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Nitrogen and sulphur fertiliser management to achieve grain protein quality targets of high-yielding modern winter milling wheat

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1. Abstract

This project aimed to provide new evidence to inform nitrogen (N) and sulphur (S) fertiliser management guidelines for modern winter milling wheat varieties, to achieve optimum grain quality and milling specifications. In order to do so, ten N field experiments were conducted during 2019, 2020 and 2021 with either 8 different N treatments or a combination of S & N applications. The work was conducted to help farmers achieve grain quality targets and assess the impact on dough rheology and baking performance.

Specific objectives and key conclusions are shown below:

1) **Review existing data to understand how soil N supply, applied N and yield potential affect grain quality.** It was shown that higher total amounts of N-supply, expressed as SNS plus applied fertiliser, were associated with higher grain protein content.

2) **Quantify the responses to N fertiliser application rate and timing**. There was no real difference between applying extra N at GS 32 and GS 39, unless where the dry spring prevented crop N uptake. N application at GS 73 consistently increased protein to higher levels than earlier applications. Grain protein could be increased from additional N applications: on average, an additional 40 kg N/ha increased grain protein by 0.5 %, an additional 80 kg N/ha increased grain protein by 1.0 %, and an additional 120 kg N/ha increased grain protein by 1.3 %.

3) **Quantify the response to S fertiliser application rate and timing.** There was no significant response to S probably because most of the sites were not deficient. There was no requirement to alter current recommendations for S fertilisation, with applications of 50 kg SO_3/ha, where a risk of S deficiency is identified.

4) **To assess the impact of N and S fertiliser rate and timing on dough rheology and baking performance**. There was no detrimental impact on baking quality when foliar urea was applied compared to applications of ammonium nitrate. Addition of S fertilisers is useful where acrylamide formation can be minimised, to sulphur-deficient wheat grown for flour milling or cereal foods.

5) **Develop the basis of new recommendations for N and S fertiliser applications for winter milling wheat quality**. There is no need to change the current rates of application.

6) **Transfer fertiliser management guidelines to farmers and agronomists.** Accurate assessment of SNS supports applying the right amount of N fertiliser for yield. Quantity of extra N applied above ‘RB209’ recommended rates is more important than the timing of it.

Although, late foliar urea applications tended to show an increase in grain protein between 0.2 to 0.5 % compared to ammonium nitrate. Varieties responded slightly differently to N applications but there was no significant effect on baking quality. Baking quality is not only determined by protein quantity but also by Hagberg Falling Number (HFN), specific weight etc. In fact, there was no difference between grain 12.5% and 13% when the other factors were correct. This highlights that achieving all milling specifications, not just protein, is important to ensure grain meets the requirements for the UK's diverse baking industry and retail sectors.

2. Introduction

2.1. Milling Winter Wheat Production and Fertilisation on UK Farms

UK millers use around five million tonnes of home-grown wheat each year, compared to around 2 million tonnes in the early 1980's (UK Flour Millers, 2022). In a typical year this makes up around 85% of the flour used by UK millers. The small percentage of wheat that is imported from North America and Europe has characteristics and qualities not found in the wheats grown in the UK because of differences in climate and soil. UK breadmaking wheat varieties comprise mainly Group 1 and 2 on the AHDB Recommended Lists (RL). There are four Group 1 winter wheats and four Group 2 winter wheats in the current UK flour Millers Wheat Guide 2022 (Table 2.1). The availability of Group 1 dropped from 1.45 million tonnes in 2018 to 0.86 million tonnes in 2020 (UK Flour Millers) following the unprecedently poor crop and quality in 2020. The 2021 wheat crop saw a return to more normal levels of production and good headline quality.

Table 2.1: Typical specifications for milling wheat. RL varieties listed for the current year (2022 / 23) and for the first year of this project (2018 / 19).

	UKFM Group 1	UKFM Group 2
Minimum specific weight (kg/hl)	76.0	76.0
Maximum moisture content (%)	15	15
Maximum admix (%)	2	2
Minimum Hagberg Falling Number (HFN, s)	250	250
Protein content (% DM)	13.0	12.5
2022 / 23 winter wheat RL varieties	Crusoe KWS Zyatt RGT Illustrious RGT Skyfall	KWS Extase KWS Palladium KWS Siskin Mayflower
2018 / 19 winter wheat RL varieties	Crusoe KWS Trinity KWS Zyatt RGT Illustrious RGT Skyfall	KWS Siskin KWS Lili Cordiale

The non-milling crop continues to dominate the wheat crop area, however, in recent years there has been a slight increase in milling wheat crop (Group 1 and 2) rising from 34% in 2016 to 41% in 2020 (5-year mean: 36%). The production of winter wheat in the UK in 2020/21 was 9.95 million tonnes with 28% of plantings of the full breadmaking specification Group 1 varieties. Nitrogen fertiliser requirements for winter wheat depend on the intended market end use (grain N levels), as well as upon soil type and the residual soil nitrogen fertility from previous cropping, organic matter content and use of organic amendments, such as manures. Milling varieties are often grown as a second wheat and receive extra nitrogen, either as a solid dressing or as late foliar urea spray, which is applied to improve the chances of achieving an adequate grain protein content for a milling premium.

Data from the British Survey of Fertiliser Practice (BSFP) (Anon, 2021) indicated that the average field application rate of nitrogen on milling wheat in 2020 was 194 kg N/ha, a decrease of 7 kg/ha over 2019 (Table 2.2). Averaged over 5 years (2016-20), the field application rate on milling wheat was 202 kg N/ha, compared to 178 kg N/ha for non-milling crops. This difference of 24 kg N/ha is less than the additional 40 kg N/ha recommended for milling varieties in the current Nutrient Management Guide (AHDB, 2022). This difference may arise from any of many possible causes beyond less extra N being applied to boost protein of milling varieties; for example, soil conditions (e.g. soil N supplies from previous cropping) or growers' perceptions of yield levels and hence N demands of modern wheat types may be changing.

Table 2.2: Average field application rates (kg N/ha) of nitrogen on winter wheat, Great Britain 2016-2020. (Source: British Survey of Fertiliser Practice 2020)

Year	Winter wheat milling	Winter wheat non-milling
2016	206	185
2017	204	179
2018	207	180
2019	201	179
2020	194	169
5-year mean	*202*	*178*

The BSFP also produces a breakdown of fertiliser use as a percentage of all product used by crop group. Although it is not possible to break this down to distinguish milling and non-milling winter wheat, it does report that ammonium nitrate (AN) is the most widely used product on winter cereals followed by urea ammonium nitrate (UAN) with 45.8% and 18.4% of all product used, respectively (Table 2.3). The third most widely used product is urea (7.8%) although no breakdown is given between granular and foliar forms.

Table 2.3: Product type by percentage of all product used for winter cereals in descending order, Great Britain 2020. (Source: British Survey of Fertiliser Practice 2020)

Product	% of all product used
Ammonium nitrate (AN)	45.8
Urea Ammonium Nitrate (UAN)	18.4
Urea	7.8
High N (>=19%N)	3.5
Low N (<19%N)	3.3
Calcium Ammonium Nitrate (CAN)	2.8
Other Straight N	1.1

2.2. Aim

The aim of this project was to provide new evidence to inform nitrogen and sulphur fertiliser management guidelines for modern winter milling wheat varieties, to achieve optimum grain quality and milling specifications.

2.3. Specific Objectives

1) Review existing data to understand how soil N supply, applied N and yield potential affect grain quality.
2) Quantify the responses to N fertiliser application rate and timing.
3) Quantify the response to S fertiliser application rate and timing.
4) To assess the impact of N and S fertiliser rate and timing on dough rheology and baking performance.
5) Develop the basis of new recommendations for N and S fertiliser applications for winter milling wheat quality.
6) Transfer fertiliser management guidelines to farmers and agronomists.

3. Materials and methods

3.1. Experimental information

Experiments were conducted over three seasons: 2019, 2020 and 2021 and included N rate and timing experiments and N timing and S rate interaction experiments. In total, eighteen N rate and timing and N & S timing experiments were done. The experiments were carried out close to six sites located near Scotland's rural college (SRUC) in East Lothian, NIAB Caythorpe in Lincolnshire, near OMEX Barworth in Lincolnshire, at NIAB Morley in Norfolk, Agrii Debden in Essex and at NIAB Sutton Scotney in Hampshire (Table 3.1). A summary of the experiments conducted at each site is detailed in Table 3.2.

Table 3.1: Site details for experiments.

Identifier	Harvest Year	Site	Grid reference	Soil type	Previous crop	Sowing date
East Lothian	2019	SRUC, Haddington	NT 489655	Clay Loam	Oilseed rape	28/09/2018
Lincolnshire	2019	Omex, Barworth	TF 171457	Silty clay loam	W Wheat	20/10/2018
Norfolk	2019	NIAB, Morley	TM 058992	Sandy Loam	Oilseed rape	31/10/2018
Essex	2019	Agrii, Debden	TL 559322	Silty Clay Loam	Spring Linseed	22/10/2018
East Lothian	2020	SRUC, Haddington	NT 489652	Clay Loam	Oilseed rape	02/10/2019
Essex	2020	Agrii, Debden	TL 559324	Silty Clay Loam	Spring Barley	31/10/2019
East Lothian	2021	SRUC, Haddington	NT 489661	Clay Loam	Oilseed rape	29/09/2020
Lincolnshire	2021	NIAB, Caythorpe	TF 009542	Sandy Loam	Vining peas	01/10/2020
Essex	2021	Agrii, Debden	TL 556328	Silty Clay Loam	Spring Linseed	11/11/2020
Hampshire	2021	NIAB, Sutton Scotney	SU 472417	Sandy Silt Loam	Oilseed rape	14/10/2020

Table 3.2: Summery of nitrogen and nitrogen with sulphur experiments.

Site / Year	Nitrogen rate and timing	Nitrogen and sulphur timing
East Lothian 2019	✓	✓
Lincolnshire 2019	✓	✓
Norfolk 2019	✓	✓
Essex 2019	✓	✓
East Lothian 2020	✓	✓
Essex 2020	✓	✓
East Lothian 2021	✓	
Lincolnshire 2021	✓	✓
Essex 2021	✓	
Hampshire 2021	✓	✓

For all experiments, all crop management inputs (apart from nitrogen and sulphur fertiliser) were applied according to commercial farm practice, including a comprehensive PGR programme, to ensure that other nutrients were not limiting, and to control weed, pest, disease and lodging incidence.

N rate and timing experiments

Three varieties were used, KWS Zyatt and RGT Skyfall (Group 1) and KWS Siskin (Group 2) in a fully randomised design with three replicates per treatment. Seed rates were between 300 and 360 seeds/m^2 depending upon site conditions. The total amount of N applied to each N rate and timing experiment was estimated from the initial SMN and AAN. The eight N rate and timing treatments consisted of:

- No N (control);
- 'RB209' recommendations, fertilised for yield only;
- 'RB209'+40 kg N/ha applied as ammonium nitrate (AN 34.5%) at GS 32-35;
- 'RB209'+40 kg N/ha applied as AN 34.5% at GS 37-39;
- 'RB209'+40 kg N/ha applied as Foliar Urea (20% w/v) at GS73;
- 'RB209'+80 kg N/ha applied as AN 34.5%at GS 32-35 and at GS 37-39,
- 'RB209'+80 kg N/ha applied as AN 34.5% at GS 37-39 and as Foliar Urea (20% w/v) at GS73
- 'RB209'+120 kg N/ha applied as AN 34.5% at GS 32-35 and at GS 37-39, and as Foliar Urea (20% w/v) at GS73.

The N timing splits are described in Table 3.3 through to Table 3.12 and application dates and growth stages are shown in Table 3.13. All sulphur was applied at GS 30-31 as magnesium sulphate (Kieserite) to supply 50 kg SO_3/ha.

Table 3.3: Application timings for N rate and timing experiment at East Lothian (2019).

Application A Pre GS 30	Application B GS 30-31	Application C GS 32-35	Application D GS 37-39	Application E GS 73	Total (kg N/ha)
0	0	0	0	0	0
60	80	80	0	0	220
60	80	120	0	0	260
60	80	80	40	0	260
60	80	80	0	40	260
60	80	120	40	0	300
60	80	80	40	40	300
60	80	120	40	40	340

Table 3.4: Application timings for N rate and timing experiment at Lincolnshire (2019).

Application A Pre GS 30	Application B GS 30-31	Application C GS 32-35	Application D GS 37-39	Application E GS 73	Total (kg N/ha)
0	0	0	0	0	0
60	85	80	0	0	225
60	85	120	0	0	265
60	85	80	40	0	265
60	85	80	0	40	265
60	85	120	40	0	305
60	85	80	40	40	305
60	85	120	40	40	345

Table 3.5: Application timings for N rate and timing experiment at Norfolk (2019).

Application A Pre GS 30	Application B GS 30-31	Application C GS 32-35	Application D GS 37-39	Application E GS 73	Total (kg N/ha)
0	0	0	0	0	0
60	80	80	0	0	220
60	80	120	0	0	260
60	80	80	40	0	260
60	80	80	0	40	260
60	80	120	40	0	300
60	80	80	40	40	300
60	80	120	40	40	340

Table 3.6: Application timings for N rate and timing experiment at Essex (2019).

Application A Pre GS 30	Application B GS 30-31	Application C GS 32-35	Application D GS 37-39	Application E GS 73	Total (kg N/ha)
0	0	0	0	0	0
60	70	70	0	0	200
60	70	110	0	0	240
60	70	70	40	0	240
60	70	70	0	40	240
60	70	110	40	0	280
60	70	70	40	40	280
60	70	110	40	40	320

Table 3.7: Application timings for N rate and timing experiment at East Lothian (2020).

Application A Pre GS 30	Application B GS 30-31	Application C GS 32-35	Application D GS 37-39	Application E GS 73	Total (kg N/ha)
0	0	0	0	0	0
60	80	110	0	0	250
60	80	150	0	0	290
60	80	110	40	0	290
60	80	110	0	40	290
60	80	150	40	0	330
60	80	110	40	40	330
60	80	150	40	40	370

Table 3.8: Application timings for N rate and timing experiment at Essex (2020).

Application A Pre GS 30	Application B GS 30-31	Application C GS 32-35	Application D GS 37-39	Application E GS 73	Total (kg N/ha)
0	0	0	0	0	0
60	60	60	0	0	180
60	60	100	0	0	220
60	60	60	40	0	220
60	60	60	0	40	220
60	60	100	40	0	260
60	60	60	40	40	260
60	60	100	40	40	300

Table 3.9: Application timings for N rate and timing experiment at East Lothian (2021).

Application A Pre GS 30	Application B GS 30-31	Application C GS 32-35	Application D GS 37-39	Application E GS 73	Total (kg N/ha)
0	0	0	0	0	0
60	80	60	0	0	200
60	80	100	0	0	240
60	80	60	40	0	240
60	80	60	0	40	240
60	80	100	40	0	280
60	80	60	40	40	280
60	80	100	40	40	320

Table 3.10: Application timings for N rate and timing experiment at Lincolnshire (2021).

Application A Pre GS 30	Application B GS 30-31	Application C GS 32-35	Application D GS 37-39	Application E GS 73	Total (kg N/ha)
0	0	0	0	0	0
60	80	80	0	0	220
60	80	120	0	0	260
60	80	80	40	0	260
60	80	80	0	40	260
60	80	120	40	0	300
60	80	80	40	40	300
60	60	120	40	40	340

Table 3.11: Application timings for N rate and timing experiment at Essex (2021).

Application A Pre GS 30	Application B GS 30-31	Application C GS 32-35	Application D GS 37-39	Application E GS 73	Total (kg N/ha)
0	0	0	0	0	0
60	80	90	0	0	230
60	80	130	0	0	270
60	80	90	40	0	270
60	80	90	0	40	270
60	80	130	40	0	310
60	80	90	40	40	310
60	80	130	40	40	350

Table 3.12: Application timings for N rate and timing experiment at Hampshire (2021).

Application A Pre GS 30	Application B GS 30-31	Application C GS 32-35	Application D GS 37-39	Application E GS 73	Total (kg N/ha)
0	0	0	0	0	0
60	80	50	0	0	190
60	80	90	0	0	230
60	80	50	40	0	230
60	80	50	0	40	230
60	80	90	40	0	270
60	80	50	40	40	270
60	80	90	40	40	310

Table 3.13: Application dates and growth stages for the N rate and timing experiments.

Site	Application A		Application B		Application C		Application D		Application E	
East Lothian 2019	18/03/2019	GS 23	16/04/2019	GS 31	07/05/2019	GS 32	21/05/2019	GS 37	12/06/2019	GS 75
Lincolnshire 2019	18/03/2019	GS 23	16/04/2019	GS 31	07/05/2019	GS 32	21/05/2019	GS37	26/06/2019	GS 73
Norfolk 2019	18/03/2019	< GS 30	29/03/2019	GS 30	24/04/2019	GS 32	13/05/2019	GS 37-39	28/06/2019	GS 73
Essex 2019	27/02/2019	GS 21-24	04/04/2019	GS 30	24/04/2019	GS 32	15/05/2019	GS 37-39	02/07/2019	GS 73
East Lothian 2020	23/03/2020	GS 23	14/04/2020	GS 31	06/05/2020	GS 33	27/05/2020	GS 39	18/06/2020	GS 70
Essex 2020	09/03/2020	GS 21-24	20/04/2020	GS 30	13/05/2020	GS 32	20/05/2020	GS 37-39	25/06/2020	GS 73
East Lothian 2021	17/03/2021	GS 23-24	13/04/2021	GS 30	05/05/2021	GS 32	18/05/2021	GS 37	01/07/2021	GS 73
Lincolnshire 2021	05/03/2021	GS 22-26	24/03/2021	GS 30	27/04/2021	GS 32	12/05/2021	GS 37	28/06/2021	GS 73
Essex 2021	08/03/2021	GS 30	16/04/2021	GS 30	10/06/2021	GS 32	24/06/2021	GS 37	09/07/2021	GS 73
Hampshire 2021	05/03/2021	GS 22-24	08/04/2021	GS 31	07/05/2021	GS 32-33	19/05/2021	GS 38-39	30/06/2021	GS 71-74

N and S interaction experiments

A further set of experiments studied the interaction of nitrogen with sulphur fertiliser. For all the S experiments, two varieties KWS Zyatt and RGT Skyfall (Group 1) were used in a fully randomised design with three replicates per treatment. Treatments are described in Table 3.14 with Nitrogen rate estimated from 'RB209' plus an additional 40 kg N/ha applied as AN at GS 37-39 or as Foliar Urea at GS 73. All sulphur was applied as magnesium sulphate (Kieserite). In 2019 and 2020 rates of 0, 25, 50 and 75 kg SO_3/ha were applied. In 2021, rates of 0, 50, 75 and 100 kg SO_3/ha were applied.

