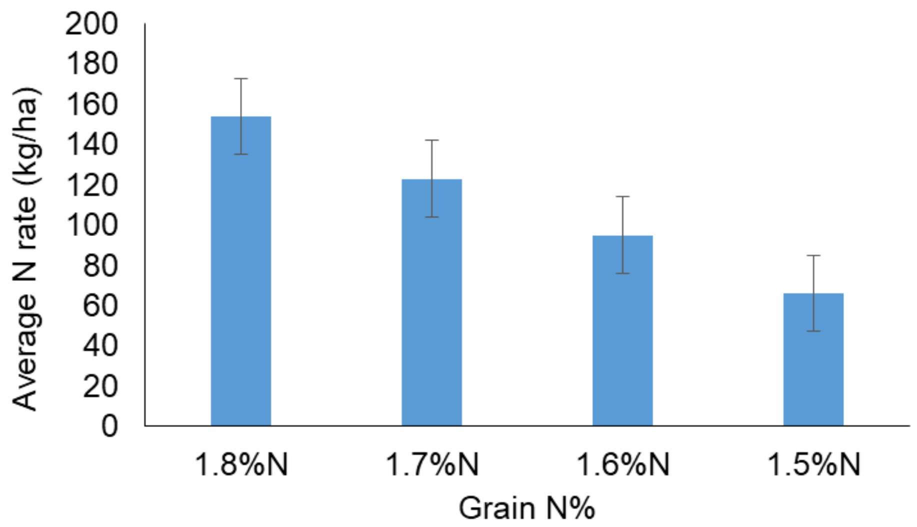

Figure 6.1 Average N rate to achieve grain N% of 1.8, 1.7, 1.6 and 1.5%. Error bars represent standard error.

To understand the relationship between N rate and grain N% further, and to confirm if a linear reduction in N rate is statistically supported, a further analysis was performed to compare the percentage of variance accounted for by a normal plus depletion model in comparison to a linear model for the four middle N rates in each experiment (N rates 2, 3, 4 and 5). As described in section 3.1.4, there was only one example where N rate and variety significantly interacted to affect grain N%. For this reason, data was averaged across varieties for this analysis. This analysis highlighted that across the experiments, the average percentage of variation accounted for was 75% for the linear regression and 73% for the normal plus depletion (Table 6.3). This demonstrates that the linear function was as useful as the normal plus depletion for describing how changes in N rate between 40 and 200 or 260 kg N/ha affect grain N%. This therefore helps to justify the same size of N rate change required to change grain N% by 0.1%, anywhere within the grain N% interval of 1.5% to 1.9%.

Table 6.3 Comparison of percentage of variance accounted for by linear regression and normal plus depletion modelling for N rates 2, 3, 4 and 5.

	% variation accounted for	
	Linear model	Normal plus depletion model
Notts 2018	45.7	42.6
East Lothian 2018	45.7	50.0
Norfolk 2018	90.4	92.8
North Yorks 2018	92.5	97.0
Notts 2019	25.8	-0.50
East Lothian 2019	94.5	97.0
Norfolk 2019	88.9	92.0
North Yorks 2019	82.5	83.1
Notts 2020	85.5	84.2
Norfolk 2020	77.2	70.8
North Yorks 2020	95.6	95.5

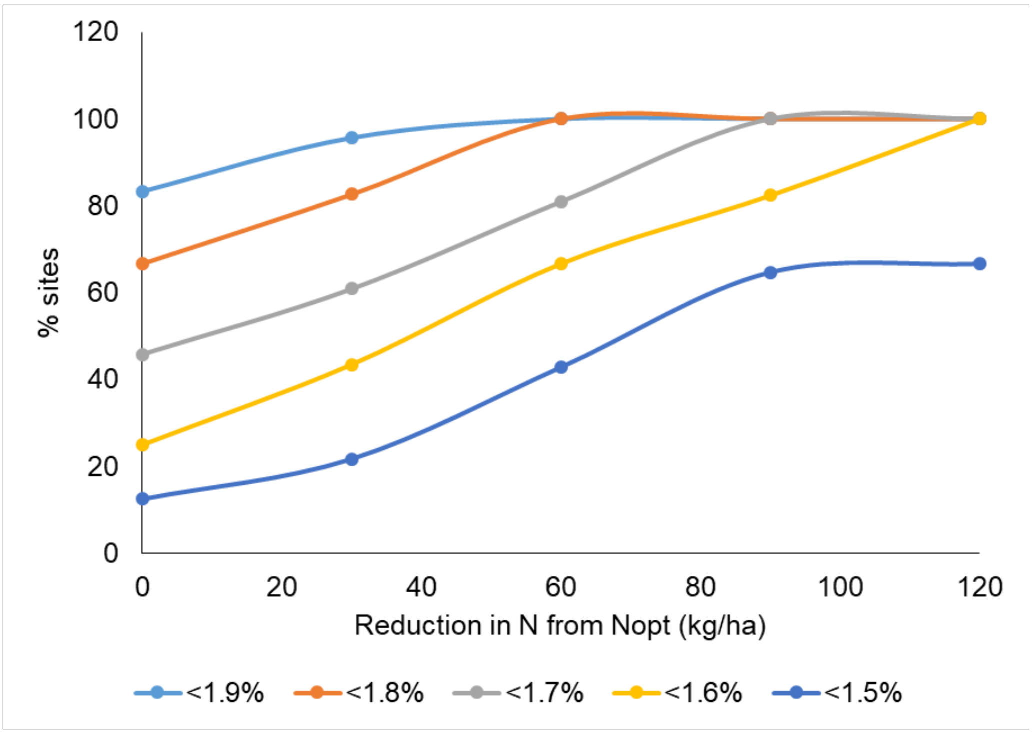

Figure 6.2 Impact of reducing N rate from the N_{opt} on the percentage of experiments achieving different grain N% targets.

Although the average grain N% at N_{opt} was 1.72% there was considerable variation between site-years, irrespective of the yield achieved (Figure 6.2). It is important, therefore to evaluate the effects of varying N rate around the optimum on the proportion of crops that might achieve a particular target grain N%. To achieve this an analysis was performed using the combined UK Experiment and UK Review datasets. In this analysis, the impact of reducing the N_{opt} rate by 30, 60, 90 and 120 kg N/ha on grain N% and the proportion of sites that met different grain N% targets was determined. At the N_{opt}, 79% of sites had a grain N% of less than 1.9%, with this proportion increasing to 96% when the N rate was reduced by 30 kg N/ha and to 100% when the N rate was reduced to 60 kg N/ha. To target 80% of sites meeting each grain N% target, the optimum N rate would need to be reduced by 30 kg N/ha for 1.8% or less, 60 kg N/ha for 1.7% or less and 90 kg N/ha for 1.6% or less. Reducing N rate by 90 kg N/ha resulted in 65% of sites having a grain N% of 1.5% or less, and a further reduction of 120 kg N/ha did not increase the percentage any further.

To understand the possible trade-off with grain yield from reducing N rate to meet different grain N% targets, the average reduction in yield caused by reducing N rate below the N_{opt} was calculated. Yield reductions were 0.23, 0.71, 1.2 and 2.1 t/ha for 30, 60, 90 and 120 kg N/ha reductions in N rate (Figure 6.3)

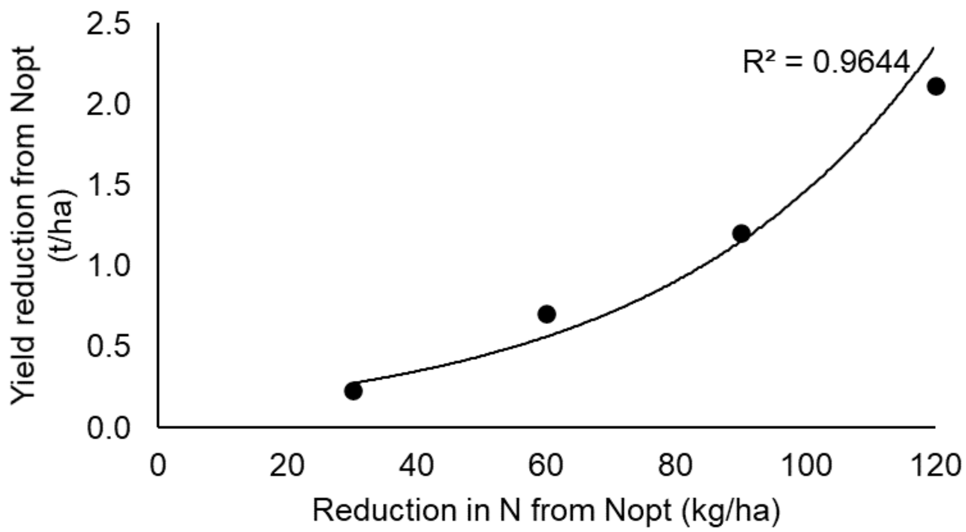

Figure 6.3 Impact on yield of reducing N rate from the N_{opt}.

The percentage of sites meeting different grain N% targets as shown in Figure 6.2 and the impact of reducing N rate on yield shown in Figure 6.3 was combined to explore the impact on gross margin of reducing N rate to achieve target grain N% for malting premiums (Figure 6.4). In this analysis it is assumed that the percentage of sites that achieved a grain N% below specific grain N% targets described in Figure 6.2 is representative of the general probability of any site achieving a specific grain N%. Other assumptions in this analysis included: a grain price of £150/t and a fertiliser price of

£0.85/kg of N and malting premiums ranging from £20/t to £40/t. This analysis demonstrated that the most economical N rate for achieving a grain N% of less than 1.8% was N_{opt} minus 30 kg N/ha (Figure 6.4). Reducing N rate by 60 kg N/ha reduced the yield value by more than the value gained as a result of increasing the likelihood of achieving the malting premium. This analysis is valuable for growers who do not have experience about what grain N% a particular farm or field generally achieves (e.g. farming new land or new to growing spring barley). For growers with more experience of growing spring barley on a particular farm then historic records of grain N% may show that it is not necessary to reduce the N rate below the N_{opt} for yield.

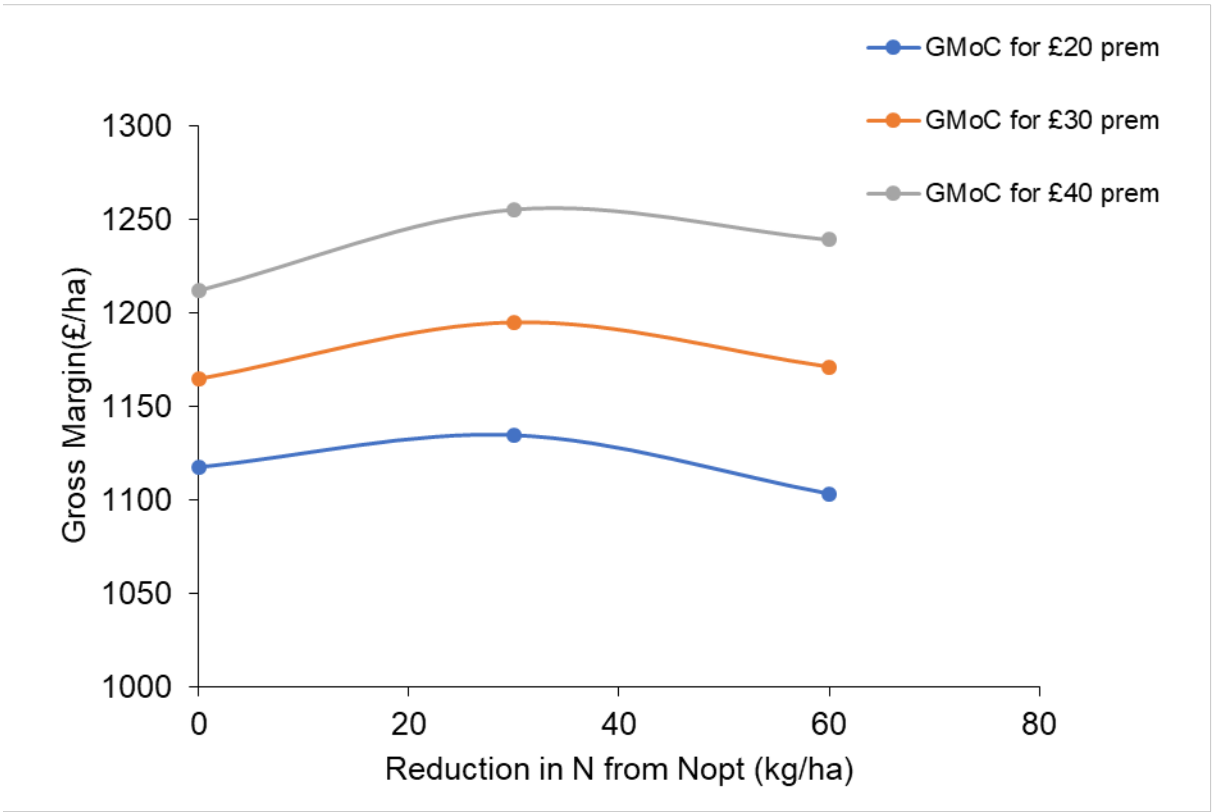

Figure 6.4 Impact on gross margin of cost of N fertiliser (GmoC) of reducing N rate from the N_{opt} to achieve a grain N% of less than 1.8%

Conclusions about N rate recommendations

- The current RB209 recommendations over-estimate economic optimum N fertiliser requirement for yield (as described in the recommended N rates for feed) by over 40 kg N/ha.
- Two options are proposed to deal with the over-estimated N rate. Both options give similar N recommendations at expected yields of 7 to 8 t/ha. Option 1 gives higher N recommendations at expected yields of 6 t/ha or less.

- Option 1: Change the yield adjustment threshold from 5.5 t/ha to 7.5 t/ha. This enables the average recommendation to be similar to the observed optimum N rate for yield and reduces the average deviation from this optimum to +/- 31 kg N/ha. This includes an adjustment for yield of 20 kg N/ha per tonne of yield. See Table 6.4 below for how the Recommendations could be presented.
- Option 2: Use a mechanistic approach to calculate N fertiliser requirement based on measurements made in the experiments of crop N demand and fertiliser uptake efficiency. It's not possible to independently test this approach because the experimental data has been used to develop it, but a comparison of its predictions against the observed optimum N rates show that it predicts the correct rate on average and the average deviation from this optimum to +/- 38 kg N/ha. This includes an adjustment for yield of 33 kg N/ha per tonne of yield. See Table 6.5 below for how the Recommendations could be presented.

- There is no need to have separate N recommendations for light sands and other soils because the SNS index accounts for any difference in soil N supply resulting from the different soil types and the yield adjustment accounts for any difference in expected yield.
- The economic N rate for yield results in an average grain N% of 1.72% and 67% of experiments had a grain N% of less than 1.8% when fertilised at this rate.
- A cost benefit analysis indicates that if a grower had little knowledge of historic spring barley grain N% on the farm/field in question, then the best approach would be to reduce the N rate recommended for optimum yield by 30 kg N/ha to achieve a grain N% of less than 1.8% with greater reliability. If historic grain N% data for the field is consistently below 1.8% then it may not be necessary to reduce N rate.

Table 6.4. N fertiliser Recommendations (kg N/ha) based on Option 1 described above

	SNS Index and range in kg N/ha				
Expected Yield (t/ha)	**0 <60**	**1 61-80**	**2 81-100**	**3 101-120**	**4 121-140**
4	90	70	40		
5	110	90	60	20	
6	130	110	80	40	
7	150	130	100	60	20
8	170	150	120	80	40
9	190	170	140	100	60

If target grain N is <1.8% reduce N rate by 30 kg N/ha to increase the reliability of achieving target. Estimate the fertiliser N reduction required for lower grain N based on 30 kg N/ha less fertiliser reducing grain N% by 0.1%.

Table 6.5. N fertiliser Recommendations (kg N/ha) based on Option 2 described above

	SNS Index and range in kg N/ha				
Expected Yield (t/ha)	**0 <60**	**1 61-80**	**2 81-100**	**3 101-120**	**4 121-140**
4	49	17			
5	82	49	17		
6	115	82	49	17	
7	148	115	82	49	17
8	181	148	115	82	50
9	214	181	148	115	82

If target grain N is <1.8% reduce N rate by 30 kg N/ha to increase the reliability of achieving target. Estimate the fertiliser N reduction required for lower grain N based on 30 kg N/ha less fertiliser reducing grain N% by 0.1%.

6.2. Optimum N timing

The eleven experiments have indicated that the timing of N application does have a significant effect on yield, with the cross-site analysis showing a 0.45 t/ha yield reduction on average from applying no N in the seedbed. There were minimal differences in yield in response to the three other N timing treatments, all of which had at least 40 kg N/ha applied at the time of drilling. The results highlight the importance for at least 40 kg N/ha to be applied at the time of drilling, but there is very little evidence that further yield gains, or losses, would be achieved by applying all of the N at the time of drilling. In only one experiment (East Lothian, 2018) did a treatment with more than one application yield more than the treatment with all N applied at the time of drilling. The experiments indicated that it was possible for grain N concentration to be increased by either delaying the first N split until GS14 to GS30 or delaying a proportion of the N until GS37/39.

Across the experiments, several dry springs were experienced, with three experiments (three application timing treatments) identified in which a particular N timing treatment would have been severely compromised due to lack of rain; the 2nd N timing at GS14 to GS30 in two experiments and the 3rd N timing at GS39 in one experiment. This pattern of rainfall may at least partially explain why the treatment where the first N application was delayed until GS14 to GS30 sometimes yielded less than the treatments that received some N at the time of drilling. The experiments had a range of drilling dates, from late February through to late April and there was no evidence to suggest that drilling date had an effect on the yield response to different N timing treatments. Additionally, across the sites, N was either incorporated (Nottinghamshire & North Yorks (2019 and 2020) or broadcast (Norfolk, East Lothian and North Yorkshire (2018)). In two of the experiments where yield was significantly affected by N timing, the N was incorporated in the seedbed (Nottinghamshire 2018 & North Yorkshire 2020), whereas at the two other sites where a significant yield effect was obtained, the N was top dressed (East Lothian 2018 and Norfolk 2019). This suggests that method of N application is less critical than timing of N, although specific experiments are needed to test effects of method of application (see section 7.4).

There was some evidence of effects of N timing on screenings, with two experiments where screenings may have fallen below the market requirements. At the Nottinghamshire site in 2018, the seedbed N treatment produced higher screenings, whereas in North Yorkshire in 2020 the Late N treatment resulted in higher screenings. There was minimal evidence that malting parameters analysed through micromalting were significantly affected by N timing, with the only significant result that the seedbed N significantly lowered total malt N. Overall, there were no consistent effects of the N timing treatments on other quality parameters (specific weight, screenings, micromalting characteristics), or lodging, or any evidence that the different varieties tested (Concerto, LG Diablo, RGT Planet and Laureate) responded differently to the N timing treatments.

Published evidence about the effect of N timing on spring barley yield from 20 experiments in Ireland concluded that there was little consistent difference between applying the first N at sowing compared to applying the first N at emergence on either grain yield or grain N concentration. Similarly, altering the proportion of the total N dose that is applied at the first application, where the remaining N is applied before stem extension, had no consistent effect on either grain yield or grain N (Hackett, 2019). Experiments done between 1978 and 1980 in Northern Ireland showed that applying part of the nitrogen as a top dressing up to 30 days after emergence had no significant effects on the grain yield, compared with applying all the nitrogen in the seed bed. Grain yields were progressively reduced with top dressings from 40 days after emergence (first node stage) onwards (Easson et al., 1984). This study suggested that a two-split N application N application approach was most beneficial in early sown crops for which it could improve yield and offsets leaching risk, especially if there is rainfall following sowing. Fifteen N timing experiments carried out by Seges in Denmark during 2018, 19 and 20 showed no significant effect on yield or grain N concentration from applying 25% to 43% of the N at GS31 compared with applying all N in the seed bed. There was evidence in these Danish experiments that either delaying the first N split until GS31, or applying less than 50% of the total N in the seed bed, did significantly reduce yield.

Regarding the effect of late applied N on grain N concentration, an analysis of available data at the beginning of this project including 14 different sites from the UK, Ireland and Denmark showed that crops receiving 25-36% of the N in the seedbed and the rest between GS13-31 had a significantly lower grain N% (1.84%) than crops which had received 25% or more of the N applied between GS32-39 (1.92%). Analysis of twenty Irish experiments showed that delaying 20% of the total N till GS31, GS37 or GS61 increased the grain N concentration in three, seven or ten experiments respectively, giving average increases in grain N% across all experiments of 0.02, 0.04 and 0.05% respectively.

The N timing treatments in this project have largely focused on N which was broadcast or incorporated, rather than placed, at drilling. Few experiments have compared placing N in the soil with broadcasting. Widdowson et al. (1961) showed that combine-drilling ammonium sulphate produced higher mean yields than broadcasting across 15 spring barley crops. Therefore, understanding the effect of placing N fertiliser with the seed should be investigated in the future. Additionally, the majority of the experiments described here were established following ploughing, with just the Nottinghamshire site established following minimum tillage. In a recent review by Storer et al. (2018), an evaluation of autumn drilled cereal requirements for autumn applied N in no-till farming situations highlighted a requirement for further research to address how best to manage the N applications of no-till crops. It is possible that there could be greater requirements for a larger proportion of N to be applied in the seedbed to spring barley in a no-till situation, although this would need to be balanced with potential leaching risk.

Recommendations for N timing

- Apply all N between the time of drilling and GS30, with at least 40 kg N/ha in the seedbed.
- To minimise the risk of nitrate leaching, do not apply more than 40 kg N/ha in the seed bed if the crop is sown before March, or on a light sand soil, or if there is a likelihood of substantial rainfall soon after drilling.