Table 3.14: Summary of nitrogen and sulphur rates used in the experiments

N rate	Seasons	SO_3 Rate (kg/ha)			
		Pre GS30	GS30-31	GS32-35	Total applied
'RB209'+40AN	19/20/21	0	0	0	0
'RB209'+40AN	19/20	0	25	0	25
'RB209'+40AN	19/20/21	0	50	0	50
'RB209'+40AN	19/20/21	0	25	25	50
'RB209'+40AN	19/20/21	0	75	0	75
'RB209'+40AN	19/20/21	25	25	25	75
'RB209'+40AN	21	0	100	0	100
'RB209'+40 Foliar N	19/20/21	0	0	0	0
'RB209'+40 Foliar N	19/20	0	25	0	25
'RB209'+40 Foliar N	19/20/21	0	50	0	50
'RB209'+40 Foliar N	19/20/21	0	25	25	50
'RB209'+40 Foliar N	19/20/21	0	75	0	75
'RB209'+40 Foliar N	19/20/21	25	25	25	75
'RB209'+40 Foliar N	21	0	100	0	100

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 shallower 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), which is the N that will be mineralised in the soil between the time of sampling and harvest and taken up by the crop. Samples from the 0-30 cm horizon were also tested for organic matter. In the nitrogen and sulphur interaction experiments in 2021 only, leaf samples were taken from the zero S and 75 SO_3 treatments at GS 37-39 for malate:sulphate analysis by Hill Court Farm Research.

Plant density and fertile tiller counts

Plant density and the average stage of tillering were recorded at late tillering (January-February) for each plot replicate by counting plants within a 0.25 m^2 quadrat. These data were also used to provide an estimate of crop N uptake according to the number of shoots present, as described in the nutrient management guide (AHDB, 2022). At crop maturity, all fertile tillers (i.e. with ears containing spikelets) were counted at three points per plot and their density recorded using a 0.25 m^2 quadrat.

Lodging at Harvest and Yield

Lodging between the start of grain fill and harvest was recorded scoring the percentage area of each plot that is lodged at an angle of 10 to 45 degrees and 45 to 90 degrees past the vertical. The grain yield of each plot was recorded using a small plot combine. Grain / seed moisture content was recorded and yields were adjusted to 85% dry matter for reporting. A 6 kg grain sample was retained from each plot for post harvest grain analyses and for rheology and baking tests, as detailed below.

Grain samples for grain protein, specific weight and Hagberg Falling Number

A 1 kg per plot grain sample (out of the 6 kg retained per plot), was sent to NIAB LabTest (nitrogen rate and timing experiments) or RAGT Seeds (nitrogen and sulphur interaction experiments) for determination of grain protein and specific weight. Grain samples were bulked to provide 200 g samples for each variety x treatment combination and sent to RAGT Seeds for Hagberg Falling Number (HFN) analysis. Grain samples from the zero S and 75 kg SO_3 /ha plots were also analysed for N:S ratio by NRM Laboratories.

Grain samples for asparagine

A bulked grain sample of 50g per treatment (combined for each replicated treatment) was sent to Curtis Analytics Ltd where grain was milled to flour and the amino acids were extracted and analysed. For each analysis, 0.5 g (+/-0.0005) of fine flour was weighed. The samples were then extracted in 10 ml of 0.01 N HCl acid, mixed for 15 minutes, rested for 15 min and centrifuged for 15 min. A 1.5 ml sample was removed and stored at -20 °C prior to further analysis. The samples were diluted 1/10 with 10 μmol norvaline (as an internal standard) and filtered into HPLC vials. The samples were analysed using an Agilent 1100 HPLC system. Asparagine concentration was reported in mmol/kg.

Grain samples for rheology and baking

Based on the moisture, grain protein, specific weight and Hagberg Falling Number (HFN) data from post-harvest analysis, grain samples were selected to be sent to Allied Technical Centre (ATC) for rheology and test baking (Table 3.15 and Table 3.16). For the nitrogen rate and timing experiments, no samples were analysed from East Lothian 19, 20 and only rheology was assessed in 2021. No samples were analysed from Lincolnshire 19 or Essex 21 (Table 3.15). For the nitrogen and sulphur interaction experiments, no samples were analysed from East Lothian 19 and 20, Lincolnshire 19 or

Essex 20 (Table 3.16). These sites were excluded as they would have given misleading rheology and baking results.

Table 3.15: Summary of rheology and baking samples tested from the nitrogen rate and timing experiments.

Site	Analysis, mill & rheology	Test Bake	No of samples Rheology / Baking	Comment
East Lothian 19	X	X	0 / 0	Low HFN in all varieties
Lincolnshire 19	X	X	0 / 0	Low HFN in all varieties
Norfolk 19	✓	✓	21 / 21	
Essex 19	✓	✓	21 / 21	
East Lothian 20	X	X	0 / 0	Low HFN in all varieties
Essex 20	✓	✓	8 / 8	Low protein for KWS Zyatt and KWS Siskin
East Lothian 21	✓	X	21 / 0	Low HFN in all varieties
Lincolnshire 21	✓	✓	21 / 21	
Essex 21	X	X	0 / 0	Low specific weights in all varieties
Hampshire 21	✓	✓ (NOT RGT Skyfall)	21 / 14	Low HFN in RGT Skyfall

Table 3.16: Summary of rheology and baking samples tested from the nitrogen and sulphur interaction experiments

Site	Analysis, mill & rheology	Test Bake	No of samples Rheology / Baking	Comment
East Lothian 19	X	X	0 / 0 (Low HFN)	Low HFN in all varieties
Lincolnshire 19	X	X	0 / 0 (Low HFN)	Low HFN in all varieties
Norfolk 19	✓	✓	24 / 24	
Essex 19	✓	✓	24 / 24	
East Lothian 20	X	X	0 / 0 (Low HFN)	Low HFN in all varieties
Essex 20	X	X	0 / 0 (Low Protein)	Low protein in all varieties
Lincolnshire 21	✓	✓	20 / 20	
Hampshire 21	✓	✓	22 / 22	

At ATC all grain samples were cleaned using a Carter-Dockage Tester prior to analysis and milling. A white flour was milled before assessing flour protein and water absorption using Near-infrared (NIR) spectroscopy techniques. The Extensibility and Resistance of the dough was measured using a Brabender Farinograph and a Brabender Extensograph according to the Manual of methods of the Cereals and Cereal Applications Testing Working Group (CCAT) Methods No 03 and 04.

For test baking, the Chorleywood Breadmaking Process (CBP) was used to produce 800 g CBP single piece oven top bread. These tests measured loaf volume, crumb colour, crumb structure and crumb texture. CBP was developed in the early 1960s and is now used for about 80% of the bread produced in the UK. It reduces the amount of time required for production by using high speed mixing combined with pressure control. Modifications to breadmaking recipes allow the use of lower protein wheats compared to traditional processes at the time.

Statistical Analysis

Analysis of Variance

Each experiment was analysed by REML variance components analysis in Genstat 20th Edition for grain yield, grain protein and specific weight. The one exception to this was for the Lincolnshire N and S interaction trial where a generalised ANOVA model was performed to analyse crop yield because model REML algorithm diverged/parameters were out of bounds. The analyses tested for the interaction between varieties and N and/or S rates, i.e. whether the response to N and/or S was different for each variety.

Apparent recovery of fertiliser N and N utilisation efficiencies

The apparent recovery of fertiliser N and N utilisation efficiencies were calculated as described by Congreves *et al.* (2021) for each N rate compared to Nil N in each N experiment for each variety.

N 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) =

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

N use efficiency (kg/kg) =

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

4. Results

4.1. Objective 1. OPTIMISATION OF N AND S FERTILISER FOR MILLING WINTER WHEAT - EXPERIMENTAL EVIDENCE

Nitrogen nutrition

Analysis of available data from UK experiments between 2005 and 2007 undertaken as part of AHDB Research Review No. 3110149017 (Roques et al., 2016) revealed that:

1) Where nitrogen (N) was applied at the optimum dose for yield (Nopt), grain %N was 2.12 for milling wheats, close to the 2.1% described in the Nutrient Management Guide (AHDB, 2022).
2) The correlation between the deviation in N application from Nopt and grain %N was weak (R^2 = 0.05, based on 92 N response curves).

Roques et al. (2016) concluded that an adjustment in N dose, either up or down, of 25 kg N/ha per 0.5% difference in grain protein (or 30 kg N/ha per 0.1% difference in grain %N) was appropriate to achieve optimum yield. The review identified that achieving protein specification of high yield milling varieties was a knowledge gap and consequently a ‘high priority’ for future work. Roques et al. (2016) found no new data on N application timings. Advice was restated that, in some circumstances, an application of soil-applied additional nitrogen during stem extension may give a small yield increase as well as an increase in grain protein. They also noted that application of a foliar urea spray during the milky ripe growth stage (GS73) results in a larger increase in grain protein but cannot be expected to increase yield.

Previous work by Weightman et al. (2011) developed a system to aid decisions on the use of foliar sprays of urea N during grain filling to boost grain protein of milling wheat crops, and assessed the moisture and N content of ears and whole plants at flowering and milky ripe (GS73) stages. Plant N% at and after anthesis related clearly to grain N%, and hence to grain protein content at harvest; however, relationships were better at the milky ripe stage than at anthesis (Weightman et al., 2011). Results from N response trials indicated that in three low protein seasons (only known after harvest when grain is tested) high-yielding varieties (i.e. Xi19) required >290 kg/ha applied N in 13 out of 14 instances to achieve 13% protein. However, the authors concluded that given the difficulties of achieving 13% protein in high-yielding wheat varieties, while staying within environmental limits for N applications, in many instances, the best approach was not to apply late N (Weightman et al., 2011). This clearly highlights the dilemmas that face growers on the rate and timing of late nitrogen applications to attain breadmaking quality.

Sulphur nutrition

Two studies that included milling wheat response to sulphur (S) fertiliser were identified within Research Review No. 3110149017 (Roques et al., 2016). Zhao et al. (1999a and 1999b) demonstrated the positive effect of S on breadmaking quality. Recent research by Shewry et al., (2009) and Curtis et al. (2014) has demonstrated the positive effect that S can have on breadmaking quality through reducing the acrylamide-forming potential of wheat. Curtis et al. (2014) concluded that the optimum S rate for minimising acrylamide formation in bread making wheat was 50 kg SO_3/ha.

Sagoo et al. (2013) quantified the S supply from farm manures to winter wheat crops on light land sites from 2009 to 2012. The project included application of manufactured S fertiliser as potassium sulphate at five rates (0, 12.5, 25, 50 and 75 kg SO_3/ha) applied in early spring. Only one trial (in central England) gave a significant positive yield response, with an optimum S dose of 25 kg SO_3/ha. Whilst few trials resulted in a significant positive yield response, the project showed that organic materials increase the S concentrations in wheat grain above those in untreated plots. Higher S concentrations in the grain have been shown to increase the relative proportion of low-molecular-weight sub-units in glutenin, which is important for dough elasticity and therefore breadmaking quality (Zhao et al. 1999a).

Overall, Research Review No. 3110149017 (Roques et al., 2016) identified limited new information on response to S application (rate or timing) to justify changing the recommendations in 'RB209' 8th edition, which were to apply 25-50 kg SO_3 /ha to cereals in medium or high deficiency risk situations, or where deficiency is identified in early spring before the start of stem extension.

AHDB Recommended List (RL) quality data 2017-2021

The AHDB RL Recommended Lists for Cereals and Oilseeds are based on the analysis of UK trials conducted across multiple sites and several years. The performance and consistency of Group 1 (RGT Skyfall, KWS Trinity, RGT Illustrious, Crusoe and KWS Zyatt) and Group 2 (KWS Siskin, KWS Lilli, Cordiale and KWS Extase) were examined over a 5-year period (2017-2021). However, not all of these varieties are currently on the 2022 / 23 AHDB RL (Table 4.1). Up to five winter wheat trials each season were managed as a breadmaking crop, i.e. to boost grain protein content, an additional 80 kg/ha of nitrogen was applied at GS 37 when applied as granular nitrogen, or up to growth stage 73 when applied as foliar urea.

Consistency of grain protein in milling wheat

Protein content is largely affected by husbandry and site factors with quite a large variation between years. Figure 4.1 shows the mean protein content in AHDB Recommended List trials 2017-2021 for breadmaking sites. All Group 1 breadmaking varieties show quite a high degree of variability in protein content. RGT Skyfall and Crusoe are the varieties most likely to achieve the UKFM specification in this group whilst KWS Zyatt has the lowest potential. Group 2 varieties also show significant variation around the mean protein content with some varieties having limited data to analyse their consistency in performance.

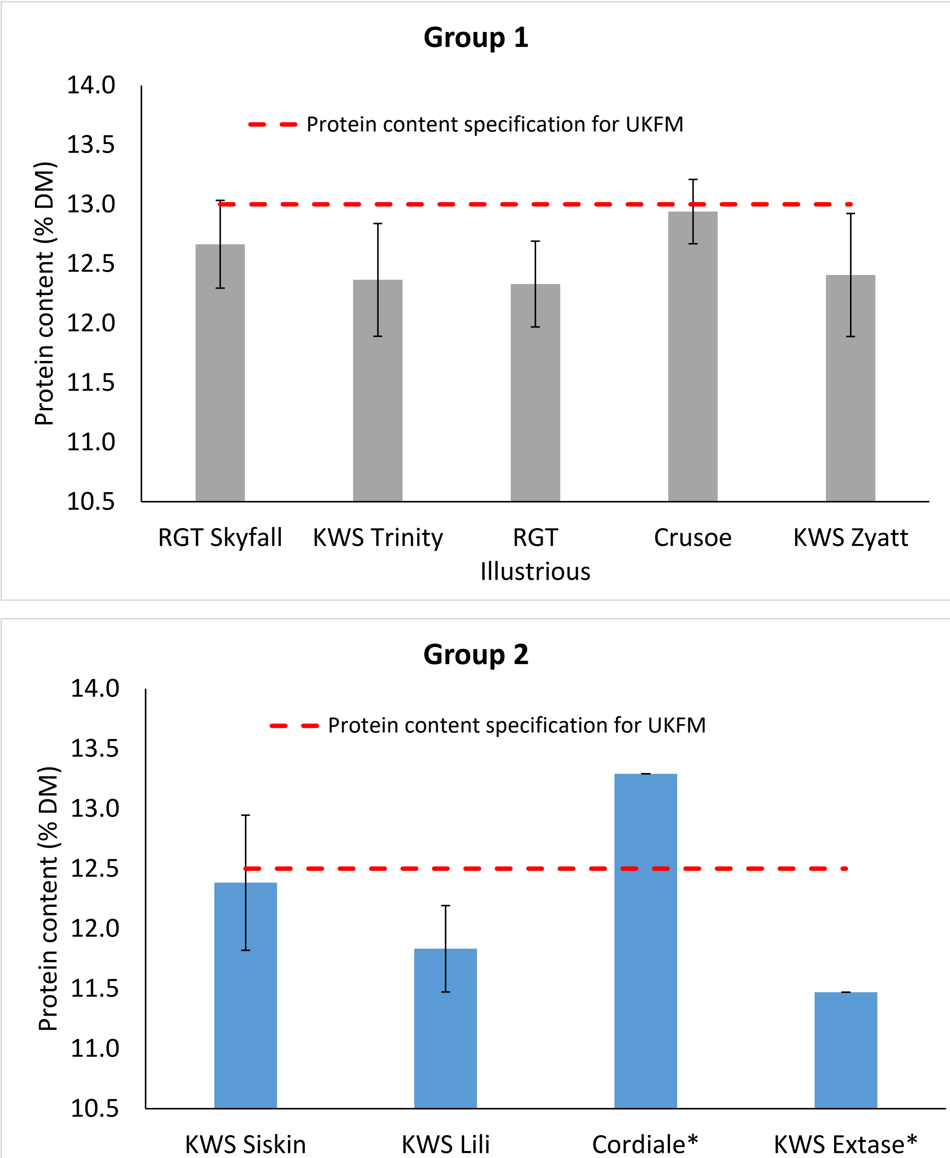

Figure 4.1: Mean protein content in Group 1 and Group 2 varieties in AHDB Recommended List trials 2017-2021 for bread making crops. The error bars have been calculated from the standard deviation around the mean with exception (*) where limited data was available.

Consistency of specific weight in milling wheat

Specific weight, which is a measure of the density of the grain, is a relatively stable characteristic, but individual varieties do vary from site to site and from year to year, therefore a variety with a consistently high specific weight has an advantage. Figure 4.2 shows the mean specific weight in AHDB Recommended List trials 2017-2021 for breadmaking sites. RGT Skyfall has the highest specific weight whilst KWS Trinity has a greater chance of a high specific weight due to its consistency. In this 5-year timeframe the mean values were at least 76 kg/hl for all Group 1 and Group 2 varieties.

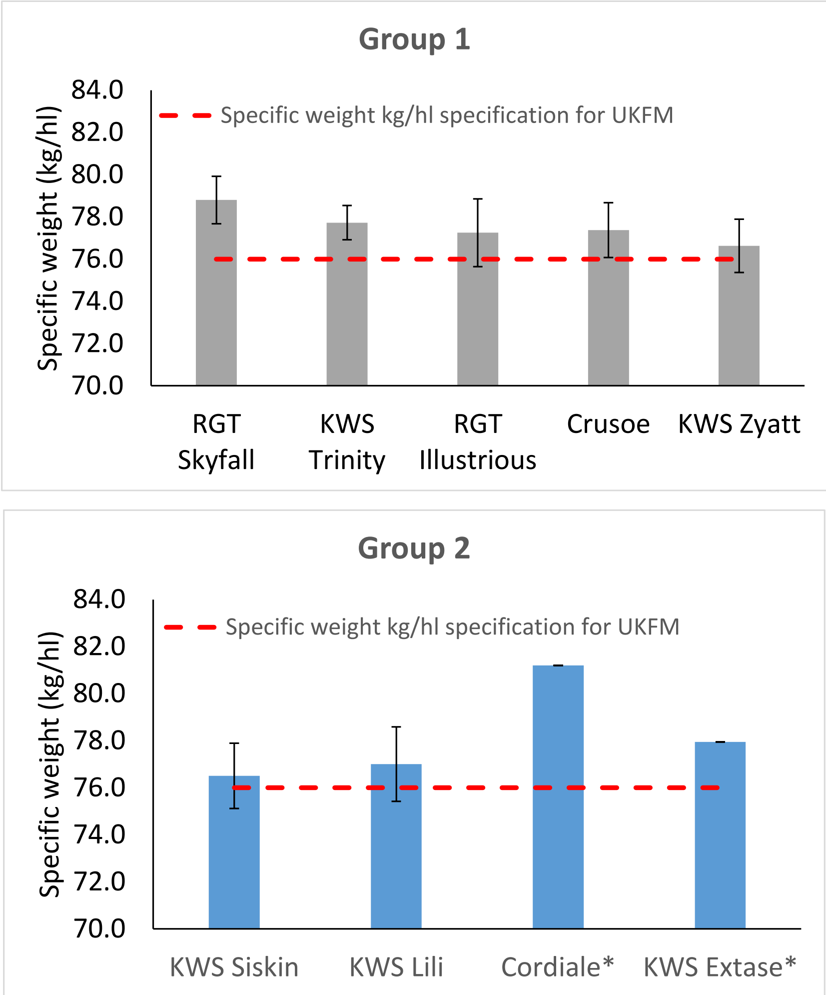

Figure 4.2: Mean specific weight in Group 1 and Group 2 varieties in AHDB Recommended List trials 2017-2021 for bread making crops. The error bars have been calculated from the standard deviation around the mean with exception (*) where limited data was available.

Consistency of Hagberg Falling Number (HFN) in milling wheat

Hagberg Falling Numbers, which indicate the activity of the enzyme α-amylase, for individual varieties varies from site to site and from year to year, but a variety with a higher Hagberg Falling Number is likely to achieve the required standards more easily because it indicates that α-amylase activity is low. Figure 4.3 shows the mean Hagberg Falling Number in AHDB Recommended List trials 2017-2021 for breadmaking sites. All varieties in Group 1 (excluding KWS Trinity) performed similarly. All varieties achieved the 250 level within this time period. Varieties in Group 2 performed consistently and achieved the 250 level.

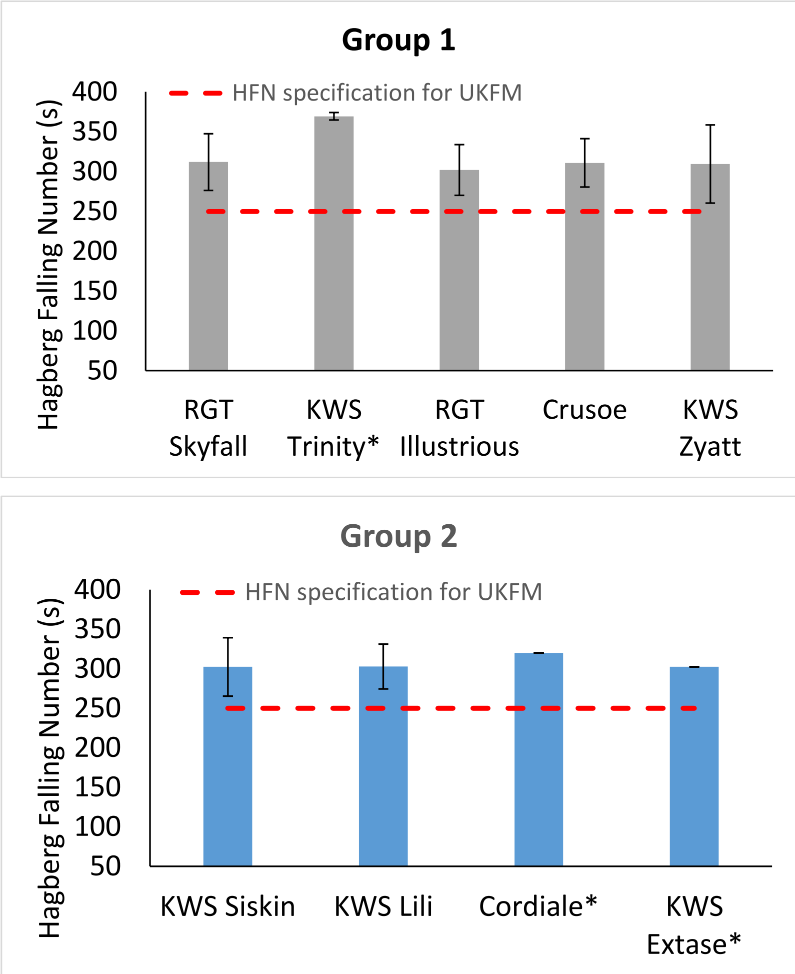

Figure 4.3: Mean Hagberg Falling Numbers in Group 1 and Group 2 varieties in AHDB Recommended List trials 2017-2021 for bread making crops. The error bars have been calculated from the standard deviation around the mean with exception (*) where limited data was available.

AHDB Cereal Quality Survey Data 2017-2021

The Cereal Quality Survey (CQS) is an annual survey looking at the key parameters of wheat quality for the most recent harvests. The grain quality of three Group 1 varieties (RGT Skyfall, KWS Zyatt and Crusoe) and two Group 2 varieties (KWS Extase and KWS Siskin) are shown in Table 4.1 for the years 2017 to 2021. Grain protein has remained relatively stable for Group 1 and 2 varieties across these 5 years with a mean of 13.0 % DM and 12.0 % DM, respectively. The average specific weight has shown more variation across years, with the highest values seen in 2020. In contrast, 2021 values of milling wheat samples in Group 1 and Group 2 show mean values of 75.5 kg/hl and 75.1 kg/hl, respectively. This is below the milling specification of 76.0 kg/hl. HFN in Group 1 dropped to below 300 seconds, not seen since 2017, although these are still above the milling specification of 250 seconds. The variation in quality parameters across seasons highlights the challenges for growers of attaining milling specification consistently.

Table 4.1: Grain quality parameters for 2017-2021. Data taken from AHDB Cereal Quality Survey.

Protein (% DM)					
	Group 1			Group 2	
	Skyfall	KWS Zyatt	Crusoe	KWS Extase	KWS Siskin
2017	13.2	-	13.7	-	12.2
2018	12.9	12.9	13.3	-	11.9
2019	12.8	13.0	13.4	-	11.7
2020	12.7	12.4	13.1	12.1	11.5
2021*[1]	13.0	13.0	13.5	11.9	12.1
5-year mean[2]*	*12.9*	*12.8*	*13.4*	*12.0*	*11.9*
St Dev	*0.19*	*0.26*	*0.21*	*0.14*	*0.29*
Specific weight (kg/hl)					
	Group 1			Group 2	
	Skyfall	KWS Zyatt	Crusoe	KWS Extase	KWS Siskin
2017	76.8	-	75.8	-	75.6
2018	78.9	78.4	78.5	-	76.7
2019	77.8	77.9	77.7	-	75.9
2020	79.6	79.7	79.6	80.3	77.1
2021*[1]	75.8	75.0	75.5	76.1	74.1
5-year mean[2]*	*77.8*	*77.7*	*77.4*	*78.2*	*75.9*
St Dev	*1.53*	*1.95*	*1.77*	*3.04*	*1.15*
Hagberg Falling Number (HFN, s)					
	Group 1			Group 2	
	Skyfall	KWS Zyatt	Crusoe	KWS Extase	KWS Siskin
2017	248	-	245	-	240
2018	342	324	334	-	321
2019	326	307	314	-	296
2020	336	306	323	319	324
2021*[1]	289	271	293	317	311
5-year mean[2]*	308	302	302	318	298
St Dev	39.49	22.49	35.15	1.80	34.37

*[1] *First provisional results 2021*

*[2] *5-year mean where data permits*

4.2. Objective 2. QUANTIFY THE EFFECT OF RATE AND TIMING OF APPLIED N FERTILISER ON GRAIN QUALITY

4.2.1. Environmental conditions

Soil N Supply

The soil N supply for each experimental site is shown in Table 4.2. SNS indices according to the Field Assessment Method (FAM) were consistent at Index 1 or Index 2 across most sites apart from Essex in 2019 and 2021. Winter rainfall at the Essex site in 2021 was high, and the crop N uptake was low, this likely led to N leaching and therefore the SMN results are lower than expected.

Table 4.2: Soil Mineral Nitrogen, Additionally Available Nitrogen, Crop Nitrogen and the Soil Nitrogen Supply index estimated from the AHDB Nutrient Management Guide for each experimental site.

Site	SMN (kg/ha)	AAN (kg/ha)	Crop N (kg/ha)	SNS Index (FAM)
East Lothian 19	47	27	15	2
Lincolnshire 19	18	14	15	2
Norfolk 19	54	26	10	2
Essex 19	86	33	8	3
East Lothian 20	30	26	15	2
Essex 20	33	42	15	2
East Lothian 21	43	25	30	2
Lincolnshire 21	9	27	15	1
Essex 21	16	26	5	3
Hampshire 21	62	60	30	2

Rainfall

The monthly rainfall totals for the period March to May and for August are presented in Table 4.3 along with the MetOffice 1991-2020 climate average. This information provides context for the results that follow in this report. For example, at the East Lothian site, spring rainfall (March-May) was higher than the long-term average in 2019 (125 %) and 2021 (168 %) but lower in 2020 (71 %). In all years, the East Lothian site had higher than average August rainfall (188, 109 and 167% of the long-term average for 2019, 2020 and 2021 respectively). In 2019, the Lincolnshire site also recorded higher than average August rainfall (119% of the long-term average). The driest site for spring rainfall was Essex in 2020 where only 47% of the 1991-2020 average was recorded. Norfolk had the driest August with only 3.5 mm recorded in 2019. All sites in 2021 had low rainfall in April but were followed by above average rainfall in May. Apart from East Lothian, the other sites had lower than average rainfall in August 2021.

Table 4.3: Rainfall data for each site in 2019, 2020 and 2021 compared to the 1991-2020 climate average.

	Rainfall (mm)					1991-2020 climate average rainfall (mm)				
Site	March	April	May	March - May cumulative	August	March	April	May	March - May cumulative	August
East Lothian 19	55.4	31.4	62.4	149.2	115.6	39.1	34.3	45.6	119.0	61.5
Lincolnshire 19	50.0	9.6	44.2	103.9	71.1	36.3	44.6	48.4	129.3	59.5
Norfolk 19	51.0	10.9	30.9	92.8	3.5	48.6	39.9	48.5	137.0	60.1
Essex 19	37.6	10.5	34.9	83.0	26.8	37.4	37.0	44.1	118.5	62.0
East Lothian 20	49.0	1.2	34.2	84.4	71.2	39.1	34.3	45.6	119.0	61.5
Essex 20	23.5	30.7	1.5	55.7	71.8	37.4	37.0	44.1	118.5	62.0
East Lothian 21	58.2	13.5	128.3	200.0	103.0	39.1	34.3	45.6	119.0	61.5
Lincolnshire 21	15.5	4.0	92.7	112.2	23.8	36.3	44.6	48.4	129.3	59.5
Essex 21	27.6	0.6	71.7	99.9	35.9	37.4	37.0	44.1	118.5	62.0
Hampshire 21	28.7	11.5	79.6	119.8	29.7	50.9	50.9	49.2	151.0	57.8

Solar Irradiance

The total solar irradiance incident (direct plus diffuse) on a horizontal plane at the surface of the earth under all sky conditions, measured in MJ/m2/day, was obtained for each field site and season, for the period October to September (Figure 4.4). Data was obtained from the NASA Langley Research Center (LaRC) POWER Project funded through the NASA Earth Science/Applied Science Program. The NASA data has been compared to recorded total net radiation for 2362 daily data (2014-20) records for Morley, Norfolk. Recorded data from the COSMOS station at Morley (COSMOS-UK data owned by UK Centre for Ecology & Hydrology).

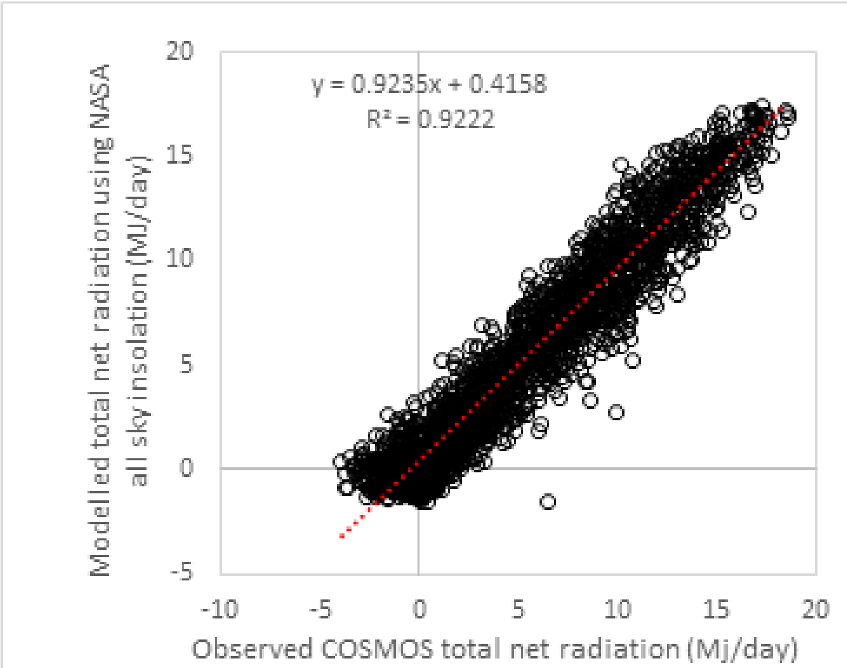

Figure 4.4: Correlation between observed COSMOS total net radiation and modelled total net radiation from NASA for Morley between 2014 and 2020.

The total solar irradiance incident is presented in Figure 4.5 to Figure 4.8 for each of the field experimental sites with the exception of the Lincolnshire sites in 2019 and 2021 where data was unobtainable. In 2019, the solar incidence for the period March to August, was near to or slightly above the long term average at all sites. The mean percentage difference compared to the long term average for the months March to August showed that East Lothian averaged 102% (range 96-109%); Lincolnshire averaged 106% (range 91-117%); Norfolk averaged 103% (range 95-109%) and Essex averaged 105% (range 103-110%).

In 2020, solar irradiance was near to the long-term average for the period March to August but with greater monthly variation than compared to 2019, with East Lothian averaging 105% (range 93-122%) and Essex averaging 114% (range 101-130%).

In 2021, the solar incidence for the period March to August, was near to or slightly below the long term average at all sites but again with greater monthly fluctuations between sites. East Lothian averaged 108% (range 89-129%); Essex averaged 102% (range 94-117%); Lincolnshire averaged 96% (range 79-107%) and Hampshire averaged 101% (range 91-119%). Overall, the East Lothian and Essex sites, in 2020, showed the greatest variation in monthly solar radiation incidence compared to the long-term mean (1984-2021).

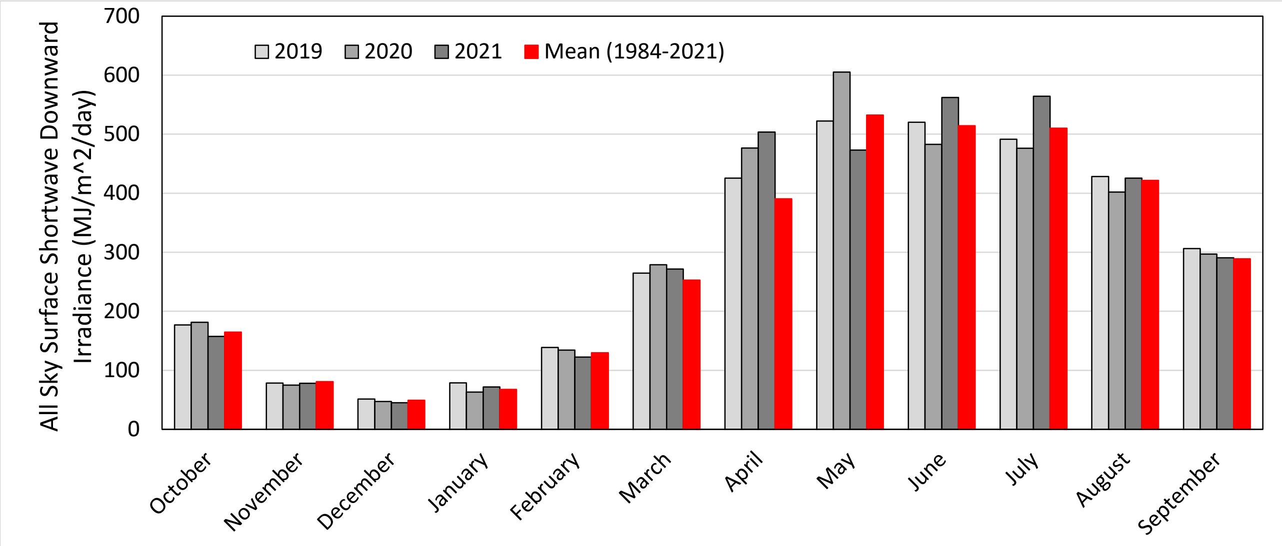

Figure 4.5: Monthly downward irradiance for the East Lothian site for 2019-2021.