6.3. Sulphur recommendations

Sulphur fertiliser significantly increased yield in only one of eleven experiments. Sulphur at a rate of 20 kg SO_3/ha did increase grain N concentration at two of eight sites. However, across all eight S response experiments there was no significant effect of sulphur fertiliser on grain N% or yield. Therefore, the impact of sulphur to increase grain N% appears to be minimal. There were no negative effects of sulphur fertiliser on the micro-malting characters, in fact it was shown that sulphur may have some positive effects on malt modification, DP and HWE. Deposition of sulphur from the atmosphere is now very low with levels measured in the UK of 3 to 6 kg S/ha (8 to 15 kg SO_3/ha) (Webb et al., 2016). It is estimated that on average the spring barley grown close to the optimum N rate in this study took up a total of 55 kg SO_3/ha. This estimate is based on an average grain yield of 7.4 t/ha, average grain S concentration of 1124 mg.S/kg of grain and a sulphur HI of 0.32 (Garstang, 1994). Research in the UK has shown that (arable) soils do not store the anthropogenic sulphur that was deposited in the past, and that leaching is resulting in further decreases in soil sulphur status (McGrath et al., 2002). Therefore, even though the experiments in this study did not show a consistent statistically significant increase in yield from sulphur fertiliser, it is concluded that current RB209 guidance to apply 25 to 50 kg SO_3/ha where there is a risk of deficiency (as indicated by a risk matrix table based on soil type and winter rainfall) remains appropriate.

7. Discussion

7.1. Predicting grain N concentration

One of the greatest challenges for quality spring barley growers is balancing N rates to achieve grain N concentration with the minimum reduction in yield. This project has shown that reducing N rate by 30 and 60 kg N/ha below the optimum reduces yield by, on average, 0.23 and 0.71 t/ha respectively, which illustrates how critical this decision is for profitability. Review of published literature and analysis of new data has shown that it is not possible to predict grain N concentration in time to inform N fertiliser management. This is due to weather and site factors having a strong influence on grain N, both of which are unpredictable. Previous research on milling wheat (Weightman et al., 2011) showed that the grain protein concentration of wheat was strongly influenced by a farm factor. Even when wheat crops received optimal N fertiliser applications some farms consistently had low grain proteins and some farms had high grain proteins. This was also demonstrated by Kindred et al (2018) who concluded that grain protein cannot be used as an entirely reliable indicator of N management. Analysis of grain N data for spring barley suggests that a similar farm factor may also occur for spring barley (*pers. comm*. R. Sylvester-Bradley). It is therefore recommended that farmers keep detailed historical records of their grain N concentration measurements and compare these with the AHDB annual cereal quality survey data, to understand whether their farm has low, typical or high grain N concentrations. This information can then be used to judge whether it is necessary to reduce N rates from the recommendation for economically optimum yield (feed). Any changes to N fertiliser practice should be made gradually and ideally tested using statistically testable on-farm trials such as the tramline trial approach described in the ADAS Guide to Farmers' Crop Trials (ADAS, 2018).

7.2. Adjusting N rate for expected yield

This project has demonstrated a very strong relationship between grain yield and the total amount of N that a spring barley crop takes up. No evidence was found that high yielding crops have a different N uptake efficiency, grain N concentration or partitioning of N between the grain and straw compared to low yielding crops, therefore it must be concluded that higher yielding crops have a greater requirement for fertiliser N (assuming the soil N supply is the same). The amount of additional fertiliser N has been estimated at 33 kg N/ha for each additional tonne of grain on the basis that each tonne of grain would be expected to be associated with a crop N demand of 20 kg (assuming the average grain N concentration of 1.72% and a NHI of 0.73). If fertiliser uptake efficiency is assumed to be 0.61 kg/kg then 33 kg of fertiliser N/ha would need to be applied to achieve this amount of N uptake (Table 6.1). Similarly, the relationship between Y_{opt} and N_{opt} supports this yield adjustment, with 33 kg N/ha required for each additional tonne of yield (Figure 5.3A)

It should be recognised that the proposed N recommendations described for option 2 in Chapter 5 include an adjustment for yield of 33 kg N/ha per tonne of yield. This is greater than the yield adjustment allowed under Nitrate Vulnerable Zone (NVZ) regulations which allow an adjustment for yield of 20 kg N/ha per tonne of yield. This difference would need to be made clear if this option is adopted in new fertiliser guidelines.

A key challenge associated with adjusting N rate for expected yield is how to estimate the expected yield given that unpredictable weather events have such a strong influence. The Yield Enhancement Network (www.yen.adas.co.uk) has shown that cereal yields do vary by farm, irrespective of weather, soil characters or inputs. Keeping detailed historical field yield records and comparing these with national average yields will help to understand where your farm sits relative to the national average. This information can be used to make realistic estimates of expected yield for a particular field. Other 'in season' factors can be used to modify the prediction of expected yield in time to adjust N management including; plant establishment and the number of shoots at the start of stem extension.

This project found no difference in fertiliser requirement between modern high yield yielding varieties and an older variety (Concerto) yielding on average 0.7 t/ha less. This agrees with Sylvester-Bradley and Kindred (2009) who found no clear difference in N optima between varieties grown in the mid-1980s and those being grown in the mid-2000s. Therefore, the effect of variety should not be accounted for in the estimate of yield expectation. It should be recognised that average yield differences between varieties introduced during the last 3 years described in the AHDB Recommended List are 0.5 t/ha. Whereas yield differences caused by environment (farm, soil type, weather) are more than 5 t/ha.

It is important to be conservative when estimating expected yield given the uncertainty inherent within this estimation. Expected yield estimates should be no greater than the maximum field yield measured on the farm in the past.

7.3. **Improving N use efficiency**

It has been reported that UK grown spring barley has a NUE (kg of grain per kg of available N from soil and fertiliser) which is typical of other cereal species (Sylvester-Bradley and Kindred, 2009). This performance resulted from a utilisation efficiency (kg of grain per kg of N uptake) which was high relative to other cereal species and an N uptake efficiency (kg of N uptake per kg of available soil N and fertiliser N) which was relatively low. Chapter 2 has reported how indirect improvements in NUE resulting from breeding higher yielding varieties have probably kept pace with increasing yields resulting in little change to fertiliser N requirement. The majority of the breeding related NUE improvement appears to have been achieved through increases in N utilisation efficiency, with more modest improvements in N uptake efficiency. This indicates that improving N uptake efficiency may be the element of NUE which has the greatest potential for improvement. This project measured an average apparent fertiliser N uptake efficiency of 0.61 kg/kg which suggests there is scope to improve this characteristic. However, it should also be recognised that for the eleven N response experiments carried out in this study the average N uptake was 140 kg N/ha in response to an average optimum fertiliser N rate of 118 kg N/ha. So, the crops took up more N than was applied as fertiliser as a result of taking up N from the soil. It therefore seems prudent to continue to target improvements in N utilisation efficiency and N uptake efficiency in order to improve NUE. Breeding is likely to be the best approach for improving N utilisation efficiency (e.g. by further increasing HI and NHI), with a combination of breeding and crop/soil management approaches to improve N uptake efficiency.

Possible methods for improving N fertiliser uptake efficiency include: applying N at a time that minimises the risk of nitrate leaching, applying when the crop is growing to minimise the potential for immobilisation between application and plant uptake, placing N next to the seed, and using additives that minimise volatilisation if using urea based fertilisers.

7.4. Further research requirements

- Set up a program of continually testing the RB209 recommendations using N response experiments
- Further work to understand the effect of placing N fertiliser with the seed should be performed, addressing implications for optimising N rate and timing.
- Confirm that current N rate and timing recommendations are relevant in no-till farming systems and understand the impact where cover crops precede spring barley crops.
- Determine implications for greenhouse gas emissions through modelling and estimate the environmental optimum N rate in each scenario to understand the impact of reducing N rates.

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9. References

ADAS (2018). *Guide to farmers' crop trials.* Accessed here.

Abeledo, L.G., Calderini, D.F., Slafer, G.A. (2008). Nitrogen economy of old and modern malting barleys. Field Crops Research. 106, 171-178.

Bingham, I.J., Karley, A.J., White, P.J., Thomas, W.T.B and Russell, J.R. (2012). Analysis of improvements in nitrogen use efficiency associated with 75 years of spring barley breeding. European Journal of Agronomy. 42, 49-58.

Carver, M.F.F. (2005). Monitoring winter barley, wheat, oilseed rape and spring barley for sulphur in England and Wales to predict fertiliser need. *AHDB Project Report* **No 374**, AHDB, Stoneleigh, Warwickshire, 36 pp.

Easson, D.L. (1984). The timing of nitrogen application for spring barley. *Journal of Agricultural Science, Cambridge* **102**, 673-678.

Garstang, J., Vaughan, J. & Dyer, C.J. (1993). Effects of soil type and nitrogen on the quality of autumn-sown malting barley. *AHDB Project Report* **No. 68**, AHDB, Stoneleigh, Warwickshire, 126 pp.

Garstang, J. R. (1994). The Analysis of Straw. Report for the Energy Technology Support Unit, Harwell.

George, B.J. (1984) Design and interpretation of nitrogen response experiments. *The Nitrogen Requirement of Cereals, Reference Book* **385**. MAFF, pp. 133–149.

Gilchrist, A.D., Christie, A.G., Fraser, J. & Inglis, L. (2012). The relationship between soil mineral nitrogen, applied nitrogen and yields in Scottish soils. *HGCA Project Report* **No. 484**.

Grant, C. A., Brown, K. R., Racz, G. J. & Bailey, L. D. (2002). Influence of source, timing and placement of nitrogen fertilization on seed yield and nitrogen accumulation in the seed of canola under reduced-and conventional-tillage management. *Can. J. Plant Sci*. **82(4)**:629-638.

Gravelle, W. D., Alley, M. M., Brann, D. E. & Joseph, K. D. S. M. (1988). Split spring nitrogen application effects on yield, lodging and nutrient uptake of soft red winter wheat. *J. Prod. Agric*. **1**: 249-256.

Hackett, R. (2019). Effect of nitrogen fertiliser application timing on grain yield and grain protein concentration of spring barley. *Irish Journal of Agricultural and Food Research*. **58**, 34-43.

Hansen, P.M., Jorgensen, J.R. & Thomsen, A. (2002). Predicting grain yield and protein content in winter wheat and spring barley using repeated canopy reflectance measurements and partial least squares regression. *Journal of Agricultural Science*. **139**, 307-318.

Jenner, C.F., Ugalde, T.D., Aspinall, D. (1991). The Physiology of Starch and Protein Deposition in the Endosperm of Wheat. Australian Journal of Plant Physiology 18, 211-226

Kendall, S.L, Holmes, H.H. & Berry, P.M. (2017). Updating N fertiliser management guidelines for winter barley. *AHDB Project Report* **No 571**. AHDB, Stoneleigh, Warwickshire, 83pp.

Kindred, D.R., Clarke, S.M., Sylvester-Bradley, R., Hatley, D., Roques, S., Morris, N. Knight, S., Langton, D. and Blake-Kalff, M.A. (2018). Using farm experience to improve N management for wheat (LearN). *AHDB Project Report* **No 596.** AHDB Stoneleigh, Warwickshire, 82pp.

Malhi, S. S., Grant, C. A., Johnston, A. M. & Gill, K. S. (2001). Nitrogen fertilization management for no-till cereal production in the Canadian Great Plains: a review. *Soil Till. Res*. **60(3-4):**101-122.

McGrath, S. P., Zhao, F. J. & Blake-Kalff, M. M. A. (2002). Crop quality effects of sulphur and nitrogen. HGCA conference 2002: Agronomic Intelligence: the Basis for Profitable Production, 12.1-12.12.

McTaggart, I.P. and Smith, K.A. (1995). The effect of rate, form and timing of fertiliser N on nitrogen uptake and grain N content in spring malting barley. Journal of Agricultural Science, Cambridge 125, 341-353.

Molina-Cano, J.L., Gracia, P. & Ciudad, F. (2001). Prediction of Final Grain Protein Content with Plant Protein Content of Malting Barley Under Mediterranean Conditions. *Journal of the Institute of Brewing*. **107 (6)**, 359-365.

Morgan, A.G., Riggs, T.J. (1981) Effects of drought on yield and on grain and malt characters in spring barley. *Journal of the Science of Food and Agriculture.* **32(4)**: 339-346.

Nolan, E. (2016). Understanding and Predicting Grain Nitrogen Concentration in Malting Barley. *PhD Thesis, University of Edinburgh*, Scotland, 238pp.

Pettersson, C.G. & Eckersten, H. (2007). Prediction of grain protein in spring malting barley grown in northern Europe. *European Journal of Agronomy*. **27**, 205-214.

Peltonen-Sainio, P., Jauhiainen, L., Nissilä, E. (2012). Improving cereal protein yields for high latitude conditions. European Journal of Agronomy 39, 1-8.

Rajala, A., Peltonen-Sainio, P., Jalli, M., Jauhiainen, L., Hannukkala, A., Tenhola-Roininen, T., Ramsay L., and Manninen, O. (2017). One century of Nordic barley breeding: nitrogen use efficiency, agronomic traits and genetic diversity. Journal of Agricultural Science. 155, 528-598.

Roques, S., Berry, P., Knight, S., Morris, Clarke, S. & Sagoo, L. (2016). RB209 review and revision: WP4 cereals and oilseeds. *AHDB Research Review* **No. 3110149017**. AHDB, Stoneleigh, Warwickshire.

Roth, G. W. & Marshall, H. G. (1987). Effects of timing of nitrogen fertilization and a fungicide on soft red winter wheat. *Agron. J*. **79**: 197-200.

Söderström, M., Börjesson, T., Pettersson, C.G., Nissen, K. & Hagner O. (2010). Prediction of protein content in malting barley using proximal and remote sensing. *Precision Agriculture*. **11**, 587-599.

Storer, K., Williams, J. & Berry, P. (2018). Use of autumn nitrogen in no-till farming systems. *AHDB Research Review* **No 91,** AHDB, Stoneleigh, Warwickshire, 44pp.

Sylvester-Bradley, R., Kindred, D.R., Blake, J.J., Dyer, C.J. & Sinclair, A.C. (2008). Optimising fertiliser nitrogen for modern wheat and barley crops. *AHDB Project Report* **No 438**, AHDB, Stoneleigh, Warwickshire, 117 pp.

Sylvester-Bradley, R. and Kindred D.R. (2009). Analysing nitrogen responses of cereals to prioritise routes to the improvement of nitrogen use efficiency. Journal of Experimental Botany. 60, 1939-1951

Wade, A. & Froment, M.A. (2003). Barley quality and size homogeneity for malting: Volume I: Agronomic effects on varieties. *AHDB Project Report* **No 320**, AHDB, Stoneleigh, Warwickshire, 70 pp.

Webb, J., Jephcote, C., Fraser, A., Wiltshire, J., Aston, S., Rose, R., Vincent, K., Roth, B. (2016). Do UK crops and grassland require greater inputs of sulphur fertilizer in response to recent and forecast reductions in sulphur emissions and deposition? *Soil Use & Management* **32**, 3-16.

Weightman, R.M., Fawcett, L., Sylvester-Bradley, R., Anthony, S., Bhandari, D. & Barrow, C. (2011). Predicting grain protein to meet market requirements for breadmaking and minimise diffuse pollution from wheat production. AHDB Cereals & Oilseeds Project Report No. 483.

Widdowson, F.V., Penny, A. & Williams, R.J.B. (1961). Applying nitrogen fertilisers for spring barley. *Journal of Agricultural Science, Cambridge* **56**, 39-47.

Widdowson, F.V., Jenkyn, J.F. & Penny, A. (1982). Results from factorial experiments testing amounts and times of granular N-fertiliser, late sprays of liquid N-fertiliser and fungicides to control mildew and brown rust on two varieties of spring barley at Saxmundham, Suffolk 1975-8. *Journal of Agricultural Science, Cambridge* **99**, 377-390.

Zebarth, B.J., Botha, E. J. & Rees, H. (2007). Rate and time of fertiliser nitrogen application on yield, protein and apparent efficiency of fertiliser nitrogen use of spring wheat. *Can. J. Plant Sci.* **87**, 709–718.

Zhao, C., Liu, L., Huang, W., Song, X. & Li, C. (2005). Predicting grain protein content of winter wheat using remote sensing data based on nitrogen status and water stress. *International Journal of Applied Earth Observation and Geoinformation*. **7**, 1-9.

Appendix 1. Objective 3 Quantify the effect of rate of soil applied N fertiliser on grain N%

Effects of N Rate on Yield and Grain N%

Table 1.1 Yield (t/ha) and N_{opt} (kg/ha) for the Norfolk 2018 N rate trial.

	N rate (kg/ha)								
Variety	0	40	100	180	260	360	Grand mean	N_{opt}	Yield at N_{opt}
RGT Planet	2.97	4.95	5.57	6.38	6.06	5.79	5.28	74	5.34
Laureate	3.63	5.02	4.45	6.13	6.70	6.70	5.44	74	5.34
Concerto	3.13	5.26	4.96	5.23	5.71	6.09	5.06	74	5.34
Grand mean	3.24	5.08	4.99	5.91	6.16	6.19	5.26	74	5.34

	P	SED	LSD
N rate	0.028	0.79	1.750
Variety	0.433	0.29	0.588
N rate x Variety	0.56	0.97	2.018

Table 1.2 Yield (t/ha) and N_{opt} (kg/ha) for the Nottinghamshire 2018 N rate trial.

	N rate (kg/ha)								
Variety	0	40	80	120	200	300	Grand mean	N_{opt}	Yield at N_{opt}
RGT Planet	5.73	7.60	7.40	8.31	8.03	8.21	7.55	104	7.79
Laureate	6.03	7.08	7.30	8.05	8.06	8.05	7.43	104	7.79
Concerto	5.74	7.12	7.14	7.99	7.76	7.83	7.27	104	7.79
Grand mean	5.83	7.27	7.28	8.12	7.95	8.03	7.41	104	7.79

	P	SED	LSD
N rate	<.001	0.35	0.781
Variety	0.028	0.10	0.203
N rate x Variety	0.724	0.42	0.849

Table 1.3 Yield (t/ha) and N_{opt} (kg/ha) for the East Lothian 2018 N rate trial.

	N rate (kg/ha)								
Variety	0	40	100	180	260	360	Grand mean	N_{opt}	Yield at N_{opt}
RGT Planet	5.88	7.55	8.84	9.46	9.13	9.76	8.44	171	9.25
Laureate	5.92	7.41	8.73	9.70	9.60	9.86	8.54	171	9.34
Concerto	5.54	6.81	7.87	8.61	8.61	9.05	7.75	171	8.56
Grand mean	5.78	7.25	8.48	9.26	9.11	9.56	8.24	171	9.0
	P	SED	LSD						
N rate	<.001	0.16	0.365						
Variety	<.001	0.18	0.358						
N rate x Variety	0.541	0.42	0.851						

Table 1.4 Yield (t/ha) and N_{opt} (kg/ha) for the North Yorkshire 2018 N rate trial.

	N rate (kg/ha)								
Variety	0	40	100	180	260	360	Grand mean	N_{opt}	Yield at N_{opt}
KWS Irina	3.23	4.74	5.23	7.88	7.68	8.09	6.14	219	7.84
	P	SED	LSD						
N rate	<.001	0.73	1.621						

Table 1.5 Yield (t/ha) and N_{opt} (kg/ha) for the Norfolk 2019 N rate trial.

	N rate (kg/ha)								
Variety	0	40	100	180	260	360	Grand mean	N_{opt}	Yield at N_{opt}
RGT Planet	2.66	4.13	4.28	3.81	4.59	4.59	4.01	83	4.48
Laureate	2.63	4.06	4.77	4.99	4.94	4.34	4.29	83	4.48
Concerto	2.50	3.84	4.66	4.75	3.84	3.91	3.92	83	4.48
Grand mean	2.6	4.0	4.6	4.5	4.5	4.3	4.1	77	4.48
	P	SED	LSD						
N rate	0.007	0.46	1.029						
Variety	0.191	0.14	0.287						
N rate x Variety	0.042	0.47	0.974						

Table 1.6 Yield (t/ha) and N_{opt} (kg/ha) for the Nottinghamshire 2019 N rate trial.

	N rate (kg/ha)								
Variety	0	40	80	120	200	300	Grand mean	N_{opt}	Yield at N_{opt}
RGT Planet	6.53	7.66	8.99	9.55	9.67	9.13	8.59	151	9.69
Laureate	6.57	7.66	9.02	9.12	9.61	8.84	8.47	151	9.56
Concerto	5.82	7.00	8.16	8.65	8.87	7.94	7.74	151	8.83
Grand mean	6.30	7.44	8.72	9.11	9.39	8.64	8.27	151	9.36
	P	SED	LSD						
N rate	<.001	0.25	0.562						
Variety	<.001	0.11	0.221						
N rate x Variety	0.893	0.33	0.682						

Table 1.7 Yield (t/ha) and N_{opt} (kg/ha) for the East Lothian 2019 N rate trial.

	N rate (kg/ha)								
Variety	0	40	100	180	260	360	Grand mean	N_{opt}	Yield at N_{opt}
RGT Planet	6.86	8.29	9.02	9.32	8.93	8.86	8.55	116	9.16
Laureate	6.77	8.15	8.86	9.21	9.02	8.27	8.37	116	8.99
Concerto	6.21	7.39	8.43	8.56	8.50	8.31	7.90	116	8.51
Grand mean	6.61	7.94	8.77	9.03	8.82	8.48	8.27	116	8.89
	P	SED	LSD						
N rate	<.001	0.28	0.616						
Variety	<.001	0.12	0.254						
N rate x Variety	0.821	0.37	0.761						

Table 1.8 Yield (t/ha) and N_{opt} (kg/ha) for the North Yorkshire 2019 N rate trial.

	N rate (kg/ha)								
Variety	0	40	100	180	260	360	Grand mean	N_{opt}	Yield at N_{opt}
Yield (t/ha)	6.51	7.91	8.95	9.08	9.17	8.93	8.42	124	9.01
	P	SED	LSD						
Yield (t/ha)	<.001	0.40	0.912						

Table 1.9 Yield (t/ha) and N_{opt} (kg/ha) for the Norfolk 2020 N rate trial.

	N rate (kg/ha)								
Variety	0	40	80	120	200	300	Grand mean	N_{opt}	Yield at N_{opt}
RGT Planet	3.55	3.51	4.14	4.19	2.91	3.14	2.49	30	3.91
Laureate	3.66	4.26	4.83	3.83	3.06	3.06	3.78	30	4.12
Concerto	2.76	2.44	3.18	2.47	2.04	2.08	3.58	30	2.83
Grand mean	3.32	3.40	4.05	3.50	2.67	2.76	3.28	30	3.62
	P	SED	LSD						
N rate	0.003	0.26	0.578						
Variety	<0.001	0.16	0.320						
N rate x Variety	0.45	0.40	0.824						

Table 1.10 Yield (t/ha) and N_{opt} (kg/ha) for the Nottinghamshire 2020 N rate trial.

	N rate (kg/ha)								
Variety	0	40	100	180	260	360	Grand mean	N_{opt}	Yield at N_{opt}
RGT Planet	5.70	6.44	7.85	8.31	8.16	7.98	7.41	169	8.24
Laureate	5.95	6.83	7.97	9.22	8.57	8.58	7.85	169	8.69
Concerto	5.44	6.03	7.16	8.14	7.59	7.33	6.95	169	7.79
Grand mean	5.70	6.43	7.66	8.56	8.11	7.96	7.40		
	P	SED	LSD						
N rate	0.002	0.52	1.158						
Variety	<0.001	0.09	0.182						
N rate x Variety	0.258	0.55	1.191						

Table 1.11 Yield (t/ha) and N_{opt} (kg/ha) for the North Yorkshire 2020 N rate trial.

	N rate (kg/ha)								
							Grand		Yield at
Variety	0	40	100	180	260	360	mean	N_{opt}	N_{opt}
Laureate	5.47	7.21	8.20	6.67	6.29	6.44	6.71	60	7.57
	P	SED	LSD						
N rate	0.031	0.66	1.464						

Table 1.12 Grain N% and N_{opt} (kg/ha) for the Norfolk 2018 N rate trial.

	N rate (kg/ha)								
							Grand		Grain N%
Variety	0	40	100	180	260	360	mean	N_{opt}	at N_{opt}
RGT Planet	1.30	1.26	1.41	1.90	2.18	2.34	1.73	74	1.32
Laureate	1.28	1.39	1.56	1.93	2.23	1.95	1.72	74	1.47
Concerto	1.26	1.28	1.57	1.91	2.15	1.98	1.69	74	1.42
Grand mean	1.28	1.31	1.51	1.91	2.19	2.09	1.72	74	1.40
	P	SED	LSD						
N rate	<.001	0.15	0.338						
Variety	0.71	0.05	0.103						
N rate x Variety	0.155	0.18	0.380						

Table 1.13 Grain N% and N_{opt} (kg/ha) for the Nottinghamshire 2018 N rate trial

Variety	N rate (kg/ha) 0	40	80	120	200	300	Grand mean	N_{opt}	Grain N% at N_{opt}
RGT Planet	1.43	1.46	1.54	1.63	1.70	1.74	1.58	104	1.59
Laureate	1.46	1.51	1.42	1.63	1.70	1.82	1.59	104	1.54
Concerto	1.46	1.56	1.56	1.68	1.76	1.92	1.66	104	
Grand mean	1.45	1.51	1.51	1.65	1.72	1.83	1.61	104	1.56
	P	SED	LSD						
N rate	<.001	0.051	0.116						
Variety	0.035	0.030	0.061						
N rate x Variety	0.502	0.079	0.161						

Table 1.14 Grain N% and N_{opt} (kg/ha) for the East Lothian 2018 N rate trial.

Variety	N rate (kg/ha) 0	40	100	180	260	360	Grand mean	N_{opt}	Grain N% at N_{opt}
RGT Planet	1.33	1.47	1.61	1.78	1.77	1.97	1.66	171	1.72
Laureate	1.36	1.41	1.61	1.82	1.90	2.07	1.70	171	1.76
Concerto	1.48	1.57	1.65	1.91	1.87	2.07	1.76	171	1.82
Grand mean	1.39	1.48	1.63	1.84	1.85	2.04	1.70	171	1.77
	P	SED	LSD						
N rate	<.001	0.05	0.121						
Variety	<.001	0.02	0.048						
N rate x Variety	0.378	0.07	0.015						

Table 1.15 Grain N% and N_{opt} (kg/ha) for the North Yorkshire 2018 N rate trial.

	N rate (kg/ha)								
							Grand		Grain N%
Variety	0	40	100	180	260	360	mean	N_{opt}	at N_{opt}
KWS Irina	1.25	1.16	1.42	1.87	2.00	2.03	1.62	219	1.97
	P	SED	LSD						
N rate	<.001	0.05	0.106						

Table 1.16 Grain N% and N_{opt} (kg/ha) for the Norfolk 2019 N rate trial.

	N rate (kg/ha)								
							Grand		Grain N%
Variety	0	40	100	180	260	360	mean	N_{opt}	at N_{opt}
RGT Planet	1.36	1.40	1.58	1.97	2.23	2.28	1.80	83	1.51
Laureate	1.37	1.35	1.82	2.07	2.28	2.37	1.88	83	1.64
Concerto	1.32	1.33	1.64	1.96	2.17	1.93	1.73	83	1.54
Grand mean	1.35	1.36	1.68	2.00	2.23	2.19	1.80	83	1.56
	P	SED	LSD						
N rate	<.001	0.13	0.296						
Variety	0.040	0.06	0.121						
N rate x Variety	0.003	0.16	0.335						

Table 1.17 Grain N% and N_{opt} (kg/ha) for the Nottinghamshire 2019 N rate trial.

	N rate (kg/ha)								
Variety	0	40	80	120	200	300	Grand mean	N_{opt}	Grain N% at N_{opt}
RGT Planet	1.28	1.38	1.45	1.52	1.63	2.02	1.55	151	1.69
Laureate	1.29	1.56	1.43	1.54	1.77	1.95	1.59	151	1.65
Concerto	1.30	1.50	1.45	1.63	1.65	1.98	1.58	151	1.70
Grand mean	1.29	1.48	1.44	1.57	1.68	1.98	1.57	151	1.68
	P	SED	LSD						
N rate	<.001	0.04	0.093						
Variety	0.298	0.03	0.065						
N rate x Variety	0.303	0.08	0.153						

Table 1.18 Grain N% and N_{opt} (kg/ha) for the East Lothian 2019 N rate trial.

	N rate (kg/ha)								
Variety	0	40	100	180	260	360	Grand mean	N_{opt}	Grain N% at N_{opt}
RGT Planet	1.27	1.33	1.56	1.73	1.95	2.07	1.65	116	1.59
Laureate	1.24	1.37	1.55	1.74	1.99	2.15	1.67	116	1.57
Concerto	1.31	1.35	1.51	1.80	1.94	2.11	1.67	116	1.57
Grand mean	1.27	1.35	1.54	1.76	1.96	2.11	1.66	116	1.58
	P	SED	LSD						
N rate	<.001	0.03	0.069						
Variety	0.286	0.02	0.032						
N rate x Variety	0.184	0.04	0.090						

Table 1.19 Grain N% and N_{opt} (kg/ha) for the North Yorkshire 2019 N rate trial.

Variety	N rate (kg/ha) 0	40	100	180	260	360	Grand mean	N_{opt}	Grain N% at N_{opt}
Grain N%	1.36	1.34	1.34	1.54	1.74	1.99	1.55	124	1.40
	P	SED	LSD						
Grain N%	<.001	0.06	0.133						

Table 1.20 Grain N% and N_{opt} (kg/ha) for the Norfolk 2020 N rate trial.

Variety	N rate (kg/ha) 0	40	80	120	200	300	Grand mean	N_{opt}	Grain N% at N_{opt}
RGT Planet	1.77	1.74	1.96	2.04	2.14	2.12	1.91	30	1.73
Laureate	1.72	1.67	1.81	1.96	2.14	2.18	1.96	30	1.67
Concerto	1.73	1.86	1.88	2.02	2.15	2.14	1.96	30	1.80
Grand mean	1.74	1.76	1.88	2.01	2.14	2.15			
	P	SED	LSD						
N rate	<.001	0.03	0.060						
Variety	0.017	0.02	0.038						
N rate x Variety	0.028	0.05	0.093						

Table 1.21 Grain N% and N_{opt} (kg/ha) for the Nottinghamshire 2020 N rate trial.

	N rate (kg/ha)								
Variety	0	40	100	180	260	360	Grand mean	N_{opt}	Grain N% at N_{opt}
RGT Planet	1.47	1.56	1.7	1.94	2.07	2.22	1.84	169	1.99
Laureate	1.42	1.43	1.73	1.98	2.12	2.24	1.82	169	1.92
Concerto	1.53	1.57	1.87	2.00	2.17	2.30	1.91	169	1.95
Grand mean	1.47	1.52	1.79	1.97	2.12	2.25			
	P	SED	LSD						
N rate	<0.001	0.05	0.101						
Variety	<0.001	0.02	0.031						
N rate x Variety	0.081	0.05	0.114						

Table 1.22 Grain N% and N_{opt} (kg/ha) for the North Yorkshire 2020 N rate trial.

	N rate (kg/ha)								
Variety	0	40	100	180	260	360	Grand mean	N_{opt}	Grain N% at N_{opt}
Laureate	1.27	1.27	1.50	1.88	2.11	2.21	1.71	60	1.33
Grand mean	1.27	1.27	1.50	1.88	2.11	2.21			
	P	SED	LSD						
N rate	<0.001	0.06	0.133						

Effects on Yield Components

Table 1.23 Ears/m² for the Norfolk 2018 trial

	N rate (kg/ha)						
Variety	0	40	100	180	260	360	Grand mean
RGT Planet	328	464	463	554	533	514	476
Laureate	461	494	430	553	606	605	525
Concerto	353	490	456	496	524	568	481
Grand mean	381	483	450	354	554	562	494
	P	SED	LSD				
N rate	0.205	75	166.5				
Variety	0.305	34	69.7				
N rate x Variety	0.944	101	207.1				

Table 1.24 Grains/ear for the Norfolk 2018 trial

	N rate (kg/ha)						
Variety	0	40	100	180	260	360	Grand mean
RGT Planet	20.4	23.3	24.9	24.6	24.2	24.5	23.7
Laureate	19.3	22.5	22.8	24.3	24.4	23.7	22.8
Concerto	21.1	23.8	25.0	23.5	25.3	24.8	23.9
Grand mean	20.2	23.2	24.2	24.2	24.6	24.3	23.5
	P	SED	LSD				
N rate	0.037	1.2	2.70				
Variety	0.456	0.90	1.86				
N rate x Variety	0.998	2.17	4.41				

Table 1.25 Grains/m² for the Norfolk 2018 trial

	N rate (kg/ha)						
Variety	0	40	100	180	260	360	Grand mean
RGT Planet	6757	10819	11523	13564	12662	12592	11320
Laureate	87.8	11190	9579	13338	14789	14213	11975
Concerto	7593	11694	11224	11606	13158	14013	11548
Grand mean	7696	11235	10776	12836	13536	13606	11614
	P	SED	LSD				
N rate	0.038	1664	3708.1				
Variety	0.552	602	1243.0				
N rate x Variety	0.565	2054	4274.3				

Table 1.26 TGW (g) for the Norfolk 2018 trial

	N rate (kg/ha)						
Variety	0	40	100	180	260	360	Grand mean
RGT Planet	43.9	45.8	48.3	47.0	47.9	45.7	46.4
Laureate	41.7	44.4	46.4	46.1	45.2	47.0	45.1
Concerto	40.6	44.9	44.2	45.2	43.4	43.2	43.6
Grand mean	42.1	45.0	46.3	46.1	45.5	45.3	45.0
	P	SED	LSD				
N rate	0.006	0.84	1.881				
Variety	0.007	0.80	1.656				
N rate x Variety	0.863	1.81	3.689				

Table 1.27 Ears/m^2 for the Nottinghamshire 2018 trial

	N rate (kg/ha)						
Variety	0	40	80	120	200	300	Grand mean
RGT Planet	518	693	681	803	679	852	701
Laureate	614	685	761	786	776	840	734
Concerto	611	751	731	766	842	860	760
Grand mean	581	710	724	785	766	845	735
	P	SED	LSD				
N rate	0.003	44	98.5				
Variety	0.014	19	39.2				
N rate x Variety	0.23	58	120.1				

Table 1.28 Grains/ear for the Nottinghamshire 2018 trial

	N rate (kg/ha)						
Variety	0	40	80	120	200	300	Grand mean
RGT Planet	20.4	21.1	20.6	19.5	21.0	19.1	20.3
Laureate	18.6	19.5	18.3	20.0	20.1	18.8	19.2
Concerto	18.9	19.8	20.2	21.9	20.0	20.0	20.1
Grand mean	19.3	20.1	19.7	20.5	20.4	19.3	19.9
	P	SED	LSD				
N rate	0.04	0.4	0.86				
Variety	0.013	0.4	0.7				
N rate x Variety	0.112	0.8	1.7				

Table 1.29 Grains/m^2 for the Nottinghamshire 2018 trial

	N rate (kg/ha)						
Variety	0	40	80	120	200	300	Grand mean
RGT Planet	10558	14498	13948	15630	14216	15924	14129
Laureate	11429	13302	13939	15590	15628	15751	14273
Concerto	11504	14785	14766	16710	16862	17209	15306
Grand mean	11164	14195	14218	15977	15569	16295	14569
	P	SED	LSD				
N rate	<0.001	732.2	1631.4				
Variety	<0.001	226.1	466.6				
N rate x Variety	0.1	860.6	1808.0				

Table 1.30 TGW for the Nottinghamshire 2018 trial

	N rate (kg/ha)						
Variety	0	40	80	120	200	300	Grand mean
RGT Planet	54.3	54.4	53.1	53.2	54.5	51.6	53.5
Laureate	52.8	53.3	52.4	51.6	51.6	51.1	52.1
Concerto	49.9	48.2	48.5	47.8	46.1	45.5	47.7
Grand mean	52.3	60.0	51.3	50.9	50.7	49.4	51.1
	P	SED	LSD				
N rate	0.059	0.8	1.84				
Variety	<0.001	0.4	0.85				
N rate x Variety	0.243	1.2	2.38				

Table 1.31 TGW (g) for the East Lothian 2018 trial

Variety	N rate (kg/ha) 0	40	100	180	260	360	Grand mean
RGT Planet	57.4	59.3	58.0	58.1	56.9	57.2	57.8
Laureate	58.4	58.6	57.9	57.2	58.1	57.8	58.0
Concerto	56.7	58.1	57.3	57.4	58.6	57.1	57.2
Grand mean	57.5	58.7	57.7	57.6	57.2	57.4	57.7
	P	SED	LSD				
N rate	0.092	0.5	1.00				
Variety	0.057	0.3	0.68				
N rate x Variety	0.711	0.8	1.61				

Table 1.32 Yield components for the North Yorkshire 2018 trial

Component	N rate (kg/ha) 0	40	100	180	260	360	Grand mean
Ears/m^2	399	477	466	692	647	684	561
Grains/ear	19.4	23.0	25.6	26.3	26.9	27.3	24.7
Grains/m^2	7714	10861	11567	18088	17424	18590	14040
TGW (g)	41.9	43.6	45.0	44.7	44.1	43.5	43.8
	P	SED	LSD				
Ears/m2	0.01	76	169.0				
Grains/ear	0.002	1.3	3.00				
Grains/m2	<0.001	1692	3829.0				
TGW (g)	0.01	0.6	1.43				

Table 1.33 Ears/m^2 for the Norfolk 2019 trial

	N rate (kg/ha)						
Variety	0	40	100	180	260	360	Grand mean
RGT Planet	283	457	466	436	554	446	440
Laureate	304	429	543	703	703	627	551
Concerto	269	461	504	529	443	477	447
Grand mean	286	449	504	556	567	517	480
	P	SED	LSD				
N rate	0.004	54	120.1				
Variety	<0.001	26	54.0				
N rate x Variety	0.046	75	153.0				

Table 1.34 Grains/ear for the Norfolk 2019 trial

	N rate (kg/ha)						
Variety	0	40	100	180	260	360	Grand mean
RGT Planet	21.5	21.2	20.1	20.6	20.9	27.4	22.0
Laureate	18.7	22.0	20.5	18.0	18.8	18.7	19.4
Concerto	23.5	20.4	21.5	21.6	21.8	22.1	21.8
Grand mean	21.2	21.2	20.7	20.1	20.5	22.7	21.1
	P	SED	LSD				
N rate	0.448	1.3	2.85				
Variety	0.017	0.9	1.88				
N rate x Variety	0.165	2.2	4.53				

Table 1.35 Grains/m² for the Norfolk 2019 trial

	N rate (kg/ha)						
Variety	0	40	100	180	260	360	Grand mean
RGT Planet	6035	9680	9366	9008	11302	12090	9580
Laureate	5608	9355	11051	12151	13090	11645	10484
Concerto	6193	9120	10805	11055	9628	10403	9534
Grand mean	5945	9385	10407	10738	11340	11380	9866
	P	SED	LSD				
N rate	<0.001	626	1394.2				
Variety	0.013	331	682.4				
N rate x Variety	0.007	910	1860.6				

Table 1.36 TGW (g) for the Norfolk 2019 trial

	N rate (kg/ha)						
Variety	0	40	100	180	260	360	Grand mean
RGT Planet	44.36	42.7	45.6	42.5	40.5	38.2	42.3
Laureate	47.0	43.3	43.2	41.2	37.7	37.4	41.6
Concerto	40.3	42.0	42.8	42.9	40.0	37.6	40.9
Grand mean	43.9	42.7	43.8	42.2	39.4	37.7	41.6
	P	SED	LSD				
N rate	0.013	1.6	3.47				
Variety	0.125	0.7	1.35				
N rate x Variety	0.049	2.0	4.20				

Table 1.37 Ears/m^2 for the Nottinghamshire 2019 trial

	N rate (kg/ha)						
Variety	0	40	80	120	200	300	Grand mean
RGT Planet	669	714	892	913	1099	1279	928
Laureate	739	807	985	1150	1176	1408	1044
Concerto	564	677	753	990	993	1330	884
Grand mean	657	732	877	1017	1089	1339	952
	P	SED	LSD				
N rate	0.002	122	272.6				
Variety	0.010	49	101.0				
N rate x Variety	0.959	157	324.0				

Table 1.38 Grains/ear for the Nottinghamshire 2019 trial

	N rate (kg/ha)						
Variety	0	40	80	120	200	300	Grand mean
RGT Planet	19.8	218	21.5	22.8	20.0	16.8	20.4
Laureate	18.5	20.2	19.7	18.0	18.8	15.5	18.4
Concerto	21.3	21.7	14.1	19.6	21.1	14.1	18.6
Grand mean	19.8	21.2	18.4	20.1	19.9	15.5	19.2
	P	SED	LSD				
N rate	0.117	1.9	4.16				
Variety	0.287	1.4	2.79				
N rate x Variety	0.709	3.3	6.68				

Table 1.39 Grains/m² for the Nottinghamshire 2019 trial

	N rate (kg/ha)						
Variety	0	40	80	120	200	300	Grand mean
RGT Planet	13234	15509	18822	20478	21509	21330	18480
Laureate	13505	16148	18901	19905	21263	20902	18438
Concerto	11855	14332	11422	18699	20422	18616	15891
Grand mean	12865	15329	16382	19695	21065	20283	17603
	P	SED	LSD				
N rate	<0.001	1382	3079.9				
Variety	0.003	755	1558.1				
N rate x Variety	0.345	2047	4179.5				

Table 1.40 TGW (g) for the Nottinghamshire 2019 trial

	N rate (kg/ha)						
Variety	0	40	80	120	200	300	Grand mean
RGT Planet	49.4	49.4	47.8	46.7	45.0	42.8	46.8
Laureate	48.6	47.4	47.8	45.7	45.2	42.3	46.2
Concerto	49.1	48.8	47.7	46.3	43.6	42.7	46.4
Grand mean	49.0	48.6	47.8	46.2	44.6	42.6	46.5
	P	SED	LSD				
N rate	<0.001	0.5	1.13				
Variety	0.054	0.3	0.56				
N rate x Variety	0.235	0.8	1.51				

Table 1.41 Yield components for the North Yorkshire 2019 trial

	N rate (kg/ha)						
Component	0	40	100	180	260	360	Grand mean
Ears/m^2	962	798	876	853	878	958	888
Grains/ear	16.9	21.3	21.9	24.4	25.1	23.8	22.2
Grains/m^2	15758	16837	19190	20795	21789	22691	19510
TGW (g)	41.7	46.9	46.5	43.7	42.1	39.4	43.4
	P	SED	LSD				
Ears/m^2	0.764	125	282.9				
Grains/ear	0.004	1.5	3.39				
Grains/m^2	0.002	1264	2859.1				
TGW (g)	0.002	1.3	2.93				