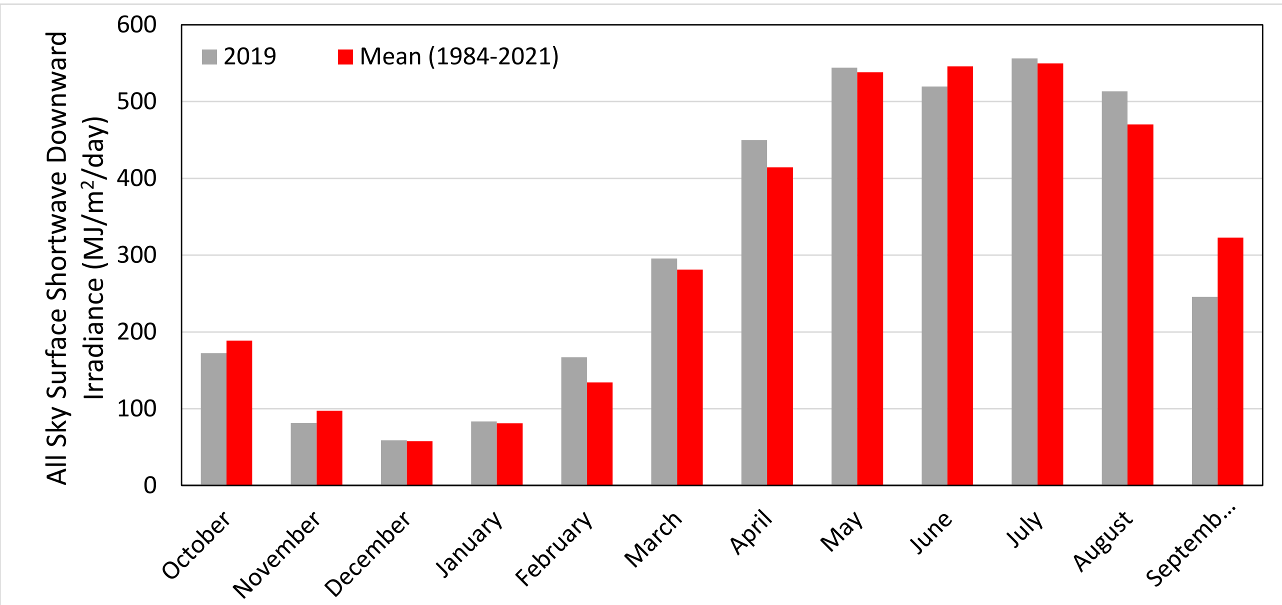

Figure 4.6: Monthly downward irradiance for the Norfolk site for 2019.

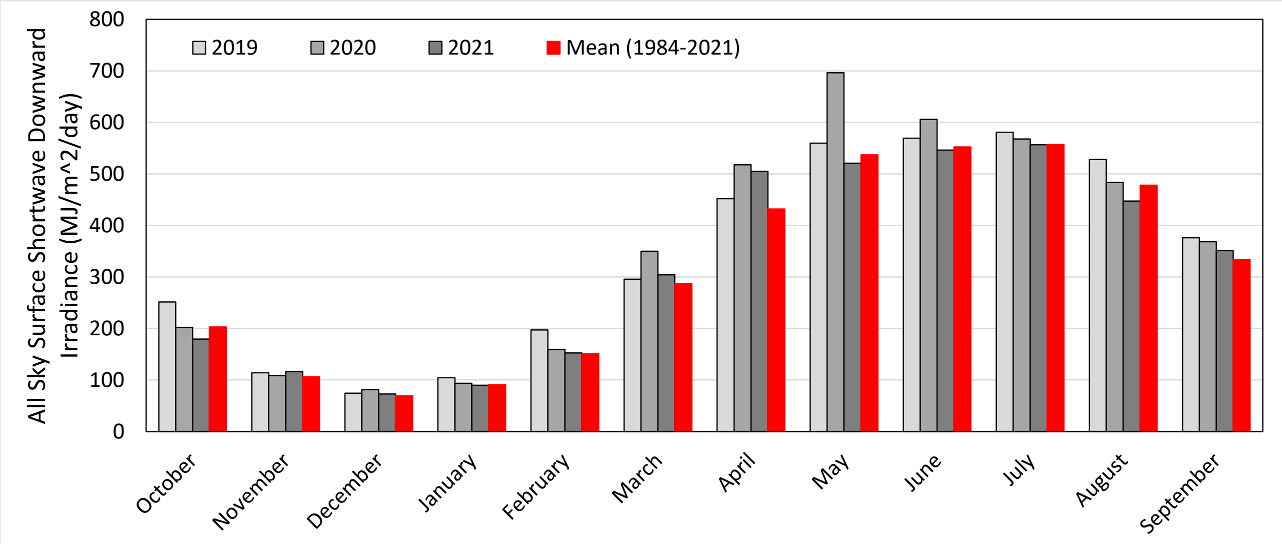

Figure 4.7: Monthly downward irradiance for the Essex site for 2019-2021.

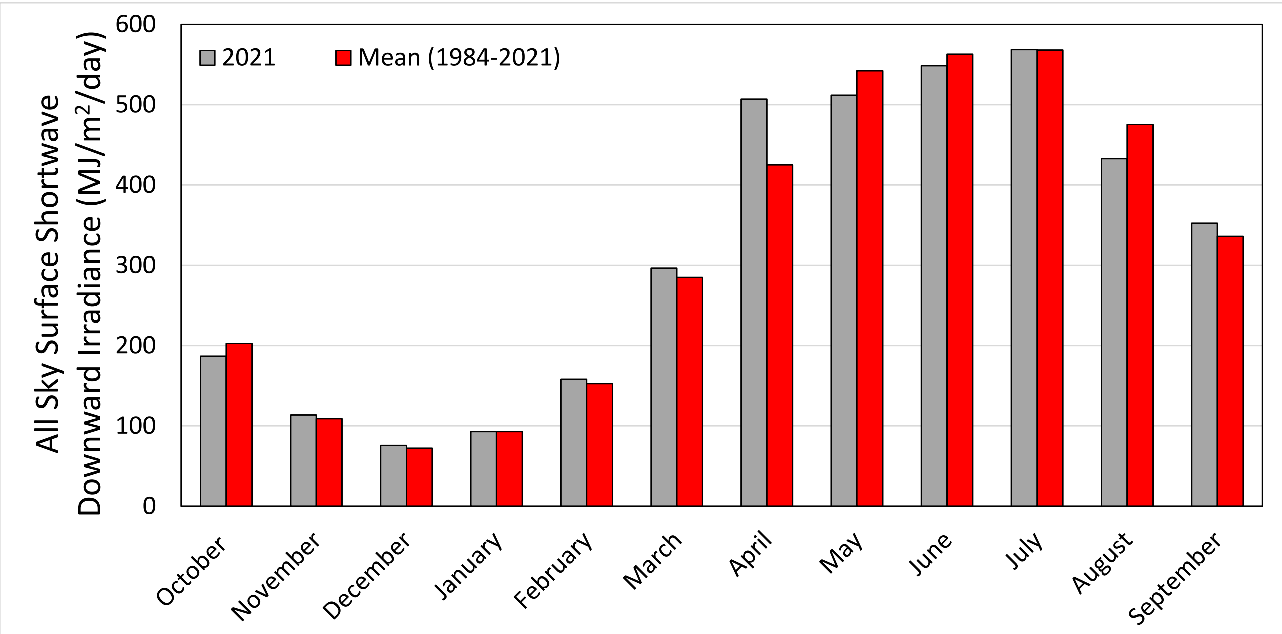

Figure 4.8: Monthly downward irradiance for the Hampshire site for 2021.

4.2.2. Rate and timing of N fertiliser applications

Analyses of data on grain yield and quality for each site and also across sites was used to explore how the rate and timing of N fertiliser applications affect grain quality, including grain yield, grain protein and grain specific weight, so that any potential trade-offs in contrasting N management strategies for winter milling wheat could be evaluated.

Effect of Variety

There were small differences between the three varieties (KWS Zyatt, KWS Siskin and RGT Skyfall), with significant differences found at some sites (Table 4.4). The patterns reflect those seen in the AHDB Cereal Quality survey (Table 4.1). Overall, there was no significant interaction between variety and the N rate and timing treatments.

Table 4.4: Levels of significance for variety differences (averaged across N rate and timing treatments); * indicates a significant interaction between variety and N rate and timing treatments. Where a significant difference was found for a site, then usually one variety was significantly different from the other two, this difference is identified.

Site	Grain yield	Grain protein	Specific weight
East Lothian 19	NS	NS	<0.1% * Lower in KWS Siskin
Lincolnshire 19	<0.1% * Lower in KWS Siskin	<0.1% Higher in RGT Skyfall	<0.1% * Lower in KWS Siskin
Norfolk 19	1% Higher in KWS Zyatt	NS	5% Higher in RGT Skyfall
Essex 19	1% Higher in RGT Skyfall	<0.1% Higher in RGT Skyfall	<0.1% Higher in RGT Skyfall
East Lothian 20	NS	<0.1% Lower in KWS Siskin	<0.1% Higher in RGT Skyfall
Essex 20	5% Higher in RGT Skyfall	<0.1% Higher in RGT Skyfall	<0.1% Lower in KWS Siskin
East Lothian 21	<0.1% Higher in KWS Zyatt	5% Higher in KWS Siskin	<0.1% Lower in KWS Siskin
Lincolnshire 21	1% Lower in RGT Skyfall	<0.1% Higher in RGT Skyfall	<0.1% Higher in RGT Skyfall
Essex 21	<0.1% Lower in KWS Zyatt	<0.1% Higher in RGT Skyfall	NS
Hampshire 21	<0.1% * Lower in RGT Skyfall	1% * Higher in RGT Skyfall	<0.1% Higher in RGT Skyfall

Grain yield and quality – exploring links to nitrogen utilisation

There were significant differences between sites in the winter wheat yield and grain N uptake achieved in the zero N plots (Table 4.5). Grain yield had a highly significant positive correlation with grain N uptake (r^2 = 0.9838) with an average grain N utilisation efficiency of 70.3 kg grain/ kg N uptake. Grain N utilisation efficiency also varied significantly between sites.

All sites showed a highly significant response to all the N addition treatments compared with zero N; with significant increases in yield, grain protein and specific weight at all N rates compared with zero N. However, the yield response to applied N was markedly different between sites (shown by the site N response index, Table 4.5). The site N response index (calculated as the 'RB209' for yield only minus yield at zero divided by yield at zero) is smaller where soil N supply is higher (Table 4.2, r^2 = 0.3354) and this negative relationship is even stronger when grain N uptake at zero N is used as an indication of soil N supply (r^2 = 0.6847).

Table 4.5: Average yield, grain N uptake and grain N utilisation efficiency at zero applied N; and site N response index (= 'RB209' yield - yield at zero / yield at zero).

Site	Average yield at zero N t/ha	Average grain N uptake at zero N kg N /ha	Grain N utilisation efficiency at zero N kg grain/ kg N uptake	Site N response index
East Lothian 19	5.23	66	79.2	1.2
Lincolnshire 19	4.00	45	88.9	2.2
Norfolk 19	6.24	104	60.0	0.8
Essex 19	7.31	89	82.1	0.4
East Lothian 20	3.96	58	68.3	1.7
Essex 20	6.21	81	76.7	0.2
East Lothian 21	6.85	97	70.6	0.8
Lincolnshire 21	3.97	53	74.9	1.5
Essex 21	5.15	91	56.6	0.4
Hampshire 21	6.43	91	70.7	0.7

There was no significant difference in yield (P=1.0) between treatments where the nitrogen rate for yield alone ('RB209') was applied compared with the treatments where additional N applications targeted at increasing grain protein were made (Table 4.6 and Appendix 1). The difference in grain yield ranged from -0.1 to +0.3 t/ha. Table 4.6 summarises the effects of N rate and timing across the three varieties on yield. Both grain N uptake efficiency and grain N utilisation efficiency decreased as N rate increased. However, differences in N use efficiency measures were greater between sites than between N rate and timing treatments (Figure 4.9).

Table 4.6: Ten site mean grain yield and response to N rate and timing compared with 'RB209' as standard.

	Yield (t/ha)			**Difference in grain yield from 'RB209' treatment (t/ha)**		
N rate	KWS Zyatt	KWS Siskin	RGT Skyfall	KWS Zyatt	KWS Siskin	RGT Skyfall
'RB209'	10.39	10.13	10.25	-	-	-
+40 AN at GS 32-35	10.51	10.25	10.33	0.12	0.12	0.08
+40 AN at GS 37-39	10.49	10.34	10.31	0.10	0.21	0.06
+40 F at GS 73	10.30	10.07	10.13	-0.09	-0.06	-0.12
+80 AN at GS 37-39	10.63	10.46	10.49	0.24	0.33	0.24
+80 F at GS 73	10.42	10.18	10.27	0.03	0.05	0.02
+120 F at GS 73	10.50	10.33	10.34	0.11	0.20	0.09
LSD (P=<0.05)		1.54			-	

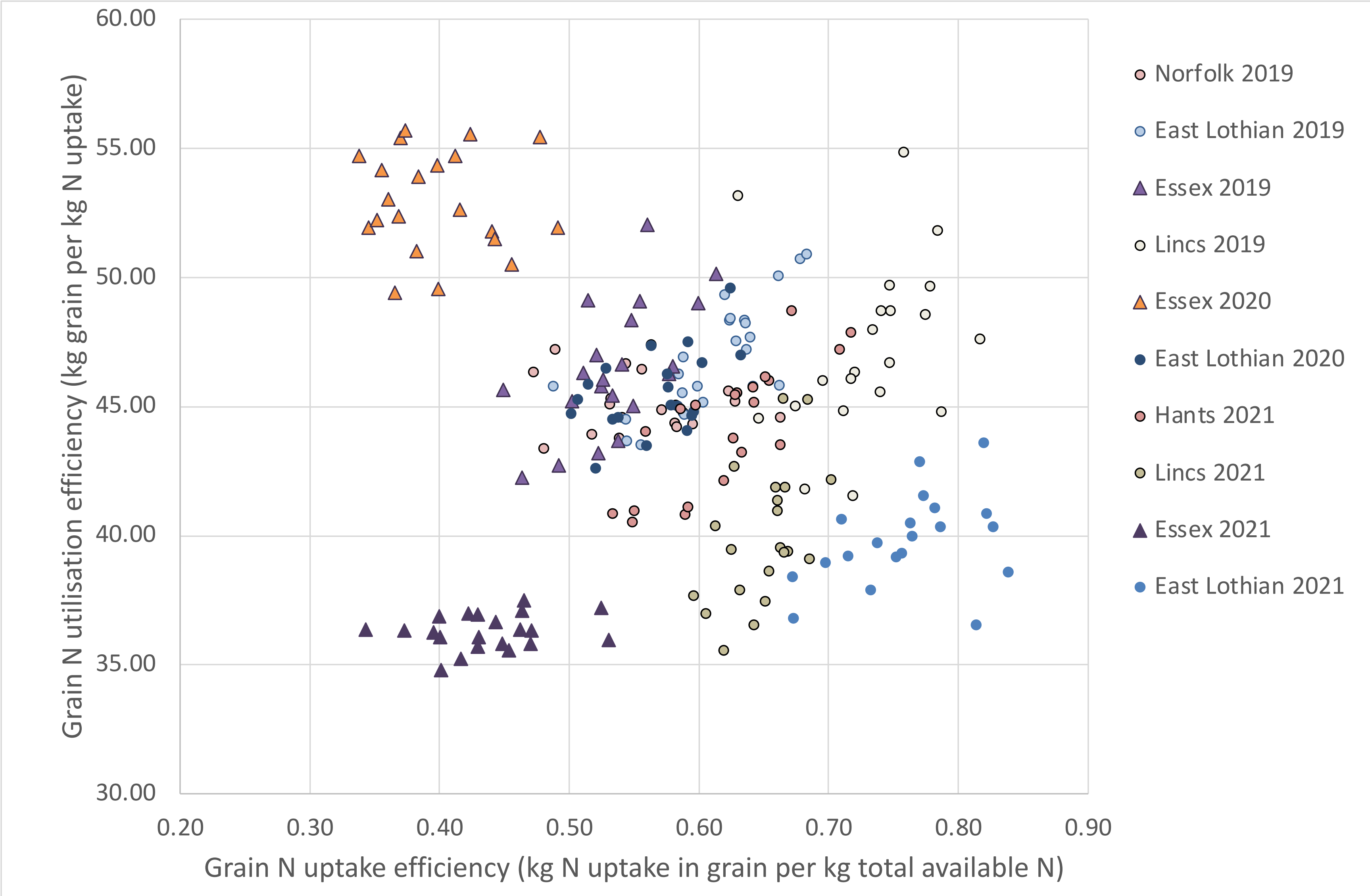

Figure 4.9: Grain N utilisation efficiency plotted against grain N uptake efficiency; average values for each variety/treatment combination for all sites.

Apparent fertiliser recovery in grain was 46% on average; varying from 19 to 69 % across sites. Grain N uptake efficiency was 59 % on average; varying from 40 to 77 % across sites. N uptake efficiency reduced on average as N rate increased (

Table 4.7). Site to site variation was much larger than the differences between treatments (Figure 4.9). However, the range of variation by treatment was very similar, hence the same relative decline in uptake efficiency is seen across sites though the absolute values are different at each site.

Grain N utilisation efficiency at the nitrogen rate for yield alone ('RB209') was very much lower than that measured with zero N (Table 4.5). Nitrogen utilisation continued to reduce on average as N rate increased above 'RB209' (

Table 4.7). Site to site variation was much larger than the differences between treatments; but, in contrast to uptake efficiency, the range of variation by treatment is markedly different for different sites (Figure 4.9). For example, Essex 2021 is distinguished by very low nitrogen utilisation efficiency (36.3 kg grain/kg N), with a narrow range (2.7 kg/kg). This contrasts with Essex 2019 where nitrogen utilisation efficiency was high (46.5 kg grain/kg N) with a wider range of 9.7 kg/kg.

Table 4.7: Average N efficiency measures for each treatment across all sites/varieties.

N rate/timing	Grain N uptake efficiency (kg N uptake in grain per kg total available N)	Grain N utilisation efficiency (kg grain per kg N uptake)	Grain N use efficiency (kg grain per kg total available N)
'RB209'	0.65	47.1	30.6
+40 AN at GS 32-35	0.60	45.2	27.2
+40 AN at GS 37-39	0.60	45.2	27.2
+40 F at GS 73	0.60	44.7	26.7
+80 AN at GS 37-39	0.56	44.1	24.6
+80 F at GS 73	0.57	42.7	24.1
+120 F at GS 73	0.52	42.2	21.9

Grain protein

Grain protein was obtained from the ten experiments performed in years 2019-2021. We found, in most cases, a consistent effect of N rate and timing on grain protein (P=<0.001) (Table 4.8 and Appendix 1). However, in the Norfolk experiment, grain protein for KWS Zyatt ranged from 12.5% ('RB209') to 12.4 % (+120kg N/ha). These small protein responses were mirrored in KWS Siskin and RGT Skyfall. In part, this maybe driven by the low radiation throughout the season but particularly during grain filling period, so there probably wasn't enough sunlight to drive protein synthesis; further detail is explained by Blake-Kalff and Blake (2022). In contrast, the Essex experiment in 2019 resulted in a good response of N to grain protein; for KWS Zyatt (Group 1) this ranged from 11.4 % ('RB209') to 13.4 % (+120 kg N/ha). Similar responses at this experiment were seen for RGT Skyfall (also Group 1). KWS resulted in slightly lower grain protein as would be expected of a Group 2 variety. In 2021, the sites at East Lothian, Lincolnshire and Hampshire all resulted in significantly increased grain proteins with N rate and timing (P=<0.001). However, the Essex experiment in 2021 resulted in little increase in grain protein to N rate or timing, averaging 13.4 %, 13.1 % and 13.5 % ('RB209') and 13.3 %, 13.4 % and 13.9 % (+120 kg N/ha) for the three varieties KWS Zyatt, KWS Siskin and RGT Skyfall, respectively (LSD=0.57). Yields at the Essex 2021 were very low because it was such a late crop to be drilled and establishment was delayed due to the wet winter followed by the dry spring.

The increment in grain protein by applying additional N above that of the 'RB209' rate ranged from 0.3 % to 1.4 % (Table 4.8). On average across all sites, an additional +40 kg N applied as AN or as late foliar urea significantly increased grain protein (P=0.001) by 0.3 % to 0.8 % above 'RB209' rate (LSD=0.58). KWS Zyatt was the most responsive in terms of increasing grain protein and RGT Skyfall and RGT Siskin being the least responsive. An addition of +80 kg N, further increased grain proteins on average by 0.5 to 0.8 % compared to 'RB209'. Grain protein response at +120 kg N increased to a maximum of 13.1 % in RGT Skyfall but in KWS Zyatt and KWS Siskin responses were lower at around 12.6 to 1.8 % compared to the 'RB209' rate.

Table 4.8: Ten site mean grain protein (% DM) and response to N rate and timing.

	Grain protein (% DM)			Difference in grain protein from 'RB209' treatment (%)		
N rate	KWS Zyatt	KWS Siskin	RGT Skyfall	KWS Zyatt	KWS Siskin	RGT Skyfall
'RB209'	11.4	11.4	11.9	-	-	-
+40 AN at GS 32-35	12.0	11.9	12.2	0.6	0.5	0.3
+40 AN at GS 37-39	12.0	11.8	12.3	0.6	0.4	0.4
+40 F at GS 73	12.2	11.9	12.4	0.8	0.5	0.5
+80 AN at GS 37-39	12.2	12.2	12.5	0.8	0.8	0.7
+80 F at GS 73	12.5	12.6	12.9	1.1	1.3	1.1
+120 F at GS 73	12.6	12.8	13.1	1.2	1.4	1.3
LSD (P=<0.05)		0.58			-	

The proportion of samples for each of the varieties, KWS Zyatt and RGT Skyfall (Group 1) and KWS Siskin (Group 2) that achieved a certain percentage of grain protein is shown in
Figure 4.10 to Figure 4.12. For the 'RB209' treatment, for all three varieties 20 % of samples were above 12.5 % grain protein. The proportion of the samples below 11.5 % protein, at 'RB209' fertilisation, were 40% for RGT Skyfall and 60% for KWS Zyatt and KWS Siskin. The patterns reflect those seen in the AHDB Cereal Quality survey (Table 4.1).

Increasing nitrogen above 'RB209', for example +40 Kg N/ha either applied as AN or F had a similar affect across all varieties with RGT Skyfall attaining the greatest proportion of samples above 12.5 % grain protein. Interestingly there was a small, but consistent increase above 13 % grain protein when +40 kg N/ha was applied as F at GS 73 with 20 % of samples being above 13 % grain protein compared to 10 % for +40kg/ha applied as AN either at GS 32-35 or 37-39. When an additional +80 kg N/ha above 'RB209' was applied, on average, 20 % (KWS Zyatt and KWS Siskin) and 40 % (RGT Skyfall) in the proportion of samples reaching 13 % grain protein was achieved. Again, a similar pattern was seen with foliar urea applications at GS 73 further increasing grain protein above that of AN application. In RGT Skyfall, up to 70 % of samples reached 13% grain protein with foliar urea compared to 10 % of samples with only AN applied. All additional applications of nitrogen fertiliser above 'RB209' reduced the proportion of samples under 11.5 % by 50 %, 40-50 % and 0-30 % for KWS Zyatt, KWS Siskin and RGT Skyfall, respectively.

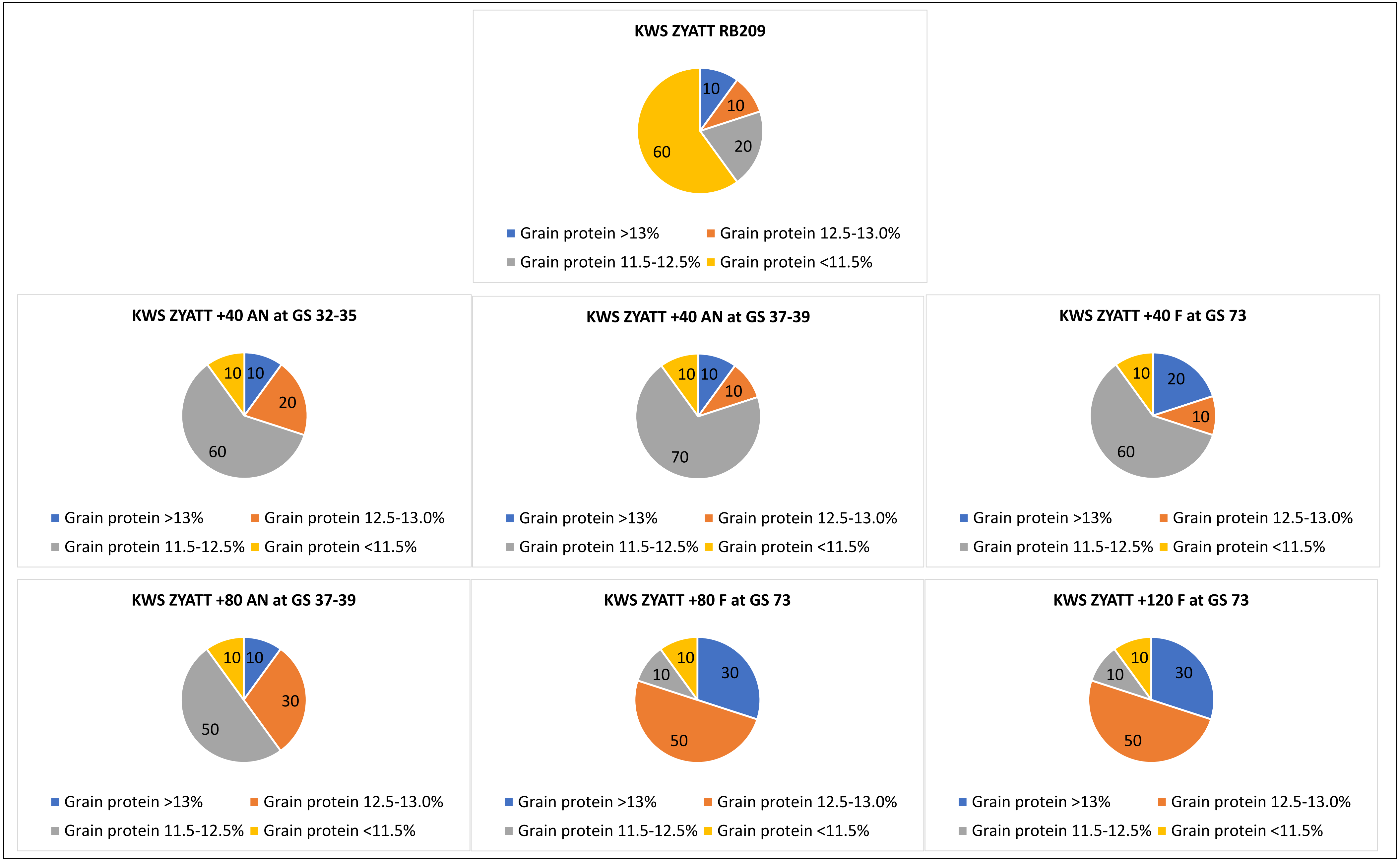

Figure 4.10: Percentage of samples for KWS Zyatt attaining grain protein within specified categories for each nitrogen treatment.

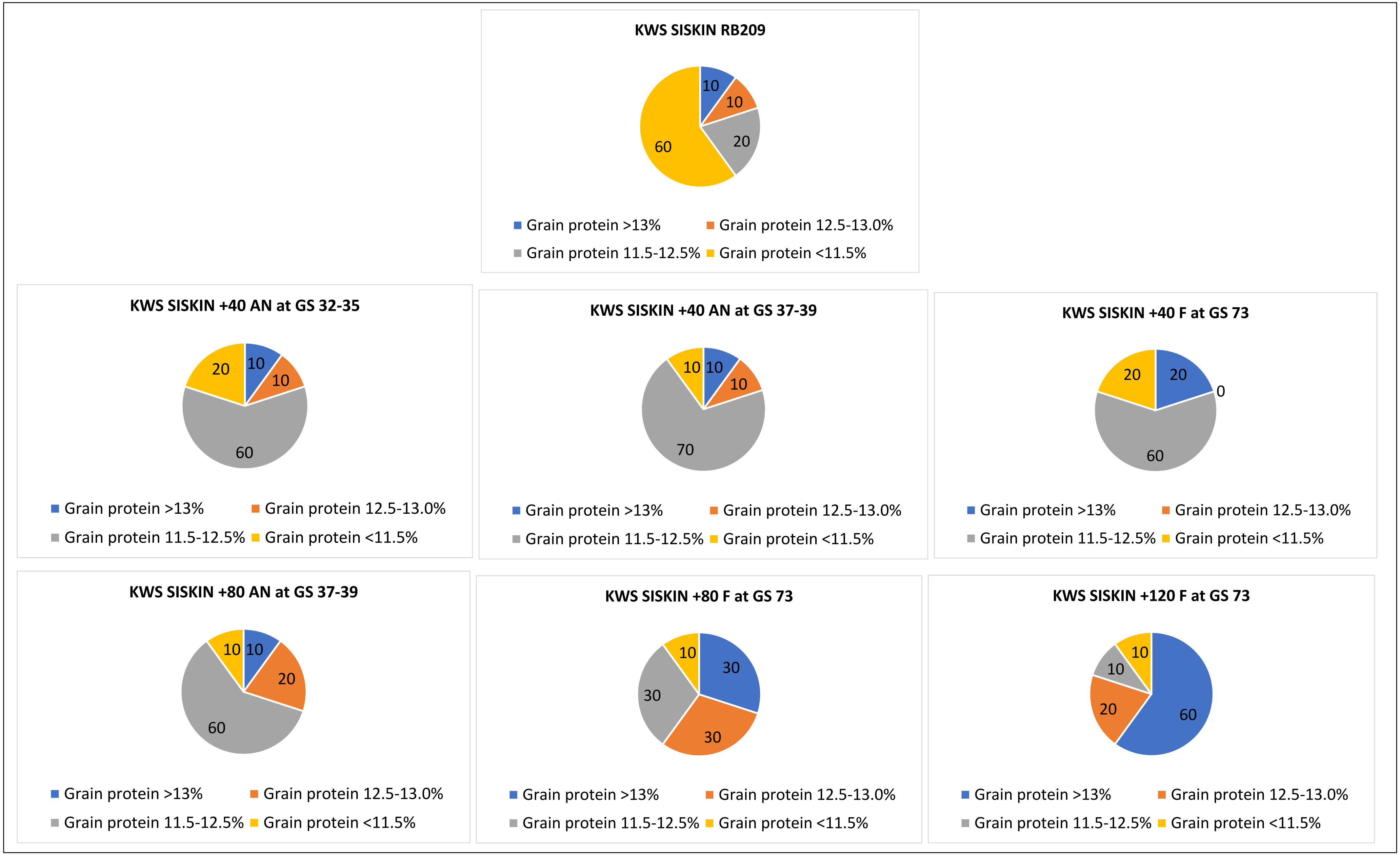

Figure 4.11: Percentage of samples for KWS Siskin attaining grain protein within specified categories for each nitrogen treatment.

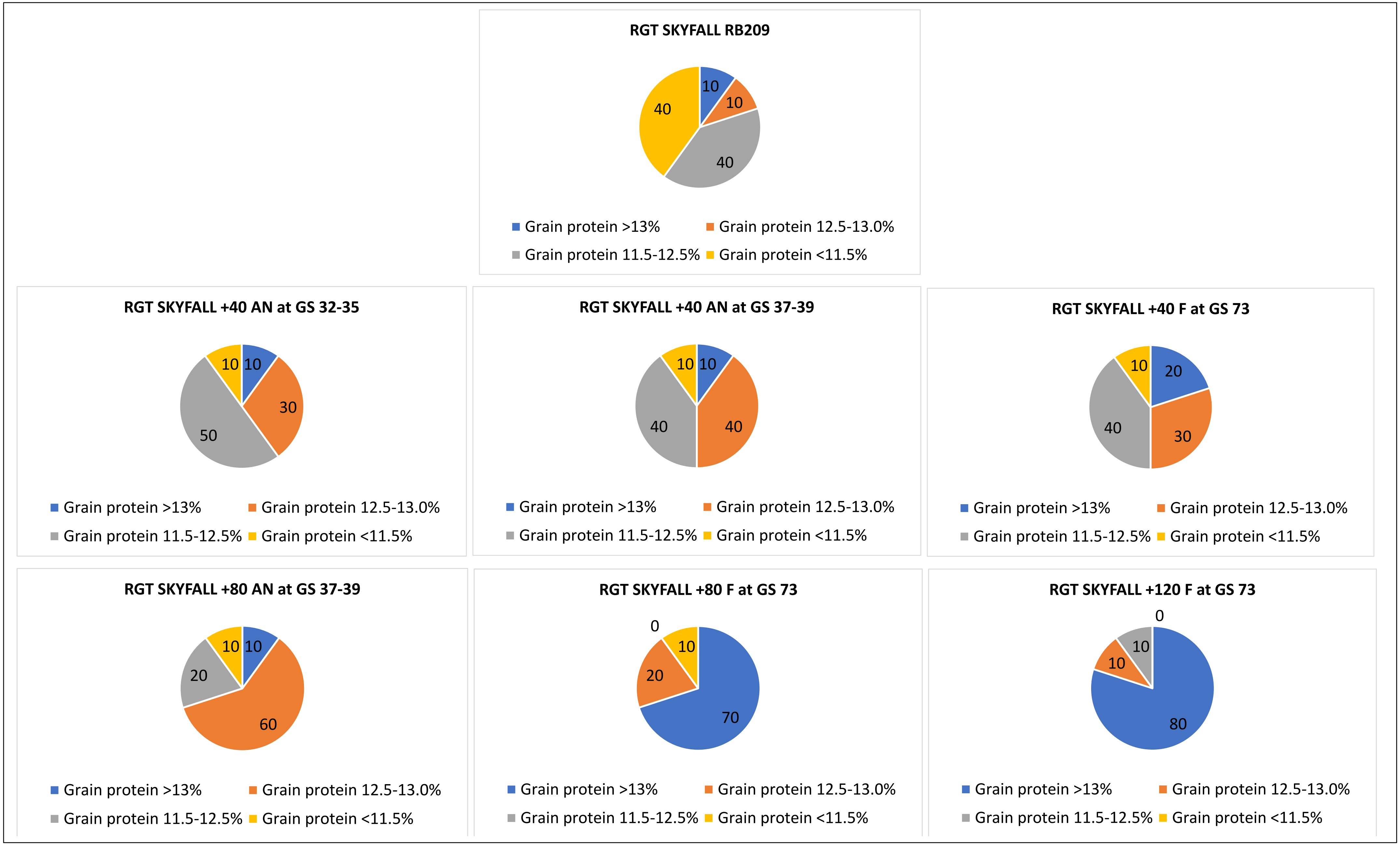

Figure 4.12: Percentage of samples for RGT Skyfall attaining grain protein within specified categories for each nitrogen treatment.