Table 1.42 Ears/m^2 for the Norfolk 2020 trial

	N rate						
Variety	0	40	80	120	200	300	Grand mean
RGT Planet	439	449	513	531	366	395	449
Laureate	457	427	597	482	382	381	469
Concerto	376	306	402	315	273	268	323
Grand mean	424	427	504	443	337	348	414
	P	SED	LSD				
N rate	0.005	34	74.9				
Variety	<0.001	21	43.5				
N rate x Variety	0.411	54	109.8				

Table 1.43 Grains/ear for the Norfolk 2020 trial

	N rate						
Variety	0	40	80	120	200	300	Grand mean
RGT Planet	16.5	15.7	17.1	15.4	15.3	16.9	16.1
Laureate	13.6	14.9	13.8	12.1	16.0	16.9	14.4
Concerto	14.8	15.4	15.0	14.5	13.6	14.6	14.6
Grand mean	15.0	15.3	15.3	14.0	15.0	15.8	15.1
	P	SED	LSD				
N rate	0.084	0.5	1.18				
Variety	0.004	0.5	1.06				
N rate x Variety	0.263	1.2	2.34				

Table 1.44 Grains/m^2 for the Norfolk 2020 trial

	N rate						
Variety	0	40	80	120	200	300	Grand mean
RGT Planet	7222	7025	8782	8135	5590	6678	7239
Laureate	6223	7933	8218	5866	5991	6090	6720
Concerto	5608	4684	6014	4564	3724	3865	4743
Grand mean	6351	6547	7671	6188	5102	5545	6234
	P	SED	LSD				
N rate	0.010	526	1172.4				
Variety	<0.001	432	891.5				
N rate x Variety	0.660	1012	2055.8				

Table 1.45 TGW (g) for the Norfolk 2020 trial

	N rate						
Variety	0	40	80	120	200	300	Grand mean
RGT Planet	46.1	44.4	45.9	45.8	44.0	43.1	44.9
Laureate	47.5	44.8	44.9	46.7	43.9	41.6	44.9
Concerto	42.6	41.8	42.2	42.3	38.9	39.0	41.1
Grand mean	43.6	43.7	44.3	44.9	42.3	41.2	43.6
	P	SED	LSD				
N rate	<0.001	0.6	1.44				
Variety	<0.001	0.4	0.85				
N rate x Variety	0.434	1.0	2.12				

Table 1.46 Ears/m^2 for the Nottinghamshire 2020 N rate trial

	N rate (kg/ha)						
Variety	0	40	100	180	260	360	Grand mean
RGT Planet	832	841	1020	1130	1138	1064	1004
Laureate	910	1049	1177	1542	1323	1452	1242
Concerto	760	730	998	1080	1025	1093	948
Grand mean	834	874	1065	1250	1162	1203	1065
	P	SED	LSD				
N rate	<0.001	69	154.1				
Variety	<0.001	35	71.4				
N rate x Variety	0.170	98	200.3				

Table 1.47 Grains/ear for the Nottinghamshire 2020 N rate trial

	N rate (kg/ha)						
Variety	0	40	100	180	260	360	Grand mean
RGT Planet	14.1	15.5	15.6	15.9	15.0	15.6	15.3
Laureate	13.7	13.7	14.0	12.8	13.6	12.4	13.3
Concerto	15.2	16.7	14.6	16.0	15.4	13.8	15.3
Grand mean	14.3	15.3	14.7	14.9	14.7	13.9	14.6
	P	SED	LSD				
N rate	0.296	0.6	1.26				
Variety	<0.001	0.4	0.84				
N rate x Variety	0.367	1.0	2.01				

Table 1.48 Grains/m^2 for the Nottinghamshire 2020 N rate trial

	N rate (kg/ha)						
Variety	0	40	100	180	260	360	Grand mean
RGT Planet	11646	12960	15921	17875	16961	16544	15318
Laureate	12353	14090	16192	19441	18044	17984	16351
Concerto	11526	12183	14458	17186	15815	15058	14376
Grand mean	11842	13078	15532	18167	16940	16529	15348
	P	SED	LSD				
N rate	0.001	1060	2360.9				
Variety	<0.001	171	354.4				
N rate x Variety	0.104	1114	2423.2				

Table 1.49 TGW (g) for the Nottinghamshire 2020 N rate trial

	N rate (kg/ha)						
Variety	0	40	100	180	260	360	Grand mean
RGT Planet	48.8	49.7	49.3	46.5	48.2	48.2	48.5
Laureate	48.1	48.4	49.3	47.4	47.5	47.6	48.1
Concerto	47.2	49.4	49.5	47.4	48.0	48.0	48.3
Grand mean	48.0	49.2	49.3	47.1	47.9	48.0	48.3
	P	SED	LSD				
N rate	0.108	0.8	1.70				
Variety	0.454	0.3	0.64				
N rate x Variety	0.476	1.0	2.03				

Table 1.50 Yield components for the North Yorkshire 2020 trial

	N rate (kg/ha)						
Component	0	40	100	180	260	360	Grand mean
Ears/m^2	722	838	1174	1033	987	1083	973
Grains/ear	15.3	17.1	15.4	15.9	16.6	15.9	16.0
Grains/m^2	11061	14354	18118	16525	15707	16921	15443
TGW (g)	49.5	50.3	45.3	40.7	40.1	38.1	44.0
	P	SED	LSD				
Ears/m2	0.048	128	284.4				
Grains/ear	0.763	1.4	3.07				
Grains/m2	0.016	1586	3532.8				
TGW (g)	<0.001	0.6	1.26				

Specific Weight and Screening Results

Table 1.51 Specific weight (kg/hl) for the Norfolk 2018 trial

	N rate (kg/ha)						
Variety	0	40	100	180	260	360	Grand mean
RGT Planet	65.6	68.2	68.5	69.6	70.5	69.0	68.6
Laureate	65.9	66.2	65.4	68.3	69.1	68.7	67.3
Concerto	65.7	67.0	69.4	69.2	68.0	67.8	67.8
Grand mean	65.7	67.1	67.8	69.0	69.2	68.5	67.9
	P	SED	LSD				
N rate	0.046	0.6	1.42				
Variety	0.007	0.6	1.24				
N rate x Variety	0.071	1.2	2.44				

Table 1.52 Specific weight (kg/hl) for the Nottinghamshire 2018 trial

	N rate (kg/ha)						
Variety	0	40	80	120	200	300	Grand mean
RGT Planet	66.4	68.3	68.3	67.7	66.9	67.0	67.4
Laureate	66.0	64.8	66.1	67.7	67.0	65.9	66.3
Concerto	68.7	66.3	68.0	68.0	67.0	66.1	67.3
Grand mean	67.0	66.5	67.5	67.8	67.0	66.3	67.0
	P	SED	LSD				
N rate	0.716	1.0	2.33				
Variety	0.051	0.5	1.04				
N rate x Variety	0.374	1.5	2.98				

Table 1.53 Specific weight (kg/hl) for the East Lothian 2018 trial

	N rate (kg/ha)						
Variety	0	40	100	180	260	360	Grand mean
RGT Planet	66.8	66.1	67.9	68.6	68.2	68.2	67.6
Laureate	64.6	65.6	65.8	66.9	67.1	67.8	66.3
Concerto	66.9	66.4	68.5	69.4	67.8	69.2	68.0
Grand mean	66.1	66.0	67.4	68.3	67.7	68.4	67.3
	P	SED	LSD				
N rate	0.221	0.6	1.43				
Variety	<.001	0.4	0.87				
N rate x Variety	0.857	1.1	2.30				

Table 1.54 Specific weight (kg/hl) for the North Yorkshire 2018 trial

	N rate (kg/ha)						
Variety	0	40	100	180	260	360	Grand mean
KWS Irina	64.7	64.1	64.5	65.0	64.8	64.6	64.6
	P	SED	LSD				
N rate	0.544	0.4	1.00				

Table 1.55 Specific weight (kg/hl) for the Norfolk 19 trial

	N rate (kg/ha)						
Variety	0	40	100	180	260	360	Grand mean
RGT Planet	61.4	60.7	61.7	59.6	62.8	61.7	61.3
Laureate	60.5	59.2	61.8	62.5	61.6	62.3	61.3
Concerto	60.9	61.0	61.3	61.6	62.3	62.1	61.5
Grand mean	60.9	60.3	61.6	61.2	62.2	62.0	61.4
	P	SED	LSD				
N rate	0.458	1.0	2.22				
Variety	0.895	0.5	1.08				
N rate x Variety	0.546	1.4	2.96				

Table 1.56 Specific weight (kg/hl) for the Nottinghamshire 2019 trial

	N rate (kg/ha)						
Variety	0	40	80	120	200	300	Grand mean
RGT Planet	61.7	62.2	62.9	62.3	62.0	61.5	62.1
Laureate	59.6	61.1	61.3	61.4	61.8	60.2	60.9
Concerto	63.2	64.3	64.1	64.7	64.8	64.1	64.2
Grand mean	61.5	62.5	62.7	62.8	62.9	62.0	62.4
	P	SED	LSD				
N rate	0.052	0.4	0.95				
Variety	<0.001	0.2	0.33				
N rate x Variety	0.073	0.5	1.11				

Table 1.57 Specific weight (kg/hl) for the East Lothian 2019 trial

	N rate (kg/ha)						
Variety	0	40	100	180	260	360	Grand mean
RGT Planet	61.9	63	61.1	59.4	60.2	58.3	60.7
Laureate	61.7	61.2	60.7	61.1	58.3	58.2	60.2
Concerto	64.0	65.1	64.6	60.5	62.5	59.8	62.7
Grand mean	62.5	63.1	62.2	60.3	60.3	58.8	61.2
	P	SED	LSD				
N rate	0.025	1.1	2.54				
Variety	0.001	0.6	1.30				
N rate x Variety	0.635	1.7	3.47				

Table 1.58 Specific weight (kg/hl) for the North Yorkshire 2019 N rate trial

	N rate (kg/ha)						
Variety	0	40	100	180	260	360	Grand mean
Specific weight	55.9	60.4	61.1	62.5	63.7	62.3	61.0
	P	SED	LSD				
Specific weight	<.001	0.77	1.747				

Table 1.59 Specific weight (kg/hl) for the Norfolk 2020 trial

	N rate						
Variety	0	40	80	120	200	300	Grand mean
RGT Planet	54.8	53.3	53.6	53.2	49.7	51.5	52.7
Laureate	54.8	54.1	53.4	54.0	52.7	53.4	53.7
Concerto	54.5	52.3	52.8	53.2	53.3	52.7	53.1
Grand mean	54.7	53.2	53.3	53.5	51.9	52.5	53.2
	P	SED	LSD				
N rate	0.050	0.7	1.62				
Variety	0.037	0.4	0.77				
N rate x Variety	0.075	1.0	2.12				

Table 1.60 Specific weight (kg/hl) for the Nottinghamshire 2020 N rate trial.

	N rate (kg/ha)						
Variety	0	40	100	180	260	360	Grand mean
RGT Planet	60.6	61.3	62.2	61.9	62.5	62.6	61.9
Laureate	59.0	58.4	61.1	61.2	62.3	61.8	60.6
Concerto	61.9	62.7	64.2	63.4	64.1	63.7	63.3
Grand mean	60.5	60.8	62.5	62.2	63.0	62.7	61.9
	P	SED	LSD				
N rate	<0.001	0.4	0.98				
Variety	<0.001	0.2	0.46				
N rate x Variety	0.076	0.6	1.28				

Table 1.61 Specific weight (kg/hl) for the North Yorkshire 2020 trial

	N rate						
Variety	0	40	100	180	260	360	Grand mean
Laureate	59.03	60.2	58.17	59.07	58.07	57.23	58.63
	P	SED	LSD				
N rate	0.171	1.0	2.32				

Table 1.62 Screening results (%) for the Norfolk 2018 trial

		N rate (kg/ha)						
Variety	Screening	0	40	80	120	200	300	Grand mean
RGT Planet	>2.5 mm	92.4	95.4	94.4	93.3	92.5	89.0	92.8
	2.25-2.5 mm	5.3	3.4	4.2	4.8	4.3	7.3	4.9
	<2.25 mm	2.3	1.2	1.4	1.9	3.3	3.7	2.3
Laureate	>2.5 mm	91.7	95.8	94.6	93.7	90.3	86.6	92.1
	2.25-2.5 mm	5.6	2.7	3.4	4.2	6.1	8.8	5.1
	<2.25 mm	2.7	1.6	2.0	2.1	3.6	4.6	2.8
Concerto	>2.5 mm	92.3	95.7	95.3	93.6	90.8	86.6	92.2
	2.25-2.5 mm	4.8	2.3	1.7	4.2	6.0	9.2	4.7
	<2.25 mm	2.5	1.6	1.6	2.1	4.3	6.8	3.1
		P	SED	LSD				
N rate	>2.5 mm	0.006	1.9	4.17				
	2.25-2.5 mm	0.020	1.4	3.02				
	<2.25 mm	0.002	0.6	1.41				
Variety	>2.5 mm	0.532	0.7	1.35				
	2.25-2.5 mm	0.657	0.5	0.95				
	<2.25 mm	0.080	0.3	0.68				
N rate x Variety	>2.5 mm	0.238	2.3	4.77				
	2.25-2.5 mm	0.295	1.6	3.42				
	<2.25 mm	0.471	0.9	1.8				

Table 1.63 Screening results (g) for the Nottinghamshire 2018 trial

		N rate (kg/ha)						
Variety	Screening	0	40	80	120	200	300	Grand mean
RGT Planet	>2.5 mm	97.6	97.7	97.5	97.3	96.3	93.9	96.7
	2.25-2.5 mm	1.3	1.6	1.7	1.7	2.4	4.3	2.2
	<2.25 mm	1.3	1.0	1.1	1.4	1.5	2.1	1.4
Laureate	>2.5 mm	96.6	97.3	97.0	96.7	96.5	94.5	96.4
	2.25-2.5 mm	1.7	1.8	2.1	2.1	2.4	3.9	2.3
	<2.25 mm	1.8	1.2	1.3	1.4	1.3	1.9	1.5
Concerto	>2.5 mm	98.0	96.8	96.7	95.7	93.3	89.8	95.1
	2.25-2.5 mm	1.2	2.3	2.2	2.8	5.1	7.6	3.5
	<2.25 mm	1.1	1.0	1.3	1.2	2.0	2.8	1.5
		P	SED	LSD				
N rate	>2.5 mm	0.012	1.1	2.44				
	2.25-2.5 mm	0.005	0.8	1.69				
	<2.25 mm	0.027	0.3	0.66				
Variety	>2.5 mm	0.001	0.4	0.86				
	2.25-2.5 mm	<0.001	0.3	0.58				
	<2.25 mm	0.323	0.1	0.27				
N rate x Variety	>2.5 mm	0.036	1.4	2.86				
	2.25-2.5 mm	0.01	0.9	1.96				
	<2.25 mm	0.09	0.4	0.81				

Table 1.64 Screening results (%) for the East Lothian 2018 trial

Variety	Screening	N rate (kg/ha)						Grand mean
		0	40	100	180	260	360	
RGT Planet	<2.5 mm	1.8	1.8	1.5	1.4	1.5	1.7	1.6
Laureate	<2.5 mm	2.1	1.4	1.5	1.3	1.6	1.4	1.6
Concerto	<2.5 mm	1.1	1.4	1.8	1.8	1.4	1.7	1.5
		P	SED	LSD				
N rate	<2.5 mm	0.982	0.3	0.56				
Variety	<2.5 mm	0.788	0.2	0.34				
N rate x Variety	<2.5 mm	0.426	0.4	0.84				

Table 1.65 Screenings (%) for the North Yorkshire 2018 trial

Variety	Screening	N rate (kg/ha)						Grand mean
		0	40	100	180	260	360	
Laureate	>2.5 mm	95.0	96.3	97.7	95.6	95.4	94.8	95.8
	2.25-2.5 mm	4.0	2.8	1.6	3.1	3.5	4.0	3.2
	<2.25 mm	1.0	0.9	0.7	1.2	1.1	1.2	1.0
		P	SED	LSD				
N rate	>2.5 mm	0.023	0.7	1.61				
	2.25-2.5 mm	0.026	0.6	1.40				
	<2.25 mm	0.016	0.13	0.28				

Table 1.66 Screening results (%) for the Norfolk 2019 trial

Variety	Screening	N rate (kg/ha)						Grand mean
		0	40	100	180	260	360	
RGT Planet	>2.5 mm	91.2	92.2	92.5	96.2	91.5	94.8	93.1
	2.25-2.5 mm	6.4	4.2	4.7	2.6	5.4	3.3	4.4
	<2.25 mm	2.5	3.6	2.8	1.2	3.1	2	2.5
Laureate	>2.5 mm	90.3	89.5	96.0	93.9	91.5	93.3	92.4
	2.25-2.5 mm	6.7	6.0	2.7	3.7	5.6	4.5	4.9
	<2.25 mm	3.0	4.5	1.3	2.5	2.9	2.2	2.7
Concerto	>2.5 mm	92.1	93.0	94.1	93.9	93.6	94.9	93.6
	2.25-2.5 mm	5.7	4.2	4.1	4.1	3.9	2.9	4.1
	<2.25 mm	2.2	2.8	1.9	2.0	2.5	2.2	2.3
		P	SED	LSD				
N rate	>2.5 mm	0.337	2.6	5.79				
	2.25-2.5 mm	0.502	1.7	3.86				
	<2.25 mm	0.168	1.0	2.27				
Variety	>2.5 mm	0.633	1.0	2.09				
	2.25-2.5 mm	0.690	0.7	1.40				
	<2.25 mm	0.639	0.4	0.86				
N rate x Variety	>2.5 mm	0.721	3.0	6.13				
	2.25-2.5 mm	0.780	2.0	4.10				
	<2.25 mm	0.660	1.2	2.46				

Table 1.67 Screening results (%) for the Nottinghamshire 2019 trial

Variety	Screening	N rate (kg/ha)						Grand mean
		0	40	80	120	200	300	
RGT Planet	>2.5 mm	96.2	95.3	93.1	93.4	92.1	89.8	93.3
	2.25-2.5 mm	2.9	3.1	5.0	4.9	5.0	6.0	4.5
	<2.25 mm	1.1	1.3	3.3	3.4	3.2	4.2	2.7
Laureate	>2.5 mm	97.0	96.9	93.5	92.7	91.8	90.9	93.8
	2.25-2.5 mm	2.7	2.4	4.1	4.6	4.8	5.1	4.0
	<2.25 mm	1.3	1.2	2.3	3.6	3.2	3.5	2.5
Concerto	>2.5 mm	97.4	98.4	94.9	94.0	93.6	91.2	94.9
	2.25-2.5 mm	1.7	1.7	3.2	3.7	4.1	4.7	3.2
	<2.25 mm	1.1	0.8	1.8	2.3	2.9	4.0	2.2
		P	SED	LSD				
N rate	>2.5 mm	<0.001	0.7	1.56				
	2.25-2.5 mm	<0.001	0.2	0.50				
	<2.25 mm	<0.001	0.3	0.70				
Variety	>2.5 mm	<0.001	0.3	0.69				
	2.25-2.5 mm	<0.001	0.2	0.33				
	<2.25 mm	0.001	0.1	0.28				
N rate x Variety	>2.5 mm	0.502	1.0	1.98				
	2.25-2.5 mm	0.769	0.4	0.79				
	<2.25 mm	0.020	0.4	0.86				

Table 1.68 Screenings (%) for the East Lothian 2019 trial

Variety	Screening	N rate (kg/ha)						Grand mean
		0	40	100	180	260	360	
RGT Planet	<2.5 mm	3.8	2.9	3.4	3.1	3.4	3.3	3.3
Laureate	<2.5 mm	3.2	3.5	3.9	3.8	3.0	3.1	3.4
Concerto	<2.5 mm	3.2	3.3	3.0	3.2	3.1	2.9	3.1
		P	SED	LSD				
N rate	<2.5 mm	0.965	0.5	1.05				
Variety	<2.5 mm	0.350	0.2	0.40				
N rate x Variety	<2.5 mm	0.558	0.6	1.26				

Table 1.69 Screenings (%) for the North Yorkshire 2019 trial

Variety	Screening	N rate (kg/ha)						Grand mean
		0	40	100	180	260	360	
Laureate	>2.5 mm	92.5	96.5	96.6	97.0	95.9	94.8	95.6
	2.25-2.5 mm	4.7	1.9	1.9	1.7	2.3	3.0	2.6
	<2.25 mm	2.8	1.4	1.5	1.4	1.8	2.2	1.9
		P	SED	LSD				
N rate	>2.5 mm	0.092	1.5	3.32				
	2.25-2.5 mm	0.056	0.9	2.00				
	<2.25 mm	0.232	0.6	1.41				

Table 1.70 Screening results (%) for the Norfolk 2020 trial

Variety	Screening	N rate (kg/ha)						Grand mean
		0	40	80	120	200	300	
RGT Planet	>2.5 mm	96.8	96.2	95.8	95.7	93.6	93.0	95.2
	2.25-2.5 mm	2.0	2.5	2.6	2.6	4.0	4.7	3.1
	<2.25 mm	1.2	1.4	1.6	1.7	2.3	2.3	1.8
Laureate	>2.5 mm	97.2	96.7	95.5	95.5	94.2	92.5	95.2
	2.25-2.5 mm	1.7	2.2	2.6	2.8	4.0	4.7	3.0
	<2.25 mm	1.1	1.2	1.8	1.7	1.8	2.8	1.7
Concerto	>2.5 mm	94.9	95.0	94.4	94.6	92.2	90.5	93.6
	2.25-2.5 mm	2.9	3.2	3.2	3.3	4.9	5.7	3.9
	<2.25 mm	2.2	1.8	2.4	2.1	2.9	3.9	2.5

		P	SED	LSD
N rate	>2.5 mm	<0.001	0.7	1.46
	2.25-2.5 mm	<0.001	0.3	0.83
	<2.25 mm	0.008	0.3	0.74
Variety	>2.5 mm	<0.001	0.2	0.42
	2.25-2.5 mm	<0.001	0.1	0.24
	<2.25 mm	<0.001	0.1	0.24
N rate x Variety	>2.5 mm	0.436	0.8	1.62
	2.25-2.5 mm	0.876	0.4	0.92
	<2.25 mm	0.117	0.4	0.85

Table 1.71 Screenings (%) for the Nottinghamshire 2020 N rate trial

Variety	Screening	N rate (kg/ha)						Grand mean
		0	40	100	180	260	360	
RGT Planet	>2.5 mm	96.6	96.9	97.2	94.2	96.4	96.6	96.3
	2.25-2.5 mm	2.4	2.2	1.9	4.1	2.5	2.5	2.6
	<2.25 mm	1.1	0.9	0.9	1.7	1.1	0.9	1.1
Laureate	>2.5 mm	96.9	96.4	96.7	96.4	97.3	96.9	96.7
	2.25-2.5 mm	2.3	2.3	2.3	2.5	1.9	2.0	2.2
	<2.25 mm	0.8	1.4	1.0	1.1	0.8	1.2	1.0
Concerto	>2.5 mm	81.9	98.3	97.9	96.8	97.3	97.5	94.9
	2.25-2.5 mm	1.3	1.0	1.3	2.3	1.5	1.5	1.5
	<2.25 mm	0.9	0.7	0.8	1.0	1.2	1.0	0.9
		P	SED	LSD				
N rate	>2.5 mm	0.452	3.0	6.63				
	2.25-2.5 mm	0.059	0.3	0.76				
	<2.25 mm	0.075	0.1	0.24				
Variety	>2.5 mm	0.698	2.2	4.58				
	2.25-2.5 mm	<0.001	0.2	0.35				
	<2.25 mm	0.291	0.1	0.23				
N rate x Variety	>2.5 mm	0.494	5.3	10.84				
	2.25-2.5 mm	0.185	0.5	0.99				
	<2.25 mm	0.149	0.2	0.50				

Table 1.72 Screening results (%) for the North Yorkshire 2020 trial

Variety	Screening	N rate (kg/ha)						Grand
		0	40	100	180	260	360	mean
Laureate	>2.5 mm	93.4	95.1	90.3	85.6	83.1	81.0	88.1
	2.25-2.5 mm	3.8	3.0	5.6	8.3	9.7	11.2	7.0
	<2.25 mm	2.7	1.9	4.1	6.1	7.2	7.8	5.0
		P	SED	LSD				
N rate	>2.5 mm	<0.001	1.4	3.07				
	2.25-2.5 mm	<0.001	0.7	1.51				
	<2.25 mm	<0.001	0.8	1.73				

Lodging, Leaning and Brackling

Table 1.73 Leaning (% of plot area) for the Nottinghamshire 2018 trial

	N rate (kg/ha)						
Variety	0	40	80	120	200	300	Grand mean
RGT Planet	0	0	0	0	0	0	0
Laureate	0	3.3	0	0	0	3.3	1.1
Concerto	0	8.3	3.3	3.3	25.0	31.6	11.9
Grand mean	0	3.9	1.1	1.1	8.3	11.7	4.4
	P	SED	LSD				
N rate	0.045	3.6	7.92				
Variety	<0.001	2.2	4.44				
N rate x Variety	0.003	5.6	11.37				

Table 1.74 Leaning, Lodging, Brackling and Necking (% areas of plot) the North Yorkshire 2019 trial

	N rate (kg/ha)						
Component	0	40	100	180	260	360	Grand mean
Leaning (%)	5.0	10.0	10.5	13.3	15.0	1.70	9.20
Lodging (%)	0	0	0	8.3	0	71.7	13.2
Brackling (%)	11.3	14.3	20.4	56.7	38.3	20.0	26.9
Necking (%)	2.3	8.3	20.6	15.0	18.3	10.0	12.4
	P	SED	LSD				
Leaning (%)	0.201	5.3	11.90				
Lodging (%)	<0.001	5.2	11.84				
Brackling (%)	0.005	8.9	20.00				
Necking (%)	0.018	4.3	9.73				

Table 1.75 Brackling (% area of plot) for the Nottinghamshire 2020 N rate trial.

	N rate (kg/ha)						
Variety	0	40	100	180	260	360	Grand mean
RGT Planet	0.3	0.3	3.3	2.0	2.0	4.0	2.0
Laureate	0	0	2.0	2.3	3.3	4.7	2.1
Concerto	0	0	0.3	2.7	2.00	1.7	1.1
Grand mean	0.1	0.1	1.9	2.3	2.4	3.4	1.7
	P	SED	LSD				
N rate	0.044	1.0	2.27				
Variety	0.114	0.5	1.00				
N rate x Variety	0.411	1.4	2.89				

Table 1.76 Leaning (% area of plot) for the Nottinghamshire 2020 N rate trial.

	N rate (kg/ha)						
Variety	0	40	100	180	260	360	Grand mean
RGT Planet	0	0	2.7	10.0	5.0	0	2.9
Laureate	0	0	0.7	10.0	5.7	0	2.7
Concerto	0	0	0	2.7	0	0	0.4
Grand mean	0	0	0.1	7.6	3.6	0	2.0
	P	SED	LSD				
N rate	0.011	1.8	4.07				
Variety	0.019	0.9	1.87				
N rate x Variety	0.213	2.6	5.27				

Table 1.77 Brackling (% area of plot) for the Norfolk 2020 trial

	N rate						
Variety	0	40	80	120	200	300	Grand mean
RGT Planet	0	0	3.3	0.0	35.0	40.0	13.1
Laureate	0	0	0.0	10.0	36.7	60.0	17.8
Concerto	0	0	6.7	16.7	78.3	78.3	30
Grand mean	0	0	3.0	8.9	50.0	59.4	20.3
	P	SED	LSD				
N rate	<0.001	4.8	10.68				
Variety	<0.001	3.8	7.89				
N rate x Variety	0.022	9.0	18.34				

Table 1.78 Lodging and Brackling (% areas of plot) for the North Yorkshire 2020 trial

	N rate (kg/ha)						
Component	0	40	100	180	260	360	Grand mean
Lodging (%)	0	0	16.7	95.0	94.7	95.0	50.2
Brackling (%)	2.0	7.3	80.0	1.7	3.3	1.7	16.0
	P	SED	LSD				
Lodging	<0.001	9.7	21.53				
Brackling (%)	<0.001	10.4	23.24				

Appendix 2. Objective 2. Quantify the effect of timing of soil applied N fertiliser and S fertiliser on grain N%

Effects of Timing on Yield

Table 1.1 Yield (t/ha) for Norfolk 2018 N timing trial.

	N timing				
Variety	Seedbed	RB209	Late	L&O	Grand mean
RGT Planet	6.13	6.40	5.55	6.49	6.14
Laureate	5.96	6.72	5.58	6.90	6.29
Concerto	5.89	5.69	5.68	5.66	5.73
LG Diablo	5.45	5.80	4.61	5.85	5.43
Grand mean	5.86	6.15	5.36	6.22	5.90
	P	SED	LSD		
Timing	0.183	0.37	0.910		
Variety	0.15	0.40	0.822		
Timing x Variety	0.968	0.783	1.600		

L&O = Little and often

Table 1.2 Yield (t/ha) for Nottinghamshire 2018 N timing trial.

	N timing				
Variety	Seedbed	RB209	Late	L&O	Grand mean
RGT Planet	7.33	6.89	5.89	6.82	6.73
Laureate	7.18	6.60	5.37	6.52	6.42
Concerto	6.31	6.40	5.58	6.16	6.11
LG Diablo	6.75	6.39	5.98	6.34	6.36
Grand mean	6.89	6.57	5.70	6.46	6.41
	P	SED	LSD		
Timing	0.003	0.18	0.440		
Variety	<0.001	0.13	0.265		
Timing x Variety	0.153	0.29	0.590		

L&O = Little and often

Table 1.3 Yield (t/ha) for East Lothian 2018 N timing trial.

	N timing				
Variety	Seedbed	RB209	Late	L&O	Grand mean
RGT Planet	8.06	9.01	7.36	8.42	8.21
Laureate	8.04	9.11	7.18	8.60	8.23
Concerto	7.05	8.41	6.66	7.86	7.49
LG Diablo	8.18	9.21	7.42	8.73	8.39
Grand mean	7.83	8.94	7.16	8.40	8.08
	P	SED	LSD		
Timing	0.029	0.44	1.065		
Variety	<.001	0.10	0.208		
Timing x Variety	0.784	0.47	1.081		

L&O = Little and often

Table 1.4 Yield (t/ha) for North Yorkshire 2018 N timing trial.

	N timing				
Variety	Seedbed	RB209	Late	L&O	Grand mean
KWS Irina	6.89	7.32	6.99	6.97	7.07
	P	SED	LSD		
Timing	0.253	0.19	0.446		

L&O = Little and often

Table 1.5 Yield (t/ha) for the Norfolk 2019 N timing trial

	N timing				
Variety	Seedbed	RB209	Late	L&O	Grand mean
RGT Planet	4.59	3.62	3.60	4.48	4.07
Laureate	4.77	4.30	4.07	5.25	4.60
Concerto	4.27	3.70	3.62	4.23	3.96
LG Diablo	4.90	4.74	4.20	5.20	4.76
Grand mean	4.63	4.09	3.87	4.79	4.35
	P	SED	LSD		
Timing	0.021	0.36	0.914		
Variety	0.002	0.21	0.434		
Timing x Variety	0.773	0.43	0.897		

L&O = Little and often

Table 1.6 Yield (t/ha) for Nottinghamshire 2019 N timing trial

	N timing				
Variety	Seedbed	RB209	Late	L&O	Grand mean
RGT Planet	9.30	9.03	9.25	9.37	9.24
Laureate	9.32	9.06	9.33	9.79	9.37
Concerto	8.76	8.37	8.72	8.81	8.66
LG Diablo	9.25	8.90	9.30	9.75	9.30
Grand mean	9.16	8.84	9.15	9.43	9.14
	P	SED	LSD		
Timing	0.153	0.21	0.523		
Variety	<0.001	0.08	0.165		
Timing x Variety	0.398	0.25	0.557		

L&O = Little and often

Table 1.7 Yield (t/ha) for the East Lothian 2019 N timing trial

	N timing				
Variety	Seedbed	RB209	Late	L&O	Grand mean
RGT Planet	8.46	8.57	8.52	8.43	8.50
Laureate	8.61	8.53	8.48	8.61	8.56
Concerto	7.94	8.30	7.76	7.89	7.97
LG Diablo	8.62	8.57	8.45	8.58	8.56
Grand mean	8.41	8.49	8.30	8.38	8.40
	P	SED	LSD		
Timing	0.104	0.06	0.153		
Variety	<0.001	0.10	0.208		
Timing x Variety	0.705	0.18	0.379		

L&O = Little and often

Table 1.8 Yield (t/ha) for North Yorkshire 2019 N timing trial

	N timing				
Variety	Seedbed	RB209	Late	L&O	Grand mean
Laureate	9.06	8.97	8.94	8.86	9.96
	P	SED	LSD		
Timing	0.825	0.21	0.511		

L&O = Little and often

Table 1.9 Yield (t/ha) for the Norfolk 2020 N timing trial.

	Timing				
Variety	Seedbed	RB209	Late	L&O	Grand mean
RGT Planet	4.06	4.01	3.99	3.55	3.90
Laureate	3.90	4.18	4.45	4.37	4.22
Concerto	2.60	2.64	3.29	3.53	3.02
LG Diablo	3.90	3.49	3.87	4.40	3.91
Grand mean	3.62	3.58	3.90	3.96	3.76
	P	SED	LSD		
Timing	0.536	0.31	0.748		
Variety	<0.001	0.25	0.520		
Timing x Variety	0.574	0.53	1.092		

L&O = Little and often

Table 1.10 Yield (t/ha) for the Nottinghamshire 2020 N timing trial.

	Timing				
Variety	Seedbed	RB209	Late	L&O	Grand mean
RGT Planet	6.79	6.06	6.31	6.80	6.49
Laureate	6.57	6.02	6.27	7.00	6.47
Concerto	5.98	5.57	5.93	5.99	5.87
LG Diablo	7.39	6.18	6.56	6.90	6.76
Grand mean	6.68	5.96	6.26	6.67	6.40
	P	SED	LSD		
Timing	0.323	0.41	1.011		
Variety	<0.001	0.12	0.254		
Timing x Variety	0.248	0.47	1.044		

L&O = Little and often

Table 1.11 Yield (t/ha) for the North Yorkshire 2020 N timing trial.

	Timing				
Variety	Seedbed	RB209	Late	L&O	Grand mean
Laureate	7.87	8.07	7.07	7.94	7.74
	P	SED	LSD		
Timing	0.029	0.26	0.627		

L&O = Little and often

Effects of N Timing on Grain N%

Table 1.12 Grain N% for Norfolk 2018 N timing trial

	N timing				
Variety	Seedbed	RB209	Late	L&O	Grand mean
RGT Planet	1.92	1.70	1.83	1.57	1.75
Laureate	2.01	1.72	1.91	1.65	1.82
Concerto	1.67	1.73	1.91	1.71	1.76
LG Diablo	1.73	1.77	1.89	1.59	1.75
Grand mean	1.83	1.73	1.89	1.63	1.77
	P	SED	LSD		
Timing	0.121	0.09	0.230		
Variety	0.534	0.06	0.124		
Timing x Variety	0.312	0.14	0.291		

L&O = Little and often

Table 1.13 Grain N% for Nottinghamshire 2018 N timing trial

	N timing				
Variety	Seedbed	RB209	Late	L&O	Grand mean
RGT Planet	2.29	1.83	1.58	1.84	1.89
Laureate	2.25	1.74	1.74	1.91	1.91
Concerto	2.42	1.91	1.86	2.20	2.10
LG Diablo	2.31	1.75	1.80	1.89	1.94
Grand mean	2.32	1.80	1.75	1.96	1.96
	P	SED	LSD		
Timing	0.002	0.09	0.209		
Variety	<0.001	0.05	0.104		
Timing x Variety	0.409	0.12	0.254		

L&O = Little and often

Table 1.14 Grain N% for East Lothian 2018 N timing trial

Variety	N timing				Grand mean
	Seedbed	RB209	Late	L&O	
RGT Planet	1.62	1.61	1.71	1.70	1.66
Laureate	1.66	1.64	1.66	1.67	1.66
Concerto	1.77	1.79	1.78	1.76	1.77
LG Diablo	1.52	1.65	1.70	1.56	1.61
Grand mean	1.65	1.67	1.71	1.67	1.67
	P	SED	LSD		
Timing	0.012	0.01	0.030		
Variety	<0.001	0.03	0.055		
Timing x Variety	0.187	0.05	0.098		

L&O = Little and often

Table 1.15 Grain N% for North Yorkshire 2018 N timing trial

Variety	N timing				Grand mean
	Seedbed	RB209	Late	L&O	
KWS Irina	1.42	1.75	1.67	1.59	1.61
	P	SED	LSD		
Timing	0.062	0.10	0.236		

L&O = Little and often

Table 1.16 Grain N% for the Norfolk 2019 N timing trial

	N timing				
Variety	Seedbed	RB209	Late	L&O	Grand mean
RGT Planet	1.73	1.82	1.79	1.80	1.78
Laureate	1.80	1.90	1.76	1.84	1.82
Concerto	1.68	1.86	1.86	1.84	1.81
LG Diablo	1.69	1.84	1.84	1.75	1.78
Grand mean	1.73	1.86	1.81	1.81	1.80
	P	SED	LSD		
Timing	0.266	0.09	0.235		
Variety	0.503	0.05	0.103		
Timing x Variety	0.715	0.11	0.221		

L&O = Little and often

Table 1.17 Grain N% for the Nottinghamshire 2019 N timing trial

	N timing				
Variety	Seedbed	RB209	Late	L&O	Grand mean
RGT Planet	1.51	1.56	1.64	1.59	1.58
Laureate	1.50	1.59	1.63	1.57	1.57
Concerto	1.57	1.59	1.60	1.58	1.59
LG Diablo	1.51	1.52	1.58	1.55	1.54
Grand mean	1.53	1.57	1.61	1.57	1.57
	P	SED	LSD		
Timing	0.031	0.02	0.052		
Variety	0.276	0.02	0.049		
Timing x Variety	0.875	0.05	0.095		

L&O = Little and often

Table 1.18 Grain N% for the East Lothian 2019 N timing trial

	N timing				
Variety	Seedbed	RB209	Late	L&O	Grand mean
RGT Planet	1.61	1.68	1.57	1.57	1.61
Laureate	1.59	1.74	1.70	1.61	1.66
Concerto	1.64	1.60	1.68	1.63	1.64
LG Diablo	1.65	1.70	1.59	1.64	1.64
Grand mean	1.62	1.68	1.63	1.61	1.64
	P	SED	LSD		
Timing	0.269	0.03	0.078		
Variety	0.439	0.03	0.068		
Timing x Variety	0.353	0.07	0.134		

L&O = Little and often

Table 1.19 Grain N% for the North Yorkshire 2019 N timing trial

	N timing				
Variety	Seedbed	RB209	Late	L&O	Grand mean
Laureate	1.53	1.54	1.60	1.46	1.53
	P	SED	LSD		
Timing	0.124	0.05	0.114		

L&O = Little and often

Table 1.20 Grain N% for the Norfolk 2020 N timing trial

Variety	Timing				Grand mean
	Seedbed	RB209	Late	L&O	
RGT Planet	1.91	2.02	1.95	1.99	1.97
Laureate	1.59	1.92	1.91	1.93	1.91
Concerto	1.96	2.07	1.93	2.01	1.99
LG Diablo	1.86	1.89	1.95	1.91	1.90
Grand mean	1.90	1.97	1.93	1.96	1.94
	P	SED	LSD		
Timing	0.137	0.03	0.065		
Variety	0.018	0.03	0.064		
Timing x Variety	0.769	0.06	0.122		

L&O = Little and often

Table 1.21 Grain N% for the Nottinghamshire 2020 N timing trial

Variety	Timing				Grand mean
	Seedbed	RB209	Late	L&O	
RGT Planet	1.95	1.75	1.95	1.96	1.90
Laureate	1.97	1.94	1.98	1.91	1.95
Concerto	2.06	2.00	2.06	2.04	2.04
LG Diablo	1.92	1.82	1.97	1.98	1.92
Grand mean	1.98	1.88	1.99	1.97	1.95
	P	SED	LSD		
Timing	0.332	0.06	0.152		
Variety	0.003	0.04	0.071		
Timing x Variety	0.494	0.09	0.181		

L&O = Little and often

Table 1.22 Grain N% for the North Yorkshire 2020 N timing trial

	Timing				
Variety	Seedbed	RB209	Late	L&O	Grand mean
Laureate	1.77	1.72	1.87	1.8	1.83
	P	SED	LSD		
Timing	0.021	0.04	0.085		

L&O = Little and often

Yield components

Table 1.23 Ears/m² for the Norfolk 2018 N timing trial

	N Timing				
Variety	Seedbed	RB209	Late	L&O	Grand mean
RGT Planet	491	645	543	619	575
Laureate	633	644	611	684	643
Concerto	550	614	651	642	592
LG Diablo	494	676	569	583	580
Grand mean	542	645	571	632	597
	P	SED	LSD		
Timing	0.202	48	117.0		
Variety	0.173	33	67.8		
Timing x Variety	0.798	74	153.7		

L&O = Little and often

Table 1.24 Grains/ear for the Norfolk 2018 N timing trial

	N Timing				
Variety	Seedbed	RB209	Late	L&O	Grand mean
RGT Planet	26.2	22.8	22.6	25.7	24.3
Laureate	21.7	21.7	19.6	23.0	21.5
Concerto	24.0	22.3	22.1	21.3	22.4
LG Diablo	24.7	20.0	20.2	18.8	20.9
Grand mean	24.1	21.7	21.1	22.2	22.3
	P	SED	LSD		
Timing	0.008	0.6	1.39		
Variety	<0.001	0.7	1.41		
Timing x Variety	0.043	1.3	2.68		

L&O = Little and often

Table 1.25 Grains/m^2 for the Norfolk 2018 N timing trial

	N Timing				
Variety	Seedbed	RB209	Late	L&O	Grand mean
RGT Planet	12986	14648	12181	15920	13934
Laureate	13706	13960	11914	15537	13779
Concerto	13151	13602	12303	13595	13163
LG Diablo	12130	13306	11524	11018	11995
Grand mean	12993	13879	11980	14018	13217
	P	SED	LSD		
Timing	0.232	968	2369.2		
Variety	0.047	710	1464.7		
Timing x Variety	0.517	1565	3223.9		

L&O = Little and often

Table 1.26 TGW (g) for the Norfolk 2018 N timing trial

	N Timing				
Variety	Seedbed	RB209	Late	L&O	Grand mean
RGT Planet	47.0	45.5	46.3	46.0	46.2
Laureate	43.5	45.4	42.7	44.3	43.9
Concerto	44.0	42.9	45.6	41.7	45.5
LG Diablo	46.3	43.4	43.4	45.7	55.7
Grand mean	45.2	44.3	44.5	44.4	44.6
	P	SED	LSD		
Timing	0.918	1.4	3.52		
Variety	0.067	1.0	2.09		
Timing x Variety	0.471	2.3	4.68		