Grain specific weight

Across the ten experiments we found no consistent effect of N rate and timing on specific weight (P=1.0). However, we did find significant differences between varieties (P=<0.001) but not a significant interaction between N rate and timing and variety (P=1.0) (Table 4.9 and Appendix 1). The mean specific weight for N rate and timing ranged from 75.6 kg/hl to 75.9 kg/hl (LSD=0.77). Varietal differences saw KWS Siskin with the lowest specific weight with a mean of 74.6 kg/hl, KWS Zyatt was intermediate with a mean of 75.8 kg/hl and RGT Skyfall had the highest specific weight of 76.9 kg/hl (LSD=0.77).

Table 4.9: Ten site mean specific weight (kg/hl) in response to N rate and timing.

	Specific Weight (kg/hl)			
N rate	KWS Zyatt	KWS Siskin	RGT Skyfall	Mean
'RB209'	75.7	74.4	77.1	75.7
+40 AN at GS 32-35	75.7	74.7	76.9	75.8
+40 AN at GS 37-39	75.9	74.5	76.9	75.8
+40 F at GS 73	76.0	74.5	77.1	75.9
+80 AN at GS 37-39	75.8	74.5	76.9	75.7
+80 F at GS 73	75.8	74.7	76.8	75.8
+120 F at GS 73	75.7	74.6	76.7	75.6
LSD (P=<0.05)		2.1		0.77

Between sites and seasons, we saw greater differences in specific weight (Figure 4.13). Across the ten sites, KWS Siskin had the lowest specific weight, and was below the UKFM specification (76.0 kg/hl) at seven of the ten sites; KWS Zyatt was below specification at 6 of the ten sites and RGT Skyfall was below specification at three out of the ten sites. The lowest specific weights in the trial series were at the Essex site in 2021, with specific weights in the range of 69.9 to 73.0 kg/hl. In contrast, the highest specific weights were at the Norfolk site in 2019, with specific weights in the range of 78.7 to 79.4 kg/hl.

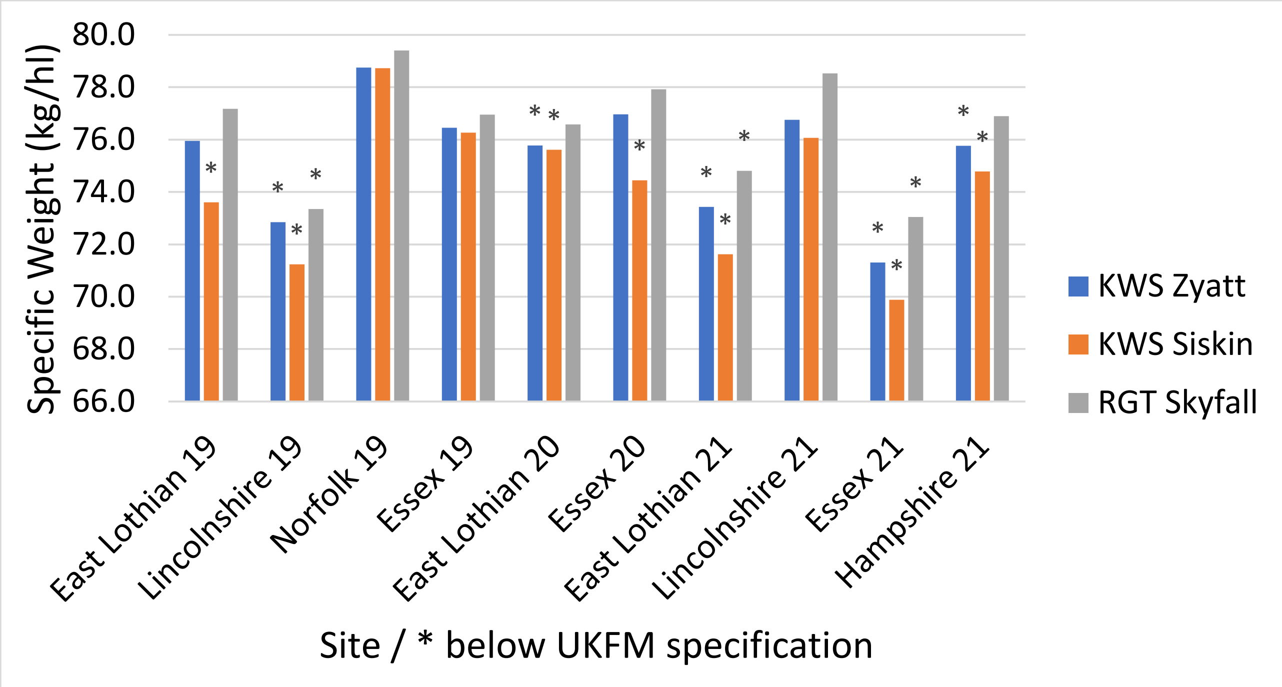

Figure 4.13: Specific weight (kg/hl) in response to Variety (Mean of N rate and timing). Where the mean values are significantly lower for that variety and the respective crop year, then a * has been placed above the corresponding bar in the graph.

The proportion of samples for each of the varieties, KWS Zyatt and RGT Skyfall (Group 1) and KWS Siskin (Group 2) that attained a given specific weights are shown in Figure 4.14. For Group 1 varieties, RGT Skyfall had the highest proportion of samples above 76.0 kg/hl with 70 %; KWS Zyatt had 59 %. For Siskin (Group 2) the proportion was 31 %. Of the samples below 76.0 kg/hl specific weight, RGT Skyfall had the lowest proportion in this category (30 %) and KWS Zyatt was intermediate with 41% and KWS Siskin with 69 % of samples below 76.0 kg/hl specific weight. The patterns reflect those seen in the AHDB Cereal Quality survey (Table 4.1).

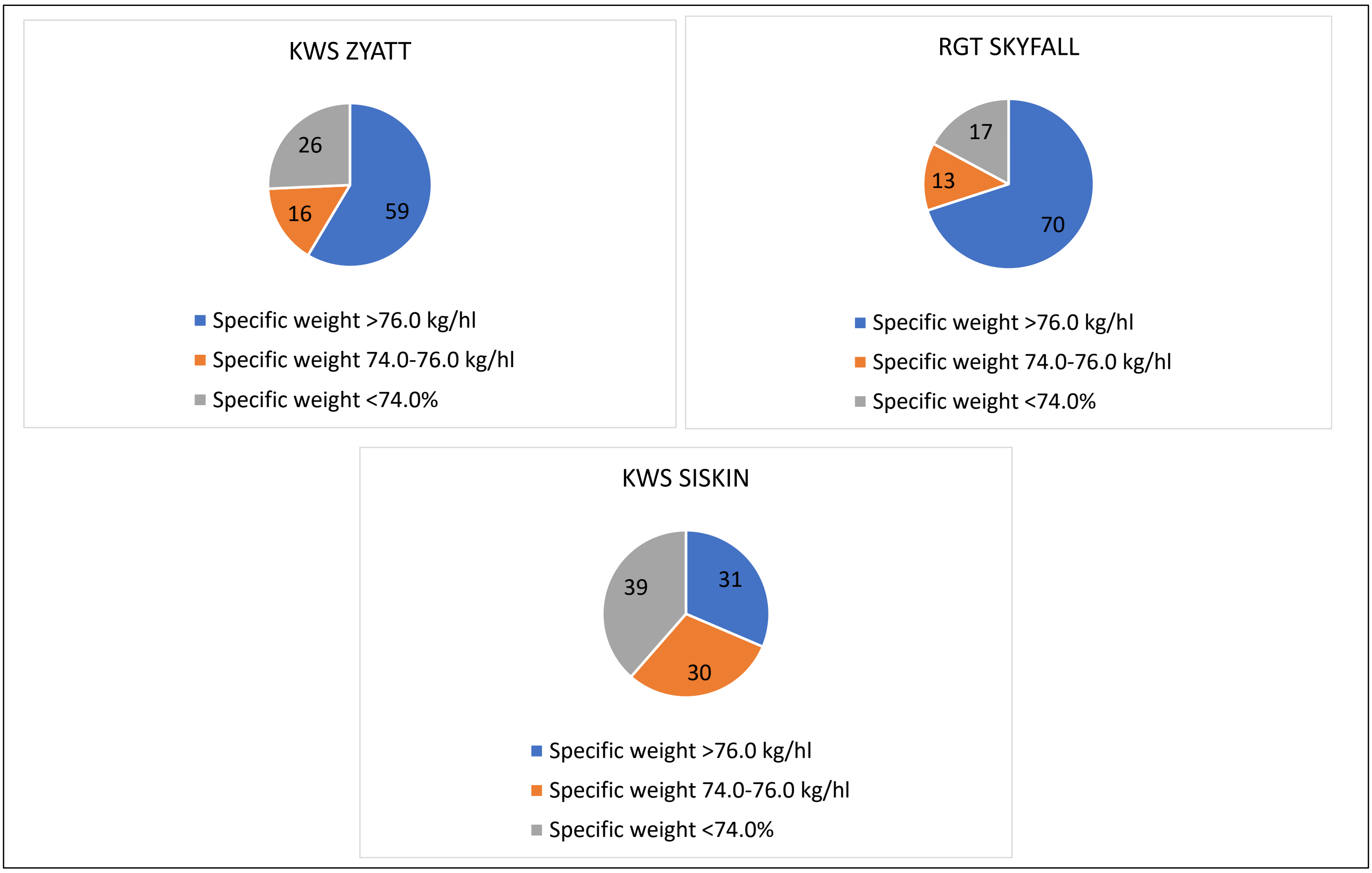

Figure 4.14: Percentage of samples attaining specific weight within specified categories for the three varieties.

Hagberg Falling Number

The Hagberg Falling Number (HFN, s) were measured in each experiment. The impact on HFN of nitrogen rate and timing had no significant (P=0.974) affect and neither did variety (P=0.1) (Table 4.10). Across the ten sites HFN averaged 255 for KWS Zyatt (range 244-264); 291 KWS Siskin (range 276-319) and 269 for RGT Skyfall (range 237-296). The main impact on HFN was the site and season. The site with the lowest HFN was East Lothian, averaging 209, 139 and 161 in 2019, 2020 and 2021 seasons, respectively. In each season, at East Lothian, HFN was low across all three varieties (Figure 4.15). Other sites specifically with low HFN were Lincolnshire in 2019 (all varieties) and Hampshire in 2021 (RGT Skyfall only). Where HFN was under 250 seconds (UKFM specification) the samples were not test baked as they were deemed unsuitable.

Table 4.10: Ten site mean Hagberg Falling Number (s) in response to N rate and timing.

	Hagberg Falling Number (s)			
N rate	KWS Zyatt	KWS Siskin	RGT Skyfall	Mean
'RB209'	255	282	272	269
+40 AN at GS 32-35	257	293	278	276
+40 AN at GS 37-39	260	276	296	277
+40 F at GS 73	244	284	237	255
+80 AN at GS 37-39	251	278	279	269
+80 F at GS 73	256	319	260	278
+120 F at GS 73	264	303	261	276
LSD (P=<0.05)		86.3		49.8

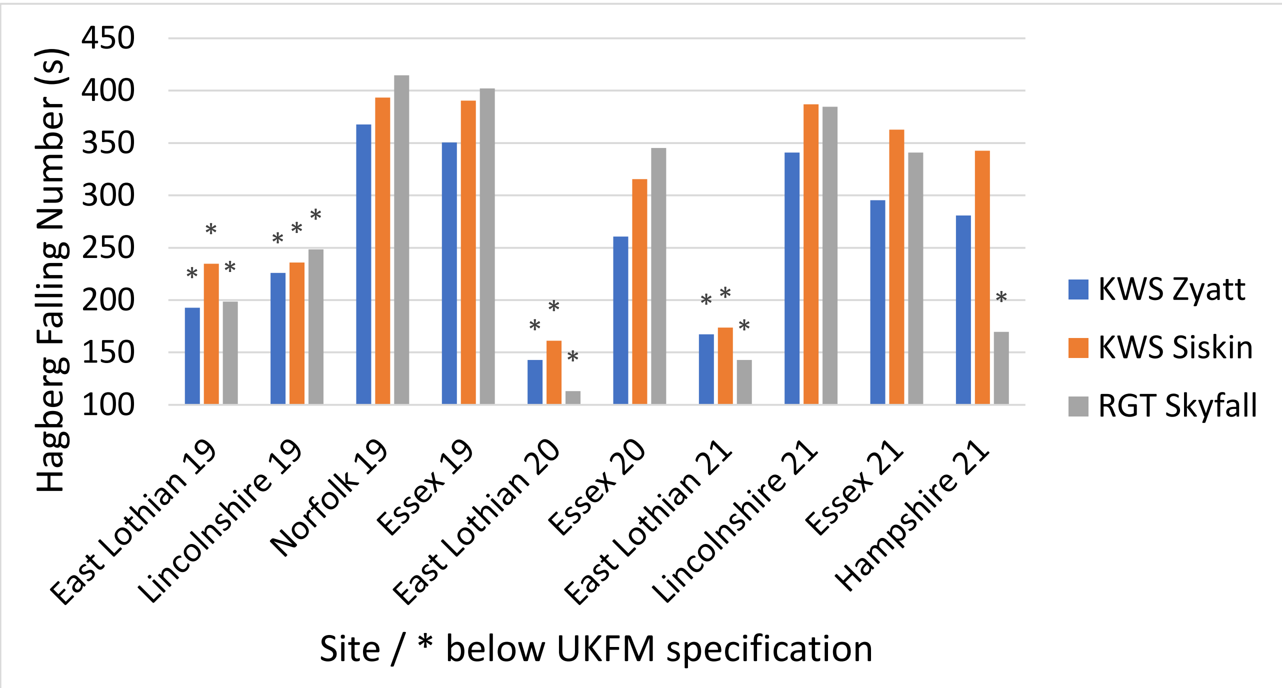

Figure 4.15: Hagberg Falling Number (s) in response to Variety (Mean of N rate and timing). Where the mean values are significantly lower for that variety and the respective crop year, then a * has been placed above the corresponding bar in the graph.

4.3. Objective 3. QUANTIFY THE EFFECT OF RATE AND TIMING OF APPLIED S FERTILISER ON GRAIN QUALITY

Analyses of data on grain yield and quality for each site and also across sites was used to explore how the rate and timing of S fertiliser applications affects grain quality, including grain yield, grain protein and grain specific weight, so that any potential trade-offs in contrasting S management strategies for winter milling wheat could be evaluated.

Effect of Variety

There were small differences between the two varieties (KWS Zyatt and RGT Skyfall), with significant differences found at some sites (Table 4.11). Overall, there was no significant interaction between variety and the S rate and timing treatments.

Table 4.11: Levels of significance for variety differences (averaged across S rate and timing treatments); * indicates a significant interaction between variety and S rate and timing treatments. Where a significant difference was found for a site, then usually one variety was significantly different from the other, this difference is identified.

Site	Grain yield	Grain protein	Specific weight
East Lothian 19	NS	<1% * Lower in KWS Zyatt	No Data
Lincolnshire 19	NS	<0.1% * Lower in KWS Zyatt	<0.1% * Lower in KWS Zyatt
Norfolk 19	<0.1% * Lower in RGT Skyfall	NS	5% * Lower in KWS Zyatt
Essex 19	<0.1% * Lower in RGT Skyfall	<0.1% * Lower in KWS Zyatt	<0.1% * Lower in RGT Skyfall
East Lothian 20	<1% * Lower in RGT Skyfall	<0.1% * Lower in KWS Zyatt	<0.1% * Lower in KWS Zyatt
Essex 20	<0.1% * Lower in KWS Zyatt	<0.1% * Lower in KWS Zyatt	NS
Lincolnshire 21	<0.1% * Lower in RGT Skyfall	<0.1% * Lower in KWS Zyatt	<0.1% * Lower in KWS Zyatt
Hampshire 21	<0.1% * Lower in RGT Skyfall	<1% * Lower in KWS Zyatt	<0.1% * Lower in KWS Zyatt

Grain yield

In each of the eight experiments S rate was investigated, as a full S response experiment where five rates of SO_3 were applied, with an additional Nil S treatment included with the interaction of +40 kgN/ha either applied as AN at GS 37-39 or as foliar urea at GS 73. Across the eight experiments which tested the full five rates, there was no significant effect of S rate on yield (Table 4.12 and Appendix 2). On an individual experiment basis, a significant yield response was obtained at the Lincolnshire site in 2019, where yield was significantly increased by 50 kg/ha SO_3, in the variety KWS Zyatt. RGT Skyfall did not show a significant response to S at this site. A yield response to S was also seen at the Hampshire site in 2021, although responses were variable with no consistent increase in yield with higher S rates.

The mean yield response (t/ha) across the eight sites over 0 kg SO_3 is shown in Figure 4.16. There was little consistent yield response to increasing S rates; either with AN or F nitrogen although, in general, F nitrogen resulted in negative responses, although these are non-significant (P=1.0). Across the eight experiments where a Nil S and a 50 kg/ha SO_3 treatment were included there were mixed responses to the S application, ranging from a yield increase of 0.2 t/ha through to a 0.42 t/ha yield reduction. Of the two varieties, KWS Zyatt appeared to be more responsive to S compared to RGT Skyfall, however, the responses were small and inconsistent.