L&O = Little and often

Table 1.27 Ears/m^2 for the Nottinghamshire 2018 timing trial

	N Timing				
Variety	Seedbed	RB209	Late	L&O	Grand mean
RGT Planet	714	630	544	656	636
Laureate	713	700	584	723	680
Concerto	789	700	662	759	728
LG Diablo	782	654	639	738	703
Grand mean	750	671	607	719	689
	P	SED	LSD		
Timing	0.046	39	96.5		
Variety	0.017	27	56.5		
Timing x Variety	0.935	62	127.3		

L&O = Little and often

Table 1.28 Grains/ear for the Nottinghamshire 2018 timing trial

	N Timing				
Variety	Seedbed	RB209	Late	L&O	Grand mean
RGT Planet	21.1	21.9	21.3	21.2	21.4
Laureate	20.9	19.2	18.9	19.8	19.7
Concerto	19.6	20.5	19.8	19.8	19.9
LG Diablo	19.2	20.0	19.4	18.4	19.3
Grand mean	20.2	20.4	19.8	19.8	20.1
	P	SED	LSD		
Timing	0.832	0.8	1.90		
Variety	0.008	0.6	1.19		
Timing x Variety	0.776	1.3	2.61		

L&O = Little and often

Table 1.29 Grains/m² for the Nottinghamshire 2018 timing trial

	N Timing				
Variety	Seedbed	RB209	Late	L&O	Grand mean
RGT Planet	15008	13788	11510	13902	13552
Laureate	14802	13374	10971	14168	13329
Concerto	15473	14338	13055	14994	14465
LG Diablo	14938	13089	12162	13592	13445
Grand mean	15055	13647	11925	14164	13698
	P	SED	LSD		
Timing	0.004	501	1225.5		
Variety	0.015	357	736.0		
Timing x Variety	0.776	795	1640.6		

L&O = Little and often

Table 1.30 TGW (g) for the Nottinghamshire 2018 timing trial

	N Timing				
Variety	Seedbed	RB209	Late	L&O	Grand mean
RGT Planet	48.9	50.0	51.2	49.1	49.8
Laureate	48.6	49.4	48.9	46.1	48.3
Concerto	40.9	44.7	42.9	41.2	42.4
LG Diablo	45.1	48.9	49.2	46.6	47.5
Grand mean	45.9	48.2	48.1	45.7	47.0
	P	SED	LSD		
Timing	0.063	0.9	2.27		
Variety	<0.001	0.6	1.21		
Timing x Variety	0.253	1.4	2.86		

L&O = Little and often

Table 1.31 TGW (g) for the East Lothian 2018 N timing trial

	N timing				
Variety	Seedbed	RB209	Late	L&O	Grand mean
RGT Planet	60.2	57.0	58.2	58.6	58.5
Laureate	59.5	58.8	57.1	58.1	58.4
Concerto	58.1	59.8	55.7	58.2	58.0
LG Diablo	62.2	59.2	60.0	60.5	60.5
Grand mean	60.0	58.7	57.8	58.9	58.8
	P	SED	LSD		
Timing	0.302	1.0	2.54		
Variety	<0.001	0.7	0.73		
Timing x Variety	<0.001	1.2	2.67		

L&O = Little and often

Table 1.32 Components of yield for the North Yorkshire 2018 N timing trial

	Timing				
Variety	Seedbed	RB209	Late	L&O	Grand mean
Ears/m^2	569	654	707	607	634
Grains/ear	27.0	25.5	22.7	25.8	25.3
Grains/m^2	15386	16551	16031	15595	15891
TGW (g)	44.7	44.2	43.6	44.7	44.3
	P	SED	LSD		
Ears/m^2	0.217	54	125.0		
Grains/ear	0.319	1.9	4.41		
Grains/m^2	0.183	443	1022.0		
TGW(g)	0.197	0.6	1.40		

L&O = Little and often

Table 1.33 Ears/m^2 for the Norfolk 2019 N timing trial

	N timing				
Variety	Seedbed	RB209	Late	L&O	Grand mean
RGT Planet	636	405	479	494	504
Laureate	523	730	586	648	622
Concerto	504	464	378	472	454
LG Diablo	687	660	624	738	677
Grand mean	588	565	517	588	564
	P	SED	LSD		
Timing	0.505	51	123.5		
Variety	0.006	63	130.8		
Timing x Variety	0.668	121	246.9		

L&O = Little and often

Table 1.34 Grains/ear for the Norfolk 2019 N timing trial

	N timing				
Variety	Seedbed	RB209	Late	L&O	Grand mean
RGT Planet	19.9	21.2	16.9	21.7	19.9
Laureate	21.0	15.2	15.7	19.6	17.9
Concerto	23.0	19.3	21.2	21.8	21.3
LG Diablo	18.0	17.4	16.0	16.5	17.0
Grand mean	20.5	18.3	17.4	19.9	19.0
	P	SED	LSD		
Timing	0.372	1.8	4.38		
Variety	0.03	1.5	3.07		
Timing x Variety	0.782	3.1	6.43		

L&O = Little and often

Table 1.35 Grains/m² for the Norfolk 2019 N timing trial

	N timing				
Variety	Seedbed	RB209	Late	L&O	Grand mean
RGT Planet	10935	8570	7950	10471	9482
Laureate	11012	9981	9061	12322	10594
Concerto	11384	8962	7839	9757	9486
LG Diablo	12421	11302	9543	11876	11286
Grand mean	11438	9704	8598	11107	10212
	P	SED	LSD		
Timing	0.012	615	1503.6		
Variety	0.003	500	1031.7		
Timing x Variety	0.761	1062	2178.7		

L&O = Little and often

Table 1.36 TGW (g) for the Norfolk 2019 N timing trial

	N timing				
Variety	Seedbed	RB209	Late	L&O	Grand mean
RGT Planet	42.0	42.4	45.2	43.1	43.2
Laureate	43.3	43.1	45.1	42.6	43.5
Concerto	37.8	41.3	46.1	43.5	42.2
LG Diablo	40.6	42.0	44.0	43.8	42.6
Grand mean	40.9	42.1	45.1	43.2	42.9
	P	SED	LSD		
Timing	0.002	0.8	2.02		
Variety	0.588	1.1	2.18		
Timing x Variety	0.577	2.0	4.10		

L&O = Little and often

Table 1.37 Ears/m² for the Nottinghamshire 2019 N timing trial

	N timing				
Variety	Seedbed	RB209	Late	L&O	Grand mean
RGT Planet	1104	976	1159	1178	1104
Laureate	1188	1278	1297	1552	1329
Concerto	988	958	1032	1101	1020
LG Diablo	1219	1184	1305	1328	1259
Grand mean	1125	1099	1198	1290	1178
	P	SED	LSD		
Timing	0.018	44	107.0		
Variety	<0.001	45	92.5		
Timing x Variety	0.47	89	182.1		

L&O = Little and often

Table 1.38 Grains/ear for the Nottinghamshire 2019 N timing trial

	N timing				
Variety	Seedbed	RB209	Late	L&O	Grand mean
RGT Planet	17.5	19.7	16.9	17.5	17.9
Laureate	16.7	15.0	15.6	14.0	15.3
Concerto	18.5	18.4	17.7	17.9	18.1
LG Diablo	16.2	15.9	15.1	15.9	15.8
Grand mean	17.2	17.2	16.3	16.3	16.8
	P	SED	LSD		
Timing	0.304	0.6	1.46		
Variety	<0.001	0.5	1.06		
Timing x Variety	0.299	1.1	2.19		

L&O = Little and often

Table 1.39 Grains/m² for the Nottinghamshire 2019 N timing trial

	N timing				
Variety	Seedbed	RB209	Late	L&O	Grand mean
RGT Planet	19283	19099	19496	20498	19594
Laureate	19770	19094	20015	21547	20106
Concerto	18272	17586	18318	19484	18415
LG Diablo	19696	18724	19630	20953	20620
Grand mean	19255	18626	19365	20620	19467
	P	SED	LSD		
Timing	0.741	419	1024.4		
Variety	0.441	221	456.7		
Timing x Variety	0.420	568	1196.2		

L&O = Little and often

Table 1.40 TGW (g) for the Nottinghamshire 2019 N timing trial

	N timing				
Variety	Seedbed	RB209	Late	L&O	Grand mean
RGT Planet	48.2	47.3	47.5	45.7	47.2
Laureate	47.1	47.5	46.6	45.4	46.7
Concerto	47.9	47.6	47.7	45.2	47.1
LG Diablo	47.0	47.6	47.4	46.6	47.1
Grand mean	47.6	47.5	47.3	45.7	47.0
	P	SED	LSD		
Timing	0.032	0.5	1.23		
Variety	0.376	0.3	0.68		
Timing x Variety	0.386	0.8	1.58		

L&O = Little and often

Table 1.41 TGW (g) for the East Lothian 2019 N timing trial

Variety	N timing				Grand mean
	Seedbed	RB209	Late	L&O	
RGT Planet	49.1	47.6	49.2	47.8	48.4
Laureate	48.5	47.9	47.5	48.3	48.1
Concerto	46.2	47.8	46.7	46.6	46.8
LG Diablo	48.7	47.7	49.8	49.0	48.7
Grand mean	48.1	47.8	48.3	47.9	48.0
	P	SED	LSD		
Timing	0.673	0.5	1.20		
Variety	0.007	0.5	1.09		
Timing x Variety	0.379	1.0	2.12		

L&O = Little and often

Table 1.42 Components of yield for the North Yorkshire 2019 N timing trial

Variety	Timing				Grand mean
	Seedbed	RB209	Late	L&O	
Ears/m^2	928	927	919	954	932
Grains/ear	21.5	21.3	21.8	21.6	21.5
Grains/m^2	19812	19643	19961	20366	19946
TGW (g)	45.7	45.7	44.8	43.8	45.0
	P	SED	LSD		
Ears/m^2	0.985	98	239.3		
Grains/ear	0.995	1.8	4.39		
Grains/m^2	0.923	1114	2725.6		
TGW(g)	0.712	1.8	4.47		

L&O = Little and often

Table 1.43 Ears/m² for the Norfolk 2020 N timing trial

Variety	N timing				Grand mean
	Seedbed	RB209	Late	L&O	
RGT Planet	500	500	485	433	479
Laureate	489	509	538	525	515
Concerto	330	324	403	434	373
LG Diablo	497	441	478	558	494
Grand mean	454	443	476	487	465
	P	SED	LSD		
Timing	0.665	38	93.9		
Variety	0.001	32	66.9		
Timing x Variety	0.598	68	139.4		

L&O = Little and often

Table 1.44 Grains/ear for the Norfolk 2020 N timing trial

Variety	N timing				Grand mean
	Seedbed	RB209	Late	L&O	
RGT Planet	15.1	15.7	16.6	16.6	16.0
Laureate	14.9	14.6	16.0	14.6	15.0
Concerto	16.0	17.1	14.0	16.1	15.8
LG Diablo	15.6	14.4	13.0	14.1	15.3
Grand mean	15.4	15.5	14.9	15.3	15.3
	P	SED	LSD		
Timing	0.907	0.9	2.21		
Variety	0.172	0.8	1.71		
Timing x Variety	0.571	1.7	3.47		

L&O = Little and often

Table 1.45 Grains/m^2 for the Norfolk 2020 N timing trial

	N timing				
Variety	Seedbed	RB209	Late	L&O	Grand mean
RGT Planet	7515	7912	8024	7419	7717
Laureate	7178	7490	7887	7687	7560
Concerto	5271	5509	5722	6916	5854
LG Diablo	7620	6267	6160	7849	6974
Grand mean	6896	6794	6948	7467	7026
	P	SED	LSD		
Timing	0.56	491	1200.7		
Variety	0.034	645	1333.3		
Timing x Variety	0.89	1219	2495.3		

L&O = Little and often

Table 1.46 TGW(g) for the Norfolk 2020 N timing trial

	N timing				
Variety	Seedbed	RB209	Late	L&O	Grand mean
RGT Planet	45.9	46.7	47.7	47.3	46.9
Laureate	45.6	46.4	45.8	46.4	46.0
Concerto	41.8	42.5	43.4	42.0	42.4
LG Diablo	45.9	46.6	47.3	45.0	46.2
Grand mean	44.8	45.6	46.0	45.2	43.4
	P	SED	LSD		
Timing	0.064	0.4	0.92		
Variety	<0.001	0.5	1.01		
Timing x Variety	0.661	0.9	1.89		

L&O = Little and often

Table 1.47 Ears/m² for the Nottinghamshire 2020 N timing trial

	N timing				
Variety	Seedbed	RB209	Late	L&O	Grand mean
RGT Planet	865	927	931	916	910
Laureate	1018	1041	915	1150	1031
Concerto	819	768	852	830	817
LG Diablo	1185	1002	1002	1115	1076
Grand mean	972	935	925	1003	959
	P	SED	LSD		
Timing	0.773	82	201.5		
Variety	<0.001	41	85.0		
Timing x Variety	0.233	109	230.8		

L&O = Little and often

Table 1.48 Grains/ear for the Nottinghamshire 2020 N timing trial

	N timing				
Variety	Seedbed	RB209	Late	L&O	Grand mean
RGT Planet	15.9	14.4	14.0	15.0	14.8
Laureate	12.8	12.1	13.9	12.5	12.8
Concerto	14.9	15.2	14.4	14.9	14.9
LG Diablo	12.9	12.6	13.7	12.9	13.0
Grand mean	14.1	13.6	14.0	13.8	13.9
	P	SED	LSD		
Timing	0.784	0.6	1.44		
Variety	<0.001	0.4	0.77		
Timing x Variety	0.177	0.9	1.81		

L&O = Little and often

Table 1.49 Grains/m² for the Nottinghamshire 2020 N timing trial

	N timing				
Variety	Seedbed	RB209	Late	L&O	Grand mean
RGT Planet	13712	12839	13035	13689	13319
Laureate	13003	12534	12683	14217	13109
Concerto	12208	11642	12310	12284	12111
LG Diablo	14889	12568	13640	14141	13810
Grand mean	13453	12396	12917	13583	13087
	P	SED	LSD		
Timing	0.55	874	2138.2		
Variety	<0.01	261	539.6		
Timing x Variety	0.175	984	2209.2		

L&O = Little and often

Table 1.50 TGW (g) for the Nottinghamshire 2020 N timing trial

	N timing				
Variety	Seedbed	RB209	Late	L&O	Grand mean
RGT Planet	49.5	47.4	48.4	49.7	48.8
Laureate	50.6	48.1	49.4	49.3	49.3
Concerto	49.0	47.9	48.2	48.8	48.4
LG Diablo	50.0	49.1	48.1	48.8	48.9
Grand mean	59.7	48.1	48.5	49.1	48.9
	P	SED	LSD		
Timing	0.235	0.7	1.72		
Variety	0.299	0.5	0.95		
Timing x Variety	0.675	1.1	2.21		

L&O = Little and often

Table 1.51 Components of yield for the North Yorkshire 2020 N timing trial

	N timing				
Component	Seedbed	RB209	Late	L&O	Grand mean
Ears/m²	989	1178	1308	1123	1149
Grains/ear	18.0	15.9	14.1	17.0	16.2
Grains/m²	17807	18708	18825	18993	18433
TGW(g)	44.3	43.4	38.9	42.0	42.2
	P	SED	LSD		
Ears/m²	0.028	75	183.4		
Grains/ear	0.003	0.6	1.48		
Grains/m²	0.181	493	1206.7		
TGW(g)	0.001	0.7	1.77		

L&O = Little and often

Specific Weight and Screening results

Table 1.52 Specific Weight (kg/hl) for Norfolk 2018 N timing trial

	N timing				
Variety	Seedbed	RB209	Late	L&O	Grand mean
RGT Planet	68.7	70.2	68.7	68.9	69.1
Laureate	68.9	66.2	66.7	67.8	67.4
Concerto	69.5	69.1	66.5	69.4	68.6
LG Diablo	66.2	69.6	65.0	67.7	67.2
Grand mean	68.3	68.8	66.7	68.4	68.1
	P	SED	LSD		
Timing	0.001	2.0	4.95		
Variety	<0.001	2.0	4.12		
Timing x Variety	0.439	4.0	8.19		

L&O = Little and often

Table 1.53 Specific Weight (kg/hl) for the Nottinghamshire 2018 N timing trial

	N timing				
Variety	Seedbed	RB209	Late	L&O	Grand mean
RGT Planet	65.6	66.7	66.9	64.8	66.0
Laureate	65.3	64.6	60.8	62.5	63.3
Concerto	60.5	65.8	62.8	63.9	63.3
LG Diablo	61.9	64.4	63.6	62.2	63.0
Grand mean	63.3	65.4	63.5	63.4	63.9
	P	SED	LSD		
Timing	0.393	1.3	3.15		
Variety	<0.001	0.7	1.47		
Timing x Variety	0.041	1.8	3.74		

L&O = Little and often

Table 1.54 Specific Weight (kg/hl) for East Lothian 2018 N timing trial

	N timing				
Variety	Seedbed	RB209	Late	L&O	Grand mean
RGT Planet	66.9	67.2	66.0	66.8	66.7
Laureate	65.7	65.0	64.3	65.1	65.0
Concerto	65.7	67.3	66.2	66.2	66.3
LG Diablo	63.9	67.0	65.1	65.8	65.5
Grand mean	65.5	66.6	65.4	66.0	65.9
	P	SED	LSD		
Timing	0.182	0.5	1.27		
Variety	0.002	0.4	0.86		
Timing x Variety	0.193	0.9	1.83		

L&O = Little and often

Table 1.55 Specific Weight (kg/hl) for the North Yorkshire 2018 N timing trial

	N timing				
Variety	Seedbed	RB209	Late	L&O	Grand mean
KWS Irina	64.4	64.5	64.2	64.2	64.3
	P	SED	LSD		
Timing	0.958	0.7	1.63		

L&O = Little and often

Table 1.56 Specific Weight (kg/hl) for the Norfolk 2019 N timing trial

	N timing				
Variety	Seedbed	RB209	Late	L&O	Grand mean
RGT Planet	61.1	60.4	63.2	62.2	61.7
Laureate	60.1	61.5	61.5	61.7	61.2
Concerto	60.6	61.4	63.9	58.2	61.0
LG Diablo	61.3	59.3	62.7	60.3	60.9
Grand mean	60.8	60.7	62.8	60.6	61.2
	P	SED	LSD		
Timing	0.007	0.4	1.10		
Variety	0.482	0.6	1.14		
Timing x Variety	0.022	1.1	2.16		

L&O = Little and often

Table 1.57 Specific Weight (kg/hl) for the Nottinghamshire 2019 N timing trial

	N timing				
Variety	Seedbed	RB209	Late	L&O	Grand mean
RGT Planet	63.3	63.2	62.8	62.9	63.0
Laureate	62.5	61.9	62.0	61.9	62.1
Concerto	65.7	65.5	65.0	65.5	65.4
LG Diablo	62.8	62.2	62.3	62.4	62.4
Grand mean	63.6	63.2	63.0	63.2	63.2
	P	SED	LSD		
Timing	0.235	0.2	0.60		
Variety	<0.001	0.2	0.41		
Timing x Variety	0.961	0.4	0.87		

L&O = Little and often

Table 1.58 Specific Weight (kg/hl) for the East Lothian 2019 N timing trial

	N timing				
Variety	Seedbed	RB209	Late	L&O	Grand mean
RGT Planet	63.0	61.5	62.4	62.0	62.2
Laureate	61.8	59.6	60.5	64.0	60.6
Concerto	64.6	63.3	63.6	64.0	63.9
LG Diablo	61.8	63.0	62.5	60.9	62.1
Grand mean	62.8	61.9	62.2	61.9	62.2
	P	SED	LSD		
Timing	0.222	0.5	1.10		
Variety	0.001	0.5	1.04		
Timing x Variety	0.496	1.0	2.00		

L&O = Little and often

Table 1.59 Specific Weight (kg/hl) for the North Yorkshire 2019 N timing trial

	N timing				
Variety	Seedbed	RB209	Late	L&O	Grand mean
Laureate	63.6	63.0	63.0	63.6	62.9
	P	SED	LSD		
Timing	0.071	0.7	1.72		

L&O = Little and often

Table 1.60 Specific Weight for the Norfolk 2020 N timing trial

Variety	Timing				Grand mean
	Seedbed	RB209	Late	L&O	
RGT Planet	53.1	53.3	52.6	53.8	53.2
Laureate	53.2	54.8	53.8	55.4	54.3
Concerto	53.7	54.2	53.7	54.0	53.9
LG Diablo	53.0	55.6	55.1	53.7	54.3
Grand mean	53.2	54.5	53.8	54.2	53.9
	P	SED	LSD		
Timing	0.145	0.5	1.15		
Variety	0.058	0.4	0.92		
Timing x Variety	0.262	0.9	1.84		

L&O = Little and often

Table 1.61 Specific Weight for the Nottinghamshire 2020 N timing trial

Variety	Timing				Grand mean
	Seedbed	RB209	Late	L&O	
RGT Planet	61.4	59.7	62.3	62.2	61.4
Laureate	60.2	58.1	61.1	60.3	59.9
Concerto	62.0	59.4	64.3	62.5	62.0
LG Diablo	60.0	59.4	60.7	61.81	57.9
Grand mean	60.9	59.1	62.1	61.7	61.0
	P	SED	LSD		
Timing	0.214	1.3	3.21		
Variety	<0.001	0.3	0.67		
Timing x Variety	0.043	1.4	3.27		

L&O = Little and often

Table 1.62 Specific Weight for the North Yorkshire 2020 N timing trial

	Timing				
Variety	Seedbed	RB209	Late	L&O	Grand mean
Laureate	60.4	59.8	59.9	58.7	59.69
	P	SED	LSD		
Timing	0.006	0.3	0.70		

L&O = Little and often

Table 1.63 Screening results (%) for the Norfolk 2018 trial

		N timing				
Variety	Screening	Seedbed	RB209	Late	L&O	Grand mean
RGT Planet	>2.5 mm	86.7	89.3	90.6	91.9	89.6
	2.25-2.5 mm	8.5	7.3	6.1	5.6	6.8
	<2.25 mm	4.8	3.4	3.3	2.6	3.5
Laureate	>2.5 mm	82.0	90.3	92.8	92.7	89.5
	2.25-2.5 mm	11.4	6.6	4.8	5.0	6.9
	<2.25 mm	6.6	3.1	2.4	2.3	3.6
Concerto	>2.5 mm	87.3	88.0	91.5	93.0	89.9
	2.25-2.5 mm	8.1	7.9	5.7	5.2	6.7
	<2.25 mm	4.7	4.2	2.8	1.9	3.4
LG Diablo	>2.5 mm	82.2	88.8	93.5	93.3	89.5
	2.25-2.5 mm	10.8	8.0	4.5	4.1	6.9
	<2.25 mm	7.0	3.2	2.0	2.6	3.7

		P	SED	LSD
N timing	>2.5 mm	0.123	3.1	7.55
	2.25-2.5 mm	0.156	2.0	4.80
	<2.25 mm	0.167	1.4	3.47
Variety	>2.5 mm	0.995	2.1	4.28
	2.25-2.5 mm	0.999	1.5	3.04
	<2.25 mm	0.975	0.7	1.51
N rate x Variety	>2.5 mm	0.912	4.7	9.80
	2.25-2.5 mm	0.963	3.2	6.62
	<2.25 mm	0.755	1.9	4.02

L&O = Little and often

Table 1.64 Screening results (%) for the Nottinghamshire 2018 trial

Variety	Screening	N timing: Seedbed	RB209	Late	L&O	Grand mean
RGT Planet	>2.5 mm	92.6	95.1	95.2	92.6	93.9
	2.25-2.5 mm	5.8	3.4	3.1	5.4	4.4
	<2.25 mm	1.5	1.6	1.5	2.0	1.7
Laureate	>2.5 mm	91.7	95.0	94.7	91.5	93.2
	2.25-2.5 mm	4.2	3.1	3.0	6.4	4.2
	<2.25 mm	1.8	1.7	2.2	2.4	2.0
Concerto	>2.5 mm	82.6	94.6	93.4	89.0	89.9
	2.25-2.5 mm	12.3	3.3	4.3	8.1	7.0
	<2.25 mm	4.8	1.7	2.2	3.0	2.9
LG Diablo	>2.5 mm	87.1	94.3	94.0	90.9	91.6
	2.25-2.5 mm	9.5	3.9	3.8	6.1	5.8
	<2.25 mm	3.2	1.7	2.0	2.4	2.3
		P	SED	LSD		
N timing	>2.5 mm	0.012	1.4	3.42		
	2.25-2.5 mm	0.009	1.0	2.41		
	<2.25 mm	0.051	0.3	0.82		
Variety	>2.5 mm	0.005	1.1	2.20		
	2.25-2.5 mm	0.006	0.8	1.66		
	<2.25 mm	<0.001	0.3	0.56		
N rate x Variety	>2.5 mm	0.144	2.3	4.76		
	2.25-2.5 mm	0.071	1.7	3.50		
	<2.25 mm	0.008	0.6	1.18		

L&O = Little and often

Table 1.65 Screening results (%) for the East Lothian 2018 N timing trial. Only <2.5mm is displayed

	N timing				
	Seedbed	RB209	Late	L&O	Grand mean
RGT Planet	1.5	3.0	1.9	2.0	2.1
Laureate	1.6	2.3	2.0	2.4	2.1
Concerto	1.3	1.5	1.5	1.6	1.5
LG Diablo	2.3	2.6	2.7	2.1	1.5
Grand mean	1.7	2.3	1.9	2.0	2.0
	P	SED	LSD		
Timing	0.067	0.2	0.47		
Variety	<0.001	0.2	0.35		
Timing x Variety	0.17	0.3	0.71		

L&O = Little and often

Table 1.66 Screening results (%) for the North Yorkshire 2018 N timing trial

	Timing				
Screening	Seedbed	RB209	Late	L&O	Grand mean
>2.5mm	97.0	95.0	93.3	96.6	95.5
2.25mm-2.5mm	2.1	3.2	5.0	2.3	3.2
<2.25mm	0.9	1.8	1.7	1.1	1.4
	P	SED	LSD		
>2.5mm	0.064	1.3	2.96		
2.25mm-2.5mm	0.007	0.7	1.50		
<2.25mm	0.527	0.7	1.57		

L&O = Little and often

Table 1.67 Screening results (%) for the Norfolk 2019 trial

		N timing				
Variety	Screening	Seedbed	RB209	Late	L&O	Grand mean
RGT Planet	>2.5 mm	94.9	95.2	94.2	94.3	94.7
	2.25-2.5 mm	3.4	3.3	3.1	3.4	3.3
	<2.25 mm	1.7	1.5	2.7	2.3	2.0
Laureate	>2.5 mm	94.2	93.2	91.7	94.0	93.3
	2.25-2.5 mm	3.8	4.8	4.5	3.7	4.2
	<2.25 mm	2.0	2.0	3.8	2.3	2.5
Concerto	>2.5 mm	97.1	95.3	95.0	95.3	95.7
	2.25-2.5 mm	1.8	2.5	2.3	2.4	2.2
	<2.25 mm	1.1	2.2	2.7	2.3	2.1
LG Diablo	>2.5 mm	95.8	91.7	88.1	91.8	91.8
	2.25-2.5 mm	2.7	5.6	5.6	5.0	4.7
	<2.25 mm	1.5	2.7	6.4	3.2	3.5
		P	SED	LSD		
N timing	>2.5 mm	0.599	2.4	6.07		
	2.25-2.5 mm	0.75	1.6	4.24		
	<2.25 mm	0.137	0.7	1.88		
Variety	>2.5 mm	<0.001	0.9	1.78		
	2.25-2.5 mm	<0.001	0.5	1.09		
	<2.25 mm	0.004	0.5	0.98		
N rate x Variety	>2.5 mm	0.111	2.2	4.87		
	2.25-2.5 mm	0.293	1.5	3.30		
	<2.25 mm	0.068	0.9	1.95		

L&O = Little and often

Table 1.68 Screening results (%) for the Nottinghamshire 2019 trial

Variety	Screening	N timing: Seedbed	RB209	Late	L&O	Grand mean
RGT Planet	>2.5 mm	94.2	93.9	93.8	91.7	93.4
	2.25-2.5 mm	3.9	3.5	3.5	5.1	4.0
	<2.25 mm	2.1	2.4	2.4	3.0	2.5
Laureate	>2.5 mm	94.9	92.9	94.9	92.3	93.7
	2.25-2.5 mm	3.0	3.5	3.8	4.9	3.8
	<2.25 mm	1.7	2.2	2.4	3.0	2.3
Concerto	>2.5 mm	96.8	95.3	94.0	92.6	94.7
	2.25-2.5 mm	2.4	2.6	3.3	3.9	3.6
	<2.25 mm	1.4	1.7	2.6	3.5	2.3
LG Diablo	>2.5 mm	94.8	94.2	95.0	92.7	94.1
	2.25-2.5 mm	3.6	2.9	3.6	3.9	3.5
	<2.25 mm	2.3	2.2	2.5	2.9	2.5
		P	SED	LSD		
N timing	>2.5 mm	0.012	0.6	1.36		
	2.25-2.5 mm	0.008	0.3	0.63		
	<2.25 mm	0.011	0.2	0.60		
Variety	>2.5 mm	0.17	0.6	1.15		
	2.25-2.5 mm	0.003	0.2	0.47		
	<2.25 mm	0.717	0.2	0.40		
N rate x Variety	>2.5 mm	0.534	1.1	2.28		
	2.25-2.5 mm	0.285	0.5	0.97		
	<2.25 mm	0.263	0.4	0.86		

L&O = Little and often

Table 1.69 Screening results (%) for the East Lothian 2019 N timing trial. Only <2.5mm is displayed

	N timing				
Variety	Seedbed	RB209	Late	L&O	Grand mean
RGT Planet	3.5	3.1	3.2	3.2	3.3
Laureate	3.7	3.8	3.1	2.9	3.4
Concerto	2.8	2.7	2.5	2.1	2.6
LG Diablo	3.4	3.8	3.5	3.1	3.5
Grand mean	3.4	3.4	3.1	2.8	3.2
	P	SED	LSD		
Timing	0.349	0.3	0.75		
Variety	0.004	0.2	0.50		
Timing x Variety	0.905	0.5	1.07		

L&O = Little and often

Table 1.70 Screening results (%) for the North Yorkshire 2019 N timing trial

	Timing				
Screening	Seedbed	RB209	Late	L&O	Grand mean
>2.5mm	96.3	96.5	96.2	93.8	95.7
2.25mm-2.5mm	2.0	1.9	2.3	3.1	2.3
<2.25mm	1.7	1.6	1.5	3.1	2.0
	P	SED	LSD		
>2.5mm	0.571	2.1	5.17		
2.25mm-2.5mm	0.615	0.9	2.30		
<2.25mm	0.515	1.2	2.90		

L&O = Little and often

Table 1.71 Screening results (%) for the Norfolk 2020 trial

		N timing				
Variety	Screening	Seedbed	RB209	Late	L&O	Grand mean
RGT Planet	>2.5 mm	95.9	95.7	97.1	96.6	96.3
	2.25-2.5 mm	2.9	2.8	1.7	2.1	2.3
	<2.25 mm	1.5	1.5	1.2	1.3	1.4
Laureate	>2.5 mm	94.5	96.0	95.2	94.9	95.2
	2.25-2.5 mm	3.7	2.5	3.0	2.9	2.9
	<2.25 mm	2.2	1.5	1.8	2.3	1.9
Concerto	>2.5 mm	93.3	94.5	94.6	94.7	94.3
	2.25-2.5 mm	4.2	3.5	3.0	3.2	3.4
	<2.25 mm	2.5	2.0	2.5	2.2	2.3
LG Diablo	>2.5 mm	94.0	95.0	95.0	93.1	94.3
	2.25-2.5 mm	3.5	3.1	3.2	4.3	3.5
	<2.25 mm	2.5	2.0	1.9	2.6	2.3
		P	SED	LSD		
N rate	>2.5 mm	0.048	0.3	0.73		
	2.25-2.5 mm	0.035	0.2	0.42		
	<2.25 mm	0.123	0.2	0.40		
Variety	>2.5 mm	<0.001	0.5	0.96		
	2.25-2.5 mm	<0.001	0.3	0.52		
	<2.25 mm	0.003	0.2	0.50		
N rate x Variety	>2.5 mm	0.547	0.9	1.76		
	2.25-2.5 mm	0.145	0.5	0.96		
	<2.25 mm	0.877	0.5	0.92		

L&O = Little and often

Table 1.72 Screening results (%) for the Nottinghamshire 2020 trial

		N timing				
Variety	Screening	Seedbed	RB209	Late	L&O	Grand mean
RGT Planet	>2.5 mm	96.1	96.2	96.1	97.6	96.5
	2.25-2.5 mm	2.8	2.7	2.7	1.6	2.5
	<2.25 mm	1.1	1.1	1.2	0.7	1.0
Laureate	>2.5 mm	97.5	97.7	97.6	97.4	97.5
	2.25-2.5 mm	1.7	1.5	1.6	1.9	1.7
	<2.25 mm	0.9	0.8	0.8	0.7	0.8
Concerto	>2.5 mm	97.7	95.1	97.7	97.7	97.0
	2.25-2.5 mm	1.3	1.6	1.5	1.5	1.5
	<2.25 mm	1.0	3.3	0.8	0.8	1.5
LG Diablo	>2.5 mm	95.6	95.0	95.5	95.9	95.5
	2.25-2.5 mm	2.6	3.1	2.9	2.9	2.9
	<2.25 mm	1.8	1.9	1.7	1.3	1.7
		P	SED	LSD		
N rate	>2.5 mm	0.341	0.6	1.44		
	2.25-2.5 mm	0.783	0.3	0.65		
	<2.25 mm	0.233	0.4	0.98		
Variety	>2.5 mm	0.024	0.6	1.31		
	2.25-2.5 mm	<0.001	0.2	0.49		
	<2.25 mm	0.265	0.5	0.98		
N rate x Variety	>2.5 mm	0.783	1.3	2.55		
	2.25-2.5 mm	0.46	0.5	1.01		
	<2.25 mm	0.646	0.9	1.86		

L&O = Little and often

Table 1.73 Screening results (%) for the North Yorkshire 2020 N timing trial

Screening	N timing				Grand mean
	Seedbed	RB209	Late	L&O	
>2.5 mm	89.9	88.3	84.2	86.9	87.3
2.25-2.5 mm	5.6	6.9	9.0	7.6	7.3
<2.25 mm	4.5	4.8	6.8	5.6	5.4
	P	SED	LSD		
>2.5 mm	0.01	1.1	2.68		
2.25-2.5 mm	0.031	0.8	1.94		
<2.25 mm	0.003	0.4	0.92		

L&O = Little and often

Lodging, Leaning and Brackling

Table 1.74 Leaning (% area of plot) for the Nottinghamshire 2019 N timing trial

	N timing				
Variety	Seedbed	RB209	Late	L&O	Grand mean
RGT Planet	0	0	16.7	0	4.2
Laureate	0	0	0	0	0
Concerto	0	0	0	0	0
LG Diablo	0	0	0	0	0
Grand mean	0	0	4.2	0	1.0
	P	SED	LSD		
Timing	0.455	3.0	7.21		
Variety	0.41	3.0	6.08		
Timing x Variety	0.466	5.9	12.04		

L&O = Little and often

Table 1.75 Lodging (% area of plot) for the Nottinghamshire 2019 N timing trial

	N timing				
Variety	Seedbed	RB209	Late	L&O	Grand mean
RGT Planet	0	0	0	0	0
Laureate	0	0	0	0	0
Concerto	0	0	23.3	0	5.8
LG Diablo	0	0	1.7	0	0.4
Grand mean	0	0	6.2	0	1.6
	P	SED	LSD		
Timing	0.378	4.0	9.75		
Variety	0.441	4.2	8.64		
Timing x Variety	0.517	8.3	16.90		

L&O = Little and often

Table 1.76 Brackling (% area of plot) for the Nottinghamshire 2019 N timing trial

	N timing				
Variety	Seedbed	RB209	Late	L&O	Grand mean
RGT Planet	2.7	9.0	16.7	16.7	11.2
Laureate	0	7.7	35.0	18.3	15.2
Concerto	8.3	20.0	11.7	28.3	17.1
LG Diablo	5.0	5.0	28.3	18.3	14.2
Grand mean	4.0	10.4	22.9	20.4	14.4
	P	SED	LSD		
Timing	<0.001	2.1	5.15		
Variety	0.336	3.2	6.55		
Timing x Variety	0.018	5.9	12.03		

L&O = Little and often

Table 1.77 Lodging and Brackling (% area of plot) for the North Yorkshire 2019 N timing trial

	Timing				
Variety	Seedbed	RB209	Late	L&O	Grand mean
Leaning (%)	13.3	6.7	15.0	0	8.8
Lodging (%)	0.7	0.7	0	2.0	0.83
Brackling (%)	46.7	65.0	81.7	53.3	61.7
Necking (%)	11.7	13.3	15.0	13.3	13.3
	P	SED	LSD		
Leaning (%)	0.319	8.1	19.70		
Lodging (%)	0.373	1.1	2.60		
Brackling (%)	0.088	11.5	28.21		
Necking (%)	0.793	3.3	7.98		

L&O = Little and often

Table 1.78 Brackling (% area of plot) for the Norfolk 2020 N timing trial

	N timing				
Variety	Seedbed	RB209	Late	L&O	Grand mean
RGT Planet	16.7	18.3	13.3	16.7	16.2
Laureate	20.0	6.7	3.3	15.0	11.2
Concerto	60.0	38.3	58.3	46.7	50.8
LG Diablo	53.3	30.0	23.3	31.7	34.6
Grand mean	37.5	23.3	24.6	27.5	28.2
	P	SED	LSD		
Timing	0.377	8.2	20.01		
Variety	<0.001	7.7	15.86		
Timing x Variety	0.871	15.6	31.95		

L&O = Little and often

Table 1.79 Brackling (% area of plot) for the Nottinghamshire 2020 N timing trial

	N timing				
Variety	Seedbed	RB209	Late	L&O	Grand mean
RGT Planet	1.0	0.7	1.7	1.7	1.3
Laureate	1.0	0.3	1.3	0.7	0.8
Concerto	0.3	0	0.7	0.3	0.3
LG Diablo	1.3	1.3	2.3	0.7	1.4
Grand mean	0.9	0.6	1.5	0.8	1.0
	P	SED	LSD		
Timing	0.654	0.7	1.78		
Variety	0.013	0.3	0.67		
Timing x Variety	0.784	0.9	1.97		

L&O = Little and often

Table 1.80 Leaning (% area of plot) for the Nottinghamshire 2020 N timing trial

	N timing				
Variety	Seedbed	RB209	Late	L&O	Grand mean
RGT Planet	0	0	0.7	0.3	0.3
Laureate	0	0	0	0	0
Concerto	0	0	1.3	0	0.3
LG Diablo	0.3	0.3	0.7	0.3	0.4
Grand mean	0.1	0.1	0.7	0.2	0.3
	P	SED	LSD		
Timing	0.285	0.3	0.77		
Variety	0.194	0.2	0.40		
Timing x Variety	0.38	0.5	0.96		

L&O = Little and often

Table 1.81 Brackling (% area of plot) for the Nottinghamshire 2020 N timing trial

	N timing				
Variety	Seedbed	RB209	Late	L&O	Grand mean
RGT Planet	1.0	0.7	1.7	1.7	1.3
Laureate	1.0	0.3	1.3	0.7	0.8
Concerto	0.3	0.0	0.7	0.3	0.3
LG Diablo	1.3	1.3	2.3	0.7	1.4
Grand mean	0.9	0.6	1.5	0.8	1.0
	P	SED	LSD		
Timing	0.654	0.7	1.78		
Variety	0.013	0.3	0.67		
Timing x Variety	0.784	0.9	1.97		

L&O = Little and often

Table 1.82 Lodging (% area of plot) for the North Yorkshire 2020 N timing trial

	N timing				
Variety	Seedbed	RB209	Late	L&O	Grand mean
Brackling (%)	26.7	5.0	1.7	1.7	8.8
Lodging (%)	66.7	90.0	95.0	93.3	86.2
	P	SED	LSD		
Brackling (%)	0.062	8.3	20.19		
Lodging (%)	0.063	9.1	22.27		

L&O = Little and often

Appendix 3. Objective 2: Quantify the effect of S fertiliser on grain N%

Table 1.1 Yield and Grain N% for Norfolk 2018

	SO_3 rate (kg/ha)					
	0	10	20	40	80	Grand mean
Yield (t/ha)	4.03	5.87	7.14	5.93	6.85	5.96
Grain N%	2.00	2.00	1.84	1.72	1.93	1.94
	P	SED	LSD			
Yield	0.0033	0.81	1.864			
Grain N%	0.31	0.14	0.322			

Table 1.2 Yield and Grain N% for Nottinghamshire 2018

	SO_3 rate (kg/ha)					
	0	10	20	40	80	Grand mean
Yield (t/ha)	6.16	6.18	6.16	6.60	6.36	6.29
Grain N%	1.74	1.69	1.73	1.66	1.63	1.69
	P	SED	LSD			
Yield	0.167	0.184	0.425			
Grain N%	0.805	0.103	0.237			

Table 1.3 Yield and Grain N% for East Lothian 2018

	SO_3 rate (kg/ha)					
	0	10	20	40	80	Grand mean
Yield (t/ha)	8.79	8.97	8.58	9.11	8.54	8.80
Grain N%	1.61	1.62	1.67	1.64	1.69	1.64
	P	SED	LSD			
Yield	0.442	0.34	0.789			
Grain N%	0.04	0.02	0.054			

Table 1.4 Yield and Grain N% for Norfolk 2019

	SO_3 rate (kg/ha)					
	0	10	20	40	80	Grand mean
Yield (t/ha)	4.27	4.46	4.91	4.89	5.22	4.75
Grain N%	1.94	1.88	1.82	1.82	1.75	1.85
	P	SED	LSD			
Yield	0.123	0.34	0.808			
Grain N%	0.867	0.07	0.092			

Table 1.5 Yield and Grain N% for East Lothian 2019

	SO_3 rate (kg/ha)					
	0	10	20	40	80	Grand mean
Yield (t/ha)	8.77	8.61	8.77	8.52	8.56	8.65
Grain N%	1.62	1.65	1.69	1.75	1.65	1.67
	P	SED	LSD			
Yield	0.78	0.26	0.633			
Grain N%	0.261	0.03	0.079			

Table 1.6 Yield and Grain N% for North Yorkshire 2019

	SO_3 rate (kg/ha)					
	0	10	20	40	80	Grand mean
Yield (t/ha)	9.0	8.84	9.19	9.29	9.32	9.13
Grain N%	1.44	1.49	1.48	1.43	1.46	1.46
	P	SED	LSD			
Yield	0.612	0.35	0.806			
Grain N%	0.583	0.04	0.093			

Table 1.7 Yield and Grain N% for Norfolk 2020

	SO_3 rate (kg/ha)					
	0	10	20	40	80	Grand mean
Yield (t/ha)	4.83	4.25	3.97	4.05	4.27	4.27
Grain N%	1.89	1.92	1.89	1.91	1.91	1.91
	P	SED	LSD			
Yield	0.729	0.67	1.533			
Grain N%	0.985	0.07	0.150			