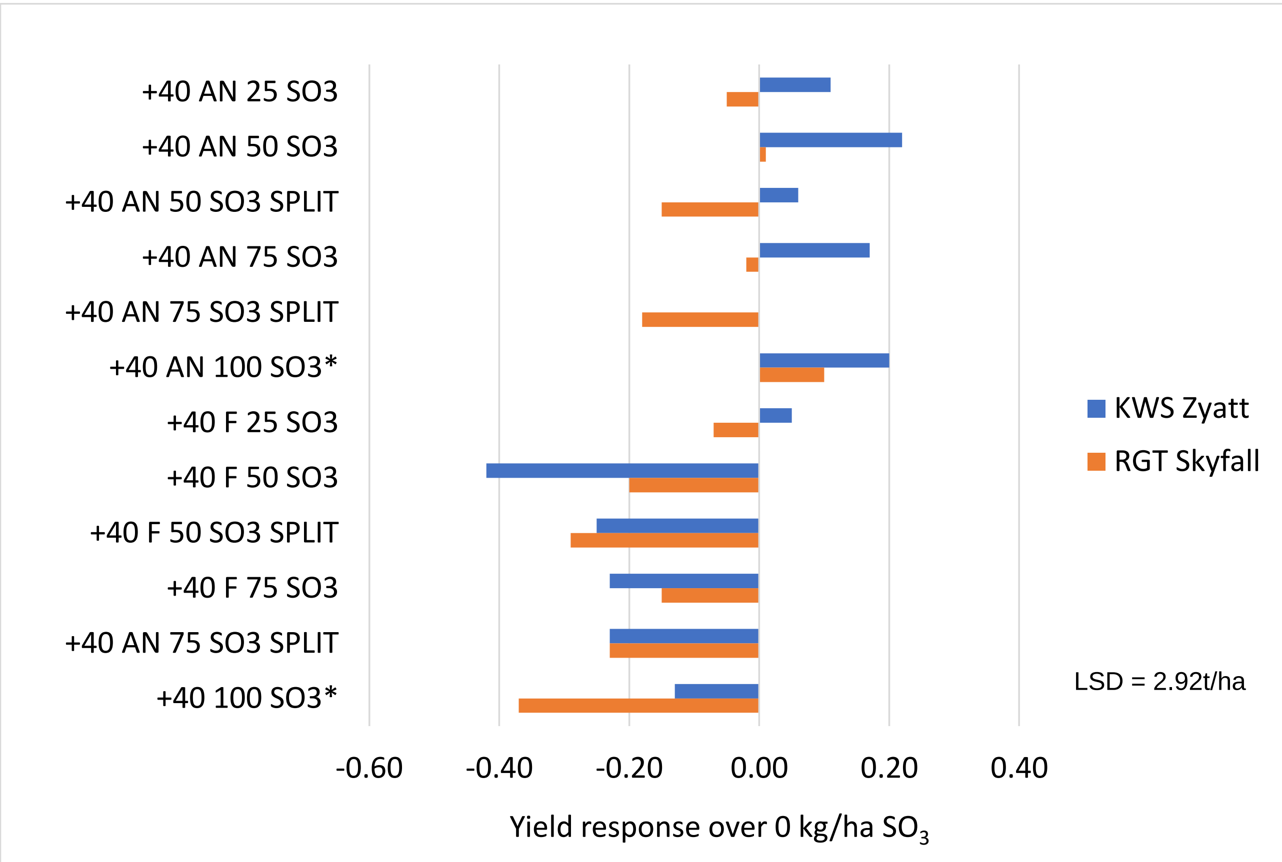

Figure 4.16: Yield (t/ha) response over 0 kg/ha SO_3. *denotes limited site data.

Table 4.12: Yield (t/ha) in response to different rates of SO_3.

	N rate (kg N/ha)	+40 AN At GS 37-39							+40 Foliar At GS 73								
	S rate (SO_3)	0	25	50	50 split	75	75 split	100	0	25	50	50 split	75	75 split	100	P	LSD
East Lothian 19	KWS Zyatt	11.30	11.60	11.64	11.47	11.62	11.95	-	11.47	11.53	11.52	11.65	11.25	11.58	-	0.587	0.597
	RGT Skyfall	11.31	11.38	11.64	11.42	11.65	11.57	-	11.64	11.33	11.22	11.46	11.30	10.97	-		
Lincs 19	KWS Zyatt	12.50	13.16	13.43	13.89	13.75	13.63	-	12.01	12.90	13.35	12.97	13.35	12.75	-	0.002	0.844
	RGT Skyfall	13.67	13.36	13.45	13.37	13.45	13.69	-	12.91	13.17	12.56	13.02	12.64	12.24	-		
Norfolk 19	KWS Zyatt	11.22	11.51	11.29	11.19	11.41	11.28	-	10.97	10.78	11.22	11.19	11.20	10.93	-	0.004	0.353
	RGT Skyfall	10.91	11.10	10.90	11.10	11.13	11.16	-	10.87	10.94	10.94	10.77	10.93	10.91	-		
Essex 19	KWS Zyatt	10.56	10.41	10.56	10.57	10.60	10.39	-	10.54	10.45	10.44	10.55	10.55	10.10	-	0.040	0.667
	RGT Skyfall	10.14	9.82	10.09	9.86	10.22	10.03	-	10.12	9.81	9.76	9.97	9.93	10.22	-		
East Lothian 20	KWS Zyatt	11.81	12.06	12.09	12.29	12.00	11.66	-	11.75	12.19	11.85	12.20	11.73	12.04	-	0.406	0.736
	RGT Skyfall	11.89	11.69	11.35	11.56	11.89	11.62	-	11.48	11.82	11.56	11.42	11.39	11.60	-		
Essex 20	KWS Zyatt	7.18	7.23	7.14	7.01	7.10	7.27	-	7.06	7.25	7.32	7.08	7.09	7.10	-	0.052	0.551
	RGT Skyfall	7.44	7.29	7.67	7.70	7.33	7.78	-	7.64	7.49	7.53	7.67	7.77	7.71	-		
Lincs 21	KWS Zyatt	10.62	-	10.55	10.17	10.44	10.55	10.44	10.17	-	10.30	10.42	10.49	10.56	10.37	0.021	0.826
	RGT Skyfall	9.59	-	10.06	9.98	10.09	9.94	10.15	9.98	-	9.56	9.82	9.99	10.02	10.12		
Hants 21	KWS Zyatt	10.95	-	11.22	10.94	10.88	11.05	10.94	10.45	-	10.74	10.56	10.50	10.71	10.45	<0.001	0.286
	RGT Skyfall	10.71	-	10.58	10.50	10.75	10.62	10.64	10.13	-	10.32	10.32	10.28	10.42	10.36		
Mean	KWS Zyatt	10.53	10.64	10.75	10.70	10.73	10.73	10.78	10.31	10.50	10.60	10.59	10.53	10.48	10.50	1.000	2.92
	RGT Skyfall	10.47	10.42	10.48	10.45	10.57	10.56	10.49	10.36	10.41	10.19	10.32	10.29	10.27	10.33		

Split = Split sulphur rate

To help to understand more about the risk of deficiency at each site, grain S analyses were used (Table 4.13). These results show that in three of the eight experiments in which grain S concentration of the Nil S treatment were measured indicated a sulphur deficiency and these all occurred in the variety KWS Zyatt.

Table 4.13: Explanatory analyses to accompany S response results. 'Def' refers to where the chemical analysis indicated a deficiency and 'Suf' indicates sufficiency.

Site	Variety	Sulphur risk matrix	Malate-sulphur tissue test ratio	Grain S concentration Nil S (mg/kg) Critical 1150	Grain S concentration 75kg/ha Split SO_3 (mg/kg)	Yield response to 75kg/ha Split SO_3
East Lothian 19	KWS Zyatt	Intermediate	-	1200 (Suf)	1280 (Suf)	0.3t/ha
	RGT Skyfall		-	1300 (Suf)	1230 (Suf)	-0.3t/ha
Lincs 19	KWS Zyatt	Intermediate	-	1120 (Def)	1220 (Suf)	0.3t/ha
	RGT Skyfall		-	1210 (Suf)	1330 (Suf)	-0.3t/ha
Norfolk 19	KWS Zyatt	High	-	1310 (Suf)	1370 (Suf)	0.3t/ha
	RGT Skyfall		-	1430 (Suf)	1380 (Suf)	0.0t/ha
Essex 19	KWS Zyatt	Intermediate	-	1390 (Suf)	1370 (Suf)	-0.5t/ha
	RGT Skyfall		-	1410 (Suf)	1470 (Suf)	0.1t/ha
East Lothian 20	KWS Zyatt	Intermediate	-	1100 (Def)	1100 (Def)	0.2t/ha
	RGT Skyfall		-	1200 (Suf)	1200 (Suf)	-0.3t/ha
Essex 20	KWS Zyatt	Intermediate	-	1100 (Def)	1200 (Suf)	-0.1t/ha
	RGT Skyfall		-	1200 (Suf)	1300 (Suf)	0.3t/ha
Lincs 21	KWS Zyatt	High	0.08 (Suf)	1200 (Suf)	1100 (Def)	-0.1t/ha
	RGT Skyfall		0.13 (Suf)	1200 (Suf)	1200 (Suf)	0.4t/ha
Hants 21	KWS Zyatt	High	2.31 (Def)	1200 (Suf)	1200 (Suf)	-0.2t/ha
	RGT Skyfall		2.24 (Def)	1200 (Suf)	1300 (Suf)	-0.3t/ha

Grain protein

Across the eight experiments, there was no significant effect of SO_3 rate on grain protein % (P=1.0), with a maximum difference of 0.3% between the five rates. There was no difference to grain protein either between variety or whether AN of F nitrogen had been applied (Table 4.14). At the Lincolnshire site in 2019, there was significantly higher grain proteins in RGT Skyfall compared to KWS Zyatt but this was not a trend that was replicated with no indication that increasing SO_3 rate resulted in higher grain protein %.

Table 4.14: Grain protein (% DM) in response to different rates of SO_3.

	N rate (kg N/ha)	+40 AN At GS 37-39							+40 Foliar At GS 73								
	S rate (SO_3)	0	25	50	50 split	75	75 split	100	0	25	50	50 split	75	75 split	100	P	LSD
East	KWS Zyatt	11.3	11.3	10.8	11.0	10.9	11.2	-	11.5	11.3	11.0	11.5	11.6	11.7	-	0.103	0.69
Lothian 19	RGT Skyfall	11.6	11.0	11.4	11.5	11.3	11.1	-	11.5	11.8	11.9	11.7	11.8	11.5	-		
Lincs 19	KWS Zyatt	10.7	10.8	11.3	11.1	10.9	10.9	-	10.4	10.2	10.7	10.3	10.8	10.4	-	<0.001	1.04
	RGT Skyfall	11.4	11.9	11.5	11.9	11.7	11.6	-	12.0	12.1	11.8	12.0	11.9	12.3	-		
Norfolk 19	KWS Zyatt	12.1	12.1	12.2	12.2	11.9	12.1	-	12.1	12.3	11.4	12.4	12.2	12.4	-	0.166	0.491
	RGT Skyfall	12.2	12.2	12.2	12.3	12.2	12.2	-	12.3	12.2	12.2	12.4	12.3	12.2	-		
Essex 19	KWS Zyatt	11.6	11.8	11.8	12.0	12.0	11.9	-	12.4	12.1	12.1	12.3	12.2	12.1	-	0.003	0.40
	RGT Skyfall	12.3	12.1	12.2	12.2	12.4	12.1	-	12.0	12.1	12.6	12.4	12.2	12.3	-		
East	KWS Zyatt	11.6	11.5	11.6	11.6	11.6	11.6	-	11.8	11.5	11.8	11.7	11.6	11.7	-	0.002	0.27
Lothian 20	RGT Skyfall	11.8	11.8	12.0	11.9	11.8	11.8	-	11.9	11.8	11.9	12.0	12.0	11.9	-		
Essex 20	KWS Zyatt	9.9	10.2	9.9	10.2	10.0	9.9	-	10.2	10.2	10.3	10.3	10.3	10.4	-	<0.001	0.34
	RGT Skyfall	10.2	10.7	10.4	10.3	10.4	10.3	-	10.7	10.5	10.7	10.7	10.3	10.9	-		
Lincs 21	KWS Zyatt	11.7	-	11.4	11.3	11.4	11.1	11.2	11.9	-	11.8	11.5	11.4	11.7	11.7	<0.001	0.48
	RGT Skyfall	11.7	-	12.1	12.1	11.9	12.1	11.8	12.2	-	11.8	12.4	12.0	11.8	11.4		
Hants 21	KWS Zyatt	11.7	-	11.9	12.0	12.0	12.2	11.9	12.5	-	12.1	12.6	12.7	12.7	12.6	<0.001	0.23
	RGT Skyfall	12.2	-	12.0	12.3	12.1	12.2	12.3	12.4	-	12.6	12.6	12.4	12.4	12.5		
Mean	KWS Zyatt	10.5	10.6	10.8	10.7	10.7	10.7	10.8	10.3	10.5	10.6	10.6	10.5	10.5	10.5	1.0	1.17
	RGT Skyfall	10.5	10.4	10.5	10.5	10.6	10.6	10.5	10.4	10.4	10.2	10.3	10.3	10.3	10.3		

Split = Split sulphur rate

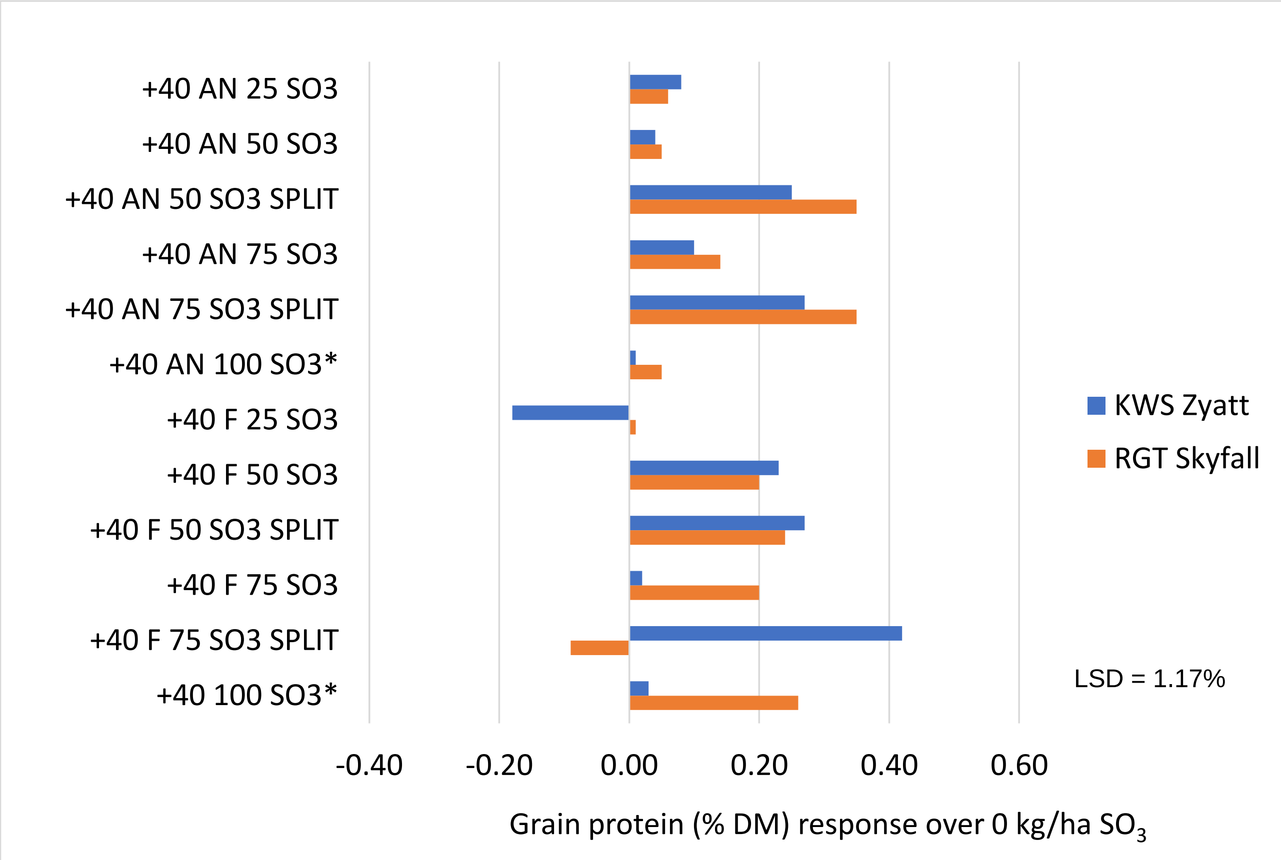

Figure 4.17: Grain protein (% DM) response over 0 kg/ha SO_3. *denotes limited site data.

Grain protein response (%) over 0 kg/ha SO_3 showed small and variable responses with no significant differences (P=0.548) when applying additional sulphur Figure 4.17. Applying split sulphur either at 50 or 75 kg/ha SO_3 with +40 AN appeared to result in the greatest responsiveness, although these were on average 0.25 % to 0.35 % increase in grain protein. The proportion of grain samples were grouped into four categories: 1) above 13 % protein, 2) 12.5 % to 13.0 %, 3) 11.5 % to 12.5 % and 4) below 11.5 % for each of the two varieties (Figure 4.18 and Figure 4.19). Due to the low grain protein response to sulphur applications the proportion of samples attaining grain protein with increasing sulphur up to 75 kg/SO_3 showed little consistent response. The application of 100 kg/ha SO_3 suggested a higher proportion of samples between 12.5 % and 13.0 % grain protein, although this should be treated with some caution due to the limited site data available for this treatment.