Table 1.8 Yield and Grain N% for North Yorkshire 2020

	SO_3 rate (kg/ha)					
	0	10	20	40	80	Grand mean
Yield (t/ha)	7.88	7.92	7.82	8.47	8.27	8.07
Grain N%	1.59	1.56	1.80	1.77	1.76	1.81
	P	SED	LSD			
Yield	0.237	0.30	0.703			
Grain N%	0.005	0.03	0.065			

Table 1.9 Components of yield for Norfolk 2018

	SO_3 rate (kg/ha)					
	0	10	20	40	80	Grand mean
Ears/m^2	392	521	684	644	662	581
Grains/ear	23.2	23.7	22.2	21.7	24.1	23.0
Grains/m^2	8991	12421	15071	13960	15564	13201
TGW(g)	44.0	47.5	47.5	42.4	44.0	45.1
	P	SED	LSD			
Ears/m^2	0.027	78	180.7			
Grains/ear	0.7	1.9	4.49			
Grains/m^2	0.024	1657	3821.0			
TGW(g)	0.064	1.8	4.04			

Table 1.10 Components of yield for Nottinghamshire 2020

	SO_3 rate (kg/ha)		
	0	40	
Ears/m^2	1265	1041	
Grains/ear	13.3	12.1	
Grains/m^2	16722	12534	
TGW(g)	47.3	48.1	
	P	SED	LSD
Ears/m^2	0.009	22	94.4
Grains/ear	0.109	0.4	1.89
Grains/m^2	0.024	657	2827.0
TGW(g)	0.362	0.7	2.83

Appendix 4. Micromalting

Table 1.1 Malting results for Nottinghamshire, N timing and variety trial, harvest 2018

Variety	Treatment	Friab	Homog	TN	TSN	SNR	DP	Wort β-glucan	HWE	PSY
		(%)	(%)	(%, dry)	(%, dry)		°IoB	mg l^{-1}	l° kg^{-1} (dry)	(l t^{-1})
RGT Planet	RB209	90.2	99.8	1.43	0.58	40.6	82	82	309	---
RGT Planet	Late	88.8	99.2	1.40	0.56	40.0	68	237	311	---
RGT Planet	L&O	89.6	99.4	1.52	0.66	43.4	84	102	311	---
Laureate	RB209	86.6	99	1.54	0.65	42.2	71	259	306	---
Laureate	Late	85.8	99.2	1.45	0.59	40.7	60	422	300	---
Laureate	L&O	88.0	98.8	1.57	0.64	40.8	79	165	301	---
Concerto	RB209	92.4	99.6	1.41	0.56	39.7	73	94	310	---
Concerto	Late	97.2	99.9	1.48	0.52	34.9	69	96	309	---
Concerto	L&O	93.0	99.8	1.39	0.51	36.5	71	130	297	---
LG Diablo	RB209	91.4	99.2	1.47	0.54	36.5	62	193	302	---
LG Diablo	Late	93.0	99.6	1.48	0.54	36.4	73	119	296	---
LG Diablo	L&O	90.2	99.8	1.43	0.58	40.6	82	82	309	---
[1]Laureate	Control	88.4	99.6	1.54	0.68	44.2	82	141	308	---

[1] Project control

Friab = Friability, Homog = Homogeneity, TN = Total malt N content, TSN = Total soluble N, SNR = Soluble N ratio, DP = Diastatic power, HWE = Hot water extract, PSY = predicted spirit yield

Table 1.2 Malting results for Nottinghamshire, S rate trial, harvest 2018

Variety	S rate	Friab	Homog	TN	TSN	SNR	DP	Wort β-glucan	HWE	PSY
	(kg/ha)	(%)	(%)	(%, dry)	(%, dry)		°IoB	mg l^{-1}	l° kg^{-1} (dry)	(l t^{-1})
Laureate	0	94	100	1.40	0.57	40.7	74	123	309	---
Laureate	10	95	100	1.45	0.58	40.0	78	120	308	---
Laureate	20	94	100	1.40	0.58	41.4	76	162	307	---
Laureate	40	96	100	1.44	0.59	41.0	82	126	309	---
Laureate	80	96	100	1.41	0.61	43.3	76	126	310	---
[1]Laureate	Control	93	100	1.59	0.66	41.5	97	58	309	---
[2]RGT RGT Planet	Standard	95	100	1.50	0.70	46.7	102	27	313	---

[1] Project control, [2] Maltster standard

Friab = Friability, Homog = Homogeneity, TN = Total malt N content, TSN = Total soluble N, SNR = Soluble N ratio, DP = Diastatic power, HWE = Hot water extract, PSY = predicted spirit yield

Table 1.3 Malting results for North Yorkshire, N timing and nil S trial, harvest 2018

Variety	Treatment	Friab	Homog	TN	TSN	SNR	DP	Wort β-glucan	HWE	PSY
		(%)	(%)	(%, dry)	(%, dry)		°IoB	mg l^{-1}	l° kg^{-1} (dry)	(l t^{-1})
KWS Irina	Seedbed	95.4	99.8	1.51	0.55	36.1	100	134	309	409
KSW Irina	RB209	93.3	99.7	1.56	0.56	36	109	158	308	406
KWS Irina	Late	96.4	99.2	1.47	0.58	39.2	110	144	309	408
KWS Irina	L&O	93.2	99.5	1.61	0.57	35	113	152	307	406
KWS Irina	Nil S	90.0	99.4	1.6	0.59	36.6	87	158	308	404
[1]KWS Irina	Control	95.3	99.8	1.57	0.63	40.2	133	120	311	404

[1] Project control

Friab = Friability, Homog = Homogeneity, TN = Total malt N content, TSN = Total soluble N, SNR = Soluble N ratio, DP = Diastatic power, HWE = Hot water extract, PSY = predicted spirit yield

Table 1.4 Malting results for [1]Norfolk N rate and varieties, [2]Nottinghamshire N rate and varieties, harvest 2019

Variety	N rate (kg/ha)	Friab (%)	Homog (%)	TN (%, dry)	TSN (%, dry)	SNR	DP °IoB	Wort β-glucan mg l^{-1}	HWE l^{o} kg^{-1} (dry)	PSY (l t^{-1})
[1]RGT Planet	40	94.7	98.3	1.24	0.53	42.7	105	207	314	---
[1]RGT Planet	100	91.5	96.9	1.52	0.65	42.8	125	216	312	---
[1]Laureate	40	98.0	98.9	1.21	0.58	47.9	103	135	315	---
[1]Laureate	100	93.6	98.8	1.64	0.73	44.5	152	189	313	---
[1]Concerto	40	92.0	98.8	1.66	0.64	38.6	107	256	312	---
[1]Concerto	100	98.3	99.7	1.26	0.55	43.7	87	199	310	---
[2]RGT Planet	120	78.1	83.9	1.78	0.62	34.8	100	311	306	---
[2]RGT Planet	200	78.8	88.3	1.57	0.65	41.4	113	91	300	---
[2]Laureate	120	79.0	87.8	1.7	0.62	36.5	90	464	305	---
[2]Laureate	200	71.6	82.8	1.41	0.56	39.7	101	350	302	---
[2]Concerto	120	80.2	89.5	1.72	0.58	33.7	82	585	307	---
[2]Concerto	200	73.1	84.5	1.53	0.58	37.9	107	374	305	---
[3]Laureate	Control	96.0	99.5	1.74	0.52	29.9	91	425	310	---

[1] Norfolk, [2] Nottinghamshire, [3] Project control

Friab = Friability, Homog = Homogeneity, TN = Total malt N content, TSN = Total soluble N, SNR = Soluble N ratio, DP = Diastatic power, HWE = Hot water extract, PSY = predicted spirit yield

Table 1.5 Malting results for [1]East Lothian N rate and varieties, [2]North Yorkshire N rate and N timing, harvest 2019

Variety	N rate/ treatment (kg/ha)	Friab (%)	Homog (%)	TN (%, dry)	TSN (%, dry)	SNR	DP °IoB	Wort β-glucan mg l^{-1}	HWE l^{o} kg^{-1} (dry)	PSY (l t^{-1})
[1]RGT Planet	100	93.6	97.4	1.47	0.65	44.5	109	107	310.1	411.4
[1]RGT Planet	180	90.4	98.8	1.60	0.70	43.5	86	183	305.4	405.0
[1]Laureate	40	93.5	96.5	1.18	0.53	45.0	69	177	313.5	417.8
[1]Laureate	100	91.3	97.4	1.47	0.65	44.5	81	146	309.8	411.8
[1]Laureate	180	88.0	96.4	1.67	0.67	40.3	82	163	304.0	402.3
[1]Concerto	40	97.0	98.7	1.28	0.55	42.7	87	123	316.9	417.2
[1]Concerto	100	91.1	96.6	1.43	0.58	40.8	72	167	310.2	413.8
[1]Concerto	180	87.0	97.0	1.70	0.67	39.5	87	190	303.8	402.2
[2]Laureate	80	99.4	99.1	1.25	0.60	48.0	83	54	317.2	421.4
[2]Laureate	120	99.0	99.6	1.44	0.68	47.3	105	52	316.9	419.5
[2]Laureate	200	96.8	99.6	1.60	0.76	47.6	110	110	313.1	413.8
[2]Laureate	Seed bed	97.5	99.7	1.43	0.69	48.2	92	96	316.1	419.4
[2]Laureate	RB209	98.5	99.5	1.52	0.70	46.2	92	47	316.0	420.1
[2]Laureate	Late	99.2	99.3	1.46	0.69	47.5	98	56	318.5	421.7
[2]Laureate	L&O	98.5	99.5	1.35	0.65	48.2	98	70	316.5	420.0
[3]Laureate	Control	99.2	99.5	1.27	0.60	47.2	86	42	316.8	421.4

[1] East Lothian, [2] North Yorkshire, [3] Project control

Friab = Friability, Homog = Homogeneity, TN = Total malt N content, TSN = Total soluble N, SNR = Soluble N ratio, DP = Diastatic power, HWE = Hot water extract, PSY = predicted spirit yield

Table 1.6 Malting results for Norfolk, N timing and variety trial, harvest 2019

Variety	Treatment	Friab (%)	Homog (%)	TN (%, dry)	TSN (%, dry)	SNR	DP °IoB	Wort β-glucan mg l⁻¹	HWE l° kg⁻¹ (dry)	PSY (l t⁻¹)
RGT Planet	Seedbed	92.3	98.5	1.57	0.71	45.3	138	123	311	---
RGT Planet	RB209	93.0	99.2	1.58	0.75	47.2	169	56	309	---
RGT Planet	Late	92.4	99.0	1.66	0.73	44.0	157	122	310	---
Laureate	Seedbed	96.1	98.6	1.58	0.72	45.4	152	79	312	---
Laureate	RB209	94.4	98.8	1.72	0.79	46.2	181	89	307	---
Laureate	Late	93.3	99.2	1.67	0.76	45.6	173	65	307	---
Laureate	L&O	93.7	98.9	1.76	0.79	44.9	170	109	308	---
Concerto	Seedbed	98.0	99.4	1.50	0.65	43.3	139	55	313	---
Concerto	RB209	89.1	98.1	1.84	0.71	38.7	175	68	308	---
Concerto	Late	90.5	97.9	1.79	0.65	36.0	160	91	309	---
Concerto	L&O	92.6	98.2	1.73	0.76	43.8	141	116	311	---
LG Diablo	Seedbed	93.0	99.2	1.55	0.66	42.2	145	135	313	---
LG Diablo	RB209	93.3	99.3	1.71	0.73	43.0	162	98	309	---
LG Diablo	Late	91.7	99.0	1.77	0.68	38.3	176	83	307	---
LG Diablo	L&O	94.0	99.2	1.62	0.69	42.7	153	118	308	---
[1]Laureate	Control	97.8	99.2	1.27	0.56	44.3	118	63	316	---

[1] Project control

Friab = Friability, Homog = Homogeneity, TN = Total malt N content, TSN = Total soluble N, SNR = Soluble N ratio, DP = Diastatic power, HWE = Hot water extract, PSY = predicted spirit yield

Table 1.7 Malting results for Nottinghamshire, N timing and variety trial, harvest 2019

Variety	Treatment	Friab	Homog	TN	TSN	SNR	DP	Wort β-glucan	HWE	PSY (l t^{-1})
		(%)	(%)	(%, dry)	(%, dry)		°IoB	mg l^{-1}	l° kg^{-1} (dry)	
RGT Planet	N Seed bed	80.6	89.2	1.4	0.55	39.3	97	224	310	406.5
RGT Planet	N Early	76.6	85.8	1.47	0.57	38.8	76	267	307	399.3
RGT Planet	N Medium	79.2	89.4	1.54	0.57	37	102	191	308	402.8
Laureate	N Seed bed	70.6	83.4	1.39	0.5	36	76	272	308	386.6
Laureate	N Early	58.8	72.2	1.46	0.49	33.6	61	483	299	370.9
Laureate	N Medium	62.8	95.8	1.51	0.53	35.1	67	485	294	362.2
Laureate	N Late	69.0	81.4	1.43	0.52	36.4	77	268	305	384.9
Concerto	N Seed bed	85.2	93.8	1.39	0.58	41.7	78	201	317	415.0
Concerto	N Early	88.8	95.8	1.45	0.55	37.9	102	145	318	415.0
Concerto	N Medium	94.0	98.2	1.47	0.58	39.5	75	119	316	414.5
Concerto	N Late	88.8	94.6	1.42	0.59	41.6	95	174	316	414.4
LG Diablo	N Seed bed	55.0	65.8	1.39	0.47	33.8	57	545	291	371.0
LG Diablo	N Early	57.0	68.4	1.41	0.49	34.8	61	438	294	375.7
LG Diablo	N Medium	66.8	77	1.55	0.53	34.2	66	329	301	386.5
LG Diablo	N Late	67.0	78.4	1.47	0.52	35.4	64	344	299	381.5
[1]Laureate	Control	88.0	96.8	1.27	0.61	48	85	171	314	411.3

[1] Project control

Friab = Friability, Homog = Homogeneity, TN = Total malt N content, TSN = Total soluble N, SNR = Soluble N ratio, DP = Diastatic power, HWE = Hot water extract, PSY = predicted spirit yield

Table 1.8 Malting results for [1]Norfolk, [2]North Yorkshire and [3]East Lothian S rate trials, harvest 2019

Variety	S rate (kg/ha)	Friab (%)	Homog (%)	TN (%, dry)	TSN (%, dry)	SNR	DP °IoB	Wort β-glucan mg l^{-1}	HWE l° kg^{-1} (dry)	PSY (l t^{-1})
[1]Laureate	0	81	93	1.84	0.80	43.2	88	197	315	401
[1]Laureate	10	83	93	1.87	0.78	41.6	92	162	314	404
[1]Laureate	20	90	97	1.72	0.74	43.3	101	143	317	406
[1]Laureate	40	93	97	1.76	0.73	41.3	111	115	314	403
[1]Laureate	80	91	97	1.66	0.51	30.5	114	135	316	406
[2]Laureate	0	98	99	1.34	0.59	44.4	85	111	319	415
[2]Laureate	10	97	99	1.38	0.60	43.7	85	112	319	417
[2]Laureate	20	96	98	1.31	0.63	48.1	84	127	319	414
[2]Laureate	40	96	99	1.43	0.49	34.2	98	124	318	416
[2]Laureate	80	97	99	1.37	0.49	35.7	87	112	317	414
[3]Laureate	0	62	73	1.62	0.56	34.8	67	662	302	392
[3]Laureate	10	70	80	1.53	0.54	35.6	72	463	303	394
[3]Laureate	20	75	83	1.59	0.57	35.8	76	371	306	398
[3]Laureate	40	70	83	1.69	0.57	33.8	82	471	304	394
[3]Laureate	80	63	73	1.62	0.57	35.4	73	525	300	391
[4]Laureate	Control	95	97	1.31	0.59	44.8	82	112	319	416

[1] Norfolk, [2] Nottinghamshire, [3] East Lothian, [4] Project control

Friab = Friability, Homog = Homogeneity, TN = Total malt N content, TSN = Total soluble N, SNR = Soluble N ratio, DP = Diastatic power, HWE = Hot water extract, PSY = predicted spirit yield

Table 1.9 Malting results for [1]Norfolk and [2]North Yorkshire S rate trials, harvest 2020

Variety	S rate (kg/ha)	Friab (%)	Homog (%)	TN (%, dry)	TSN (%, dry)	SNR	DP °IoB	Wort β-glucan mg l^{-1}	HWE l° kg-1 (dry)	PSY (l t^{-1})
[1]Laureate	0	78.6	90.8	---	---	---	---	---	289.9	354.8
[1]Laureate	10	81.8	91.4	---	---	---	---	---	291.8	---
[1]Laureate	20	82.0	94.4	---	---	---	---	---	302.1	365.9
[1]Laureate	40	82.6	93.6	---	---	---	---	---	304.4	383.2
[1]Laureate	80	80.4	91.8	---	---	---	---	---	296.0	372.3
[3]Laureate	Control	94.8	99.2	---	---	---	---	---	315.4	414.4
[2]Laureate	0	49.8	65.4	---	---	---	---	---	287.7	374.6
[2]Laureate	10	47.0	60.2	---	---	---	---	---	283.9	373.9
[2]Laureate	20	54.6	65.4	---	---	---	---	---	287.3	379.1
[2]Laureate	40	55.6	65.6	---	---	---	---	---	289.6	384.4
[2]Laureate	80	50.8	61.2	---	---	---	---	---	287.3	380.0
[3]Laureate	Control	95.0	98.6	---	---	---	---	---	313.5	417.7

[1] Norfolk, [2] North Yorkshire, [3] Project controls

Friab = Friability, Homog = Homogeneity, TN = Total malt N content, TSN = Total soluble N, SNR = Soluble N ratio, DP = Diastatic power, HWE = Hot water extract, PSY = predicted spirit yield

Table 1.10 Malting results for Nottinghamshire, N timing and variety trial, harvest 2020

Variety	Treatment	Friab (%)	Homog (%)	TN (%, dry)	TSN (%, dry)	SNR	DP °IoB	Wort β-glucan mg l^{-1}	HWE l^{o} kg^{-1} (dry)	PSY (l t^{-1})
RGT Planet	Seedbed	74	90	1.84	0.74	39.9	122	155	308	400
RGT Planet	RB209	52	84	1.95	0.73	37.5	95	139	313	406
RGT Planet	Late	71	85	1.82	0.70	38.4	132	157	306	399
RGT Planet	L&O	77	94	1.78	0.71	39.7	109	331	302	391
Laureate	Seedbed	72	90	1.80	0.71	39.4	106	172	307	400
Laureate	RB209	73	87	1.72	0.71	41.1	96	105	308	396
Laureate	Late	71	90	1.89	0.64	33.8	105	198	306	399
Laureate	L&O	72	84	1.82	0.70	38.4	119	105	308	402
Concerto	Seedbed	58	78	1.94	0.74	38.0	120	196	306	400
Concerto	RB209	---	---	---	---	---	---	---	---	---
Concerto	Late	66	92	1.85	0.66	35.9	107	156	307	400
Concerto	L&O	49	65	1.91	0.68	35.5	124	118	306	389
LG Diablo	Seedbed	75	89	1.74	0.64	36.8	108	166	307	402
LG Diablo	RB209	84	96	1.62	0.60	37.2	106	80	309	407
LG Diablo	Late	73	92	1.80	0.63	35.1	106	128	304	398
LG Diablo	L&O	73	88	1.83	0.66	36.0	120	162	305	400
[1]Laureate	Control	90	98	1.50	0.61	40.4	111	51	316	405

[1] Project control

Friab = Friability, Homog = Homogeneity, TN = Total malt N content, TSN = Total soluble N, SNR = Soluble N ratio, DP = Diastatic power, HWE = Hot water extract, PSY = predicted spirit yield

Table 1.11 Malting results for Norfolk, N rate and variety trial, harvest 2020

Variety	N rate (kg/ha)	Friab (%)	Homog (%)	TN (%, dry)	TSN (%, dry)	SNR	DP °IoB	Wort β-glucan mg l^{-1}	HWE l° kg^{-1} (dry)	PSY (l t^{-1})
RGT Planet	0	84.7	96.8	1.86	0.58	31.3	---	445	293.7	371.7
RGT Planet	40	84.7	96.8	1.86	0.57	30.4	---	402	292.2	372.7
RGT Planet	80	79.7	94.7	2.1	0.59	27.9	---	493	288	362.0
RGT Planet	120	84.6	98.1	2.08	0.73	35.3	---	284	288.5	363.5
Laureate	0	89.7	97.3	1.74	0.61	34.8	---	305	299.2	391.5
Laureate	40	83.6	95.8	1.78	0.6	33.8	---	407	295.4	387.2
Laureate	80	85.5	97	1.93	0.7	36.1	---	280	294.2	388.4
Laureate	120	88.8	99.1	2.13	0.8	37.5	---	156	294.5	378.3
Concerto	0	90.6	98.6	1.77	0.56	31.9	---	369	299.1	389.6
Concerto	40	86.4	97.7	1.88	0.56	29.7	---	492	295.4	377.9
Concerto	80	84.8	97.1	2	0.61	30.5	---	395	292.6	380.9
[1]Laureate	Control	96.9	99.2	1.57	0.56	35.9	---	110	314.5	420.3
[2]Laureate	Control	99.0	99.6	1.31	0.54	41.7	---	50	313.9	418.6

[1] Project control, [2]Maltster's control

Friab = Friability, Homog = Homogeneity, TN = Total malt N content, TSN = Total soluble N, SNR = Soluble N ratio, DP = Diastatic power, HWE = Hot water extract, PSY = predicted spirit yield