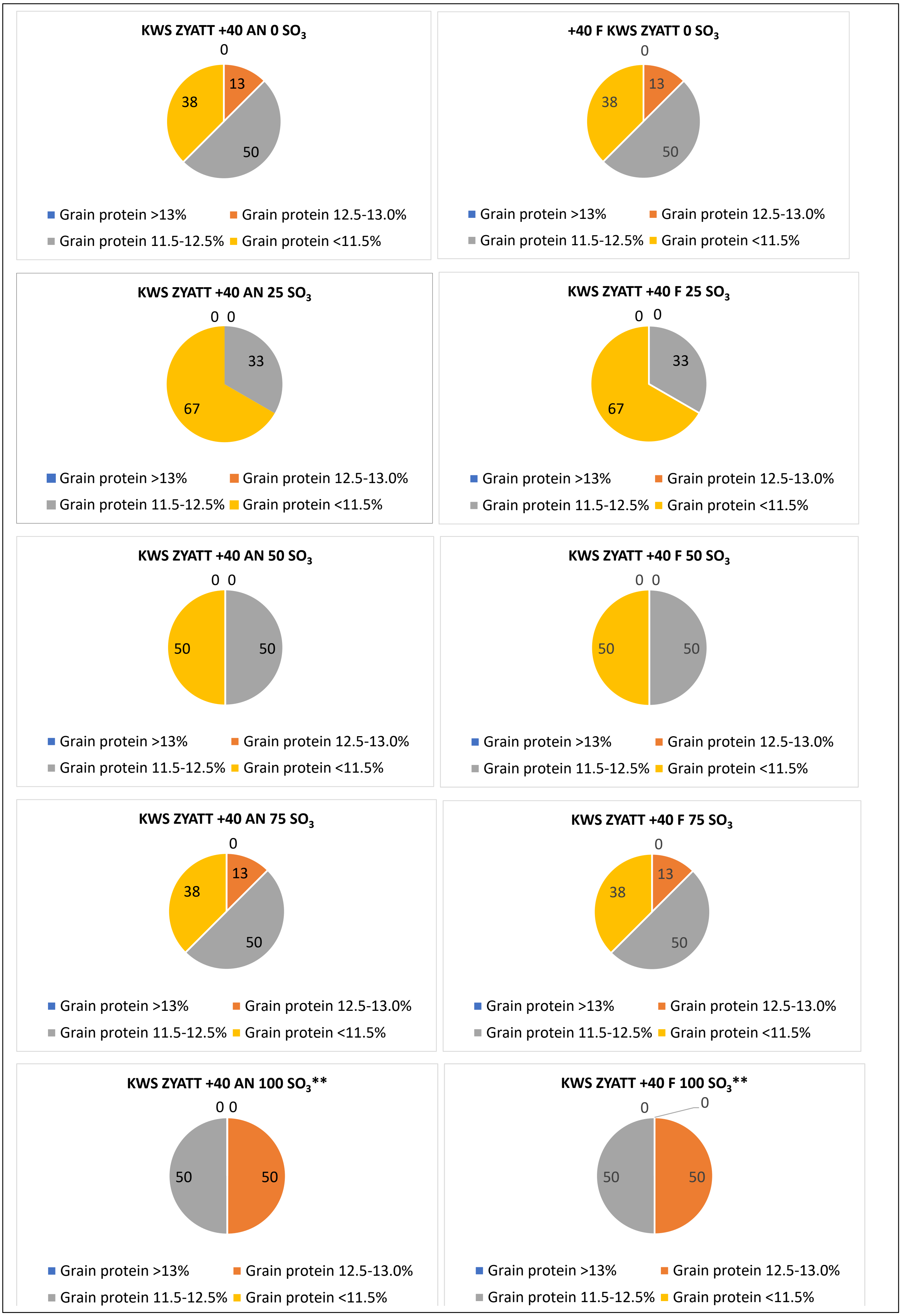

Figure 4.18: Percentage of samples for KWS Zyatt attaining grain protein within specified categories for each sulphur treatment. **denotes limited site data.

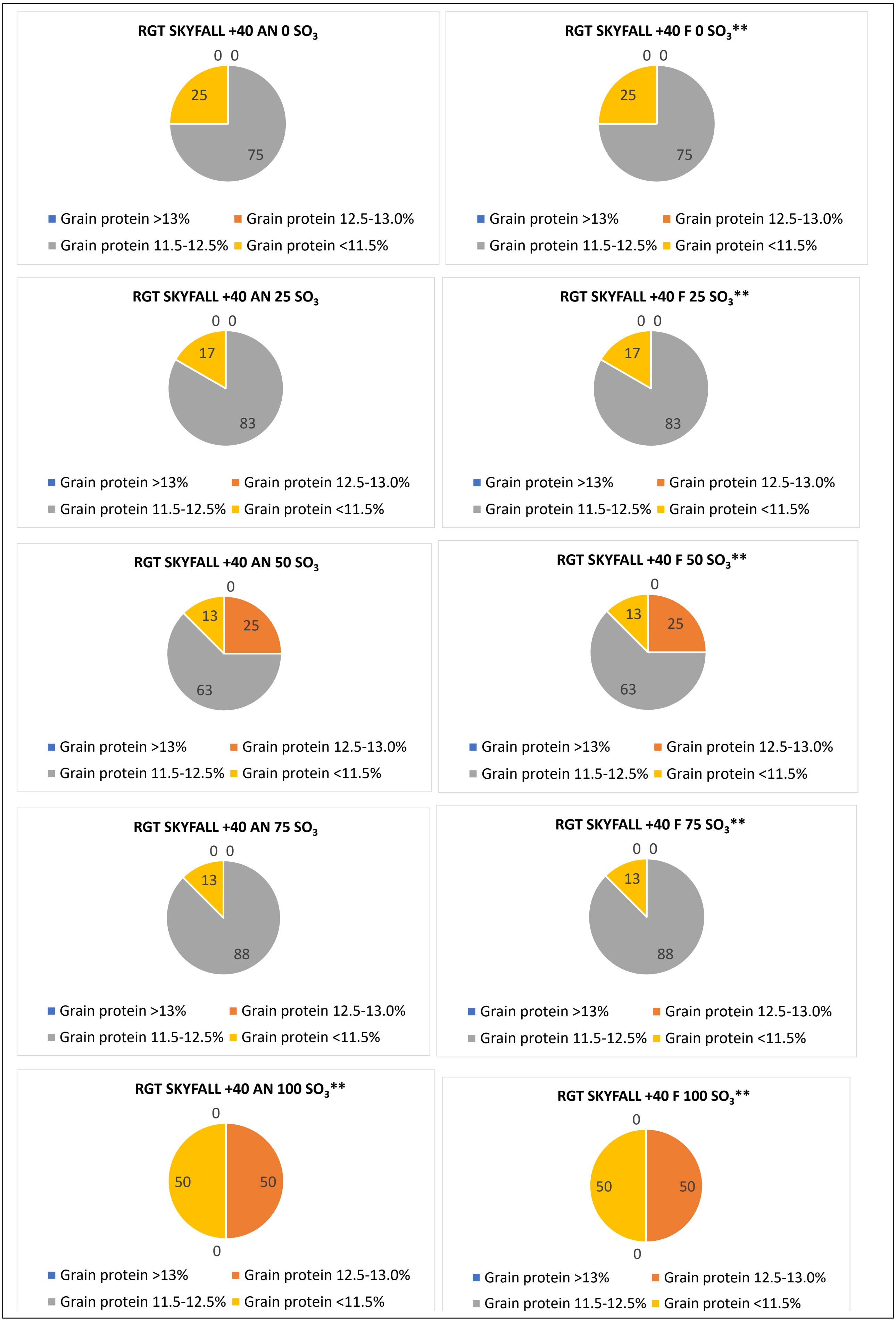

Figure 4.19: Percentage of samples for RGT Skyfall attaining grain protein within specified categories for each sulphur treatment. **denotes limited site data.

Grain specific weight

Across the seven experiments (no data was available at the East Lothian site in 2019) there was no consistent effect of S rate and timing on specific weight (P=1.0). However, there were significant differences between varieties (P=0.045) but not a significant interaction between S rate and timing and variety (P=1.0) (Table 4.15 and Appendix 2). The mean specific weight for S rate and timing ranged from 75.9 kg/hl to 77.3 kg/hl (LSD=3.57). Varietal differences between KWS Zyatt and RGT Skyfall were small with the mean specific weights of 76.3 kg/hl and 76.9 (LSD=0.61), respectively.

Between sites and seasons, greater differences in specific weight were seen (Figure 4.20). Across the seven sites, KWS Zyatt resulted in specific weights below the UKFM specification (76.0 kg/hl) at three of the seven sites; RGT Skyfall was below specification at two out of the seven sites. The lowest specific weights in the trial series were at the Lincolnshire site in 2019 and East Lothian in 2020, with specific weights in the range of 74.1 to 75.2 kg/hl. In contrast, the highest specific weights were at the Essex site in 2019, with specific weights in the range of 79.5.7 to 79.8 kg/hl.

Table 4.15: Seven site mean specific weight (kg/hl) in response to S rate and timing.

	Specific Weight (kg/hl)		
SO_3 rate	KWS Zyatt	RGT Skyfall	Mean
+40 AN 0 SO_3	76.4	77.0	76.7
+40 AN 25 SO_3	76.5	76.7	76.6
+40 AN 50 SO_3	76.3	76.8	76.5
+40 AN 50 SO_3 Split	76.1	76.8	76.5
+40 AN 75 SO_3	76.3	76.9	76.6
+40 AN 75 SO_3 Split	76.3	76.8	76.5
+40 AN 100 SO	75.9	77.3	76.6
+40 F 0 SO_3	76.6	77.0	76.8
+40 F 25 SO_3	76.4	76.8	76.6
+40 F 50 SO_3	76.3	76.9	76.6
+40 F 50 SO_3 Split	76.4	77.0	76.7
+40 F 75 SO_3	76.4	76.8	76.6
+40 F 75 SO_3 Split	76.4	77.0	76.7
+40 F 100 SO_3	76.1	77.0	76.5
LSD ($P=<0.05$)	3.57		2.52

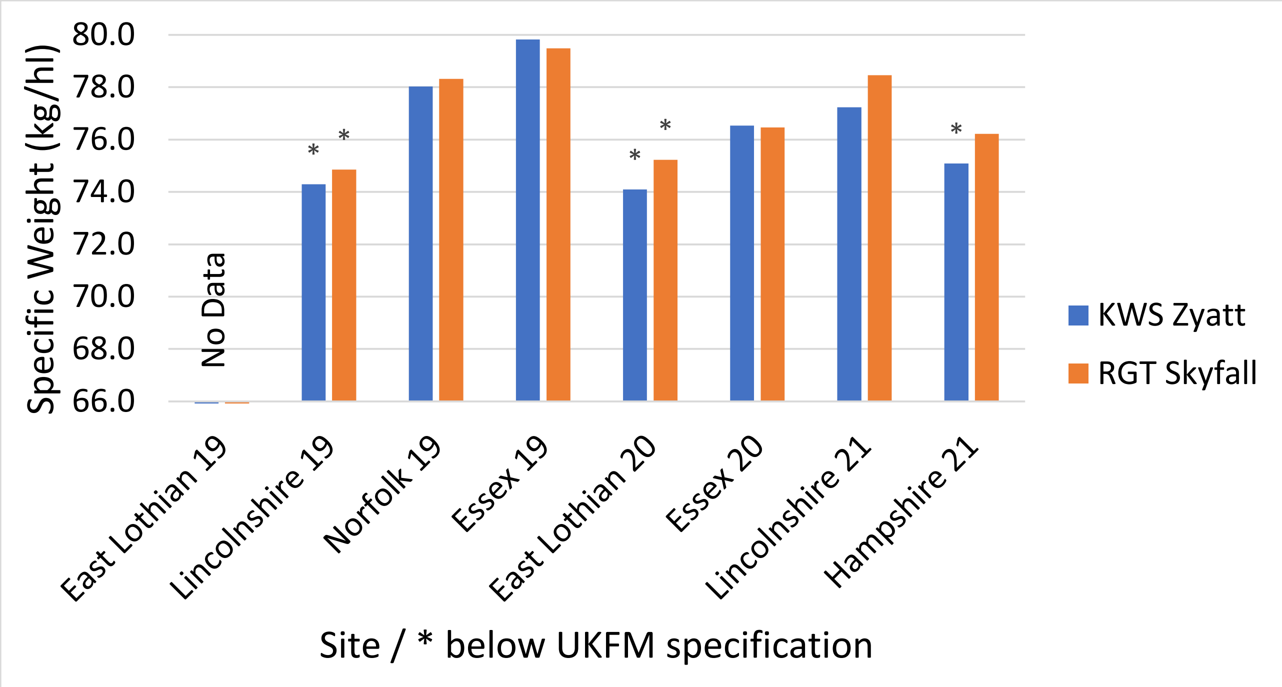

Figure 4.20: Specific weight (kg/hl) in response to Variety (Mean of S rate and timing). Where the mean values are significantly lower for that variety and the respective crop year, then a * has been placed above the corresponding bar in the graph.

Hagberg Falling Number

The Hagberg Falling Number (HFN, s) were measured in each experiment. The impact on HFN of sulphur rate and timing had no significant (P=1.0) affect and neither did variety (P=0.418) (Table 4.16). Across the eight sites HFN averaged 260 for KWS Zyatt (range 238-275 and 271 for RGT Skyfall (range 229-288). The main impact on HFN was the site and season (Figure 4.21). The site with the lowest HFN was East Lothian, averaging 165 and 113 in 2019 and 2020 seasons, respectively. Other sites specifically with low HFN were Lincolnshire in 2019 (all varieties) and Hampshire in 2021 (RGT Skyfall only). Where HFN was under 250 seconds (UKFM specification) the samples were not test baked as they were deemed unsuitable.

Table 4.16: Eight site mean HFN (s) in response to S rate and timing.

	Hagberg Falling Number (s)		
SO_3 rate	KWS Zyatt	RGT Skyfall	Mean
+40 AN 0 SO_3	242	275	259
+40 AN 25 SO_3	252	283	267
+40 AN 50 SO_3	258	280	269
+40 AN 50 SO_3 Split	275	285	280
+40 AN 75 SO_3	263	271	267
+40 AN 75 SO_3 Split	265	276	271
+40 AN 100 SO	253	270	262
+40 F 0 SO_3	260	288	274
+40 F 25 SO_3	238	269	254
+40 F 50 SO_3	272	272	272
+40 F 50 SO_3 Split	264	266	265
+40 F 75 SO_3	261	270	265
+40 F 75 SO_3 Split	274	253	264
+40 F 100 SO_3	269	229	249
LSD (P=<0.05)	203		143

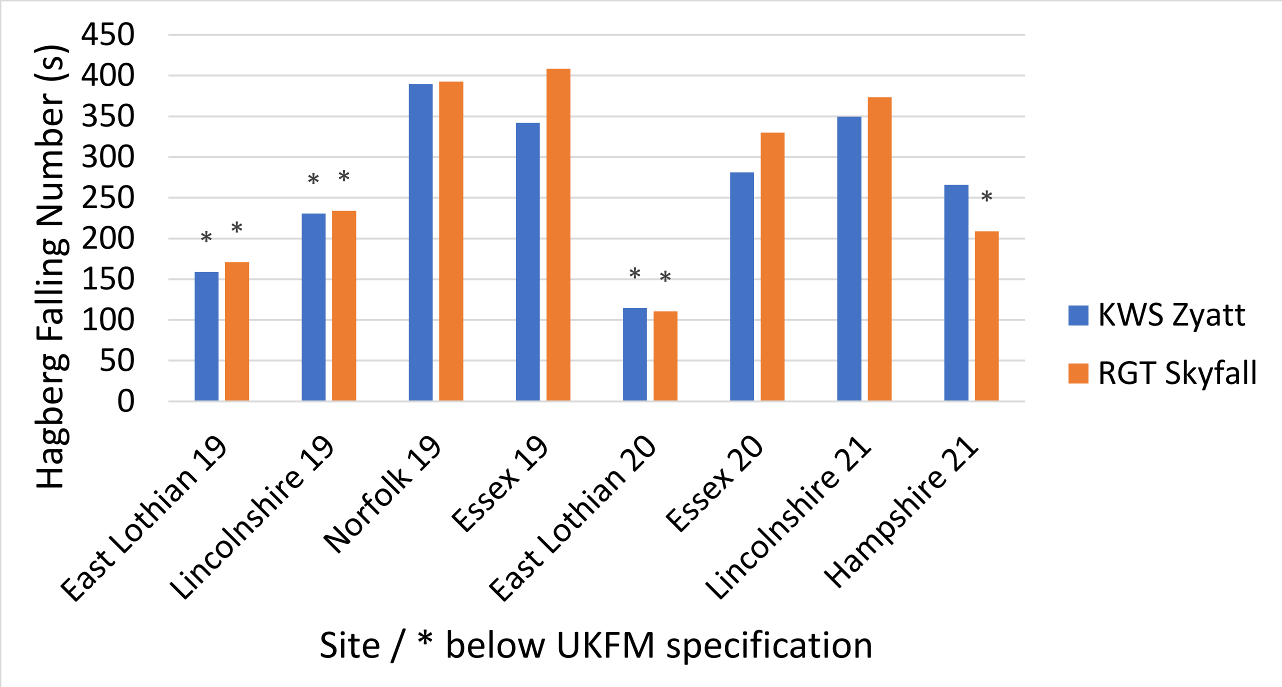

Figure 4.21: HFN (s) in response to Variety (Mean of S rate and timing). Where the mean values are significantly lower for that variety and the respective crop year, then a * has been placed above the corresponding bar in the graph.

Grain asparagine

Asparagine concentration was tested across all treatments and sites to evaluate the impact of sulphur fertilisation on asparagine formation in the grain. Across eight experimental sites, there was a significant difference in asparagine concentration (P=<.001) (Figure 4.22). The highest asparagine concentrations were at the Norfolk site in 2019, mean concentrations were 4.12 mmol/kg for KWS Zyatt and 3.79 mmol.kg for RGT Skyfall. Other sites with mean concentrations above 3.00 mmol/kg were Essex in 2019 and East Lothian in 2020. The site with the lowest mean concentrations was Lincolnshire in 2021. At the Lincolnshire 2021 site asparagine concentrations were 1.36 mmol/kg and 1.39 mmol/kg for KWS Zyatt and RGT Skyfall, respectively. There was little difference in asparagine concentrations between the two varieties across the sites (P=0.245).

When looking at the sulphur rates and timings across the two varieties, there was no clear response to higher sulphur rates reducing the asparagine concentration in the grain (P=0.972) (Figure 4.23). There was also no significant difference in the interaction between sulphur rates and variety (P=0.995) although KWS Zyatt tended to show a reduction in asparagine concentrations and RGT Skyfall tended to show a variable although increasing asparagine concentration when sulphur rates were applied. Overall, there was no clear trend that asparagine concentrations were significantly reduced by sulphur fertiliser applications.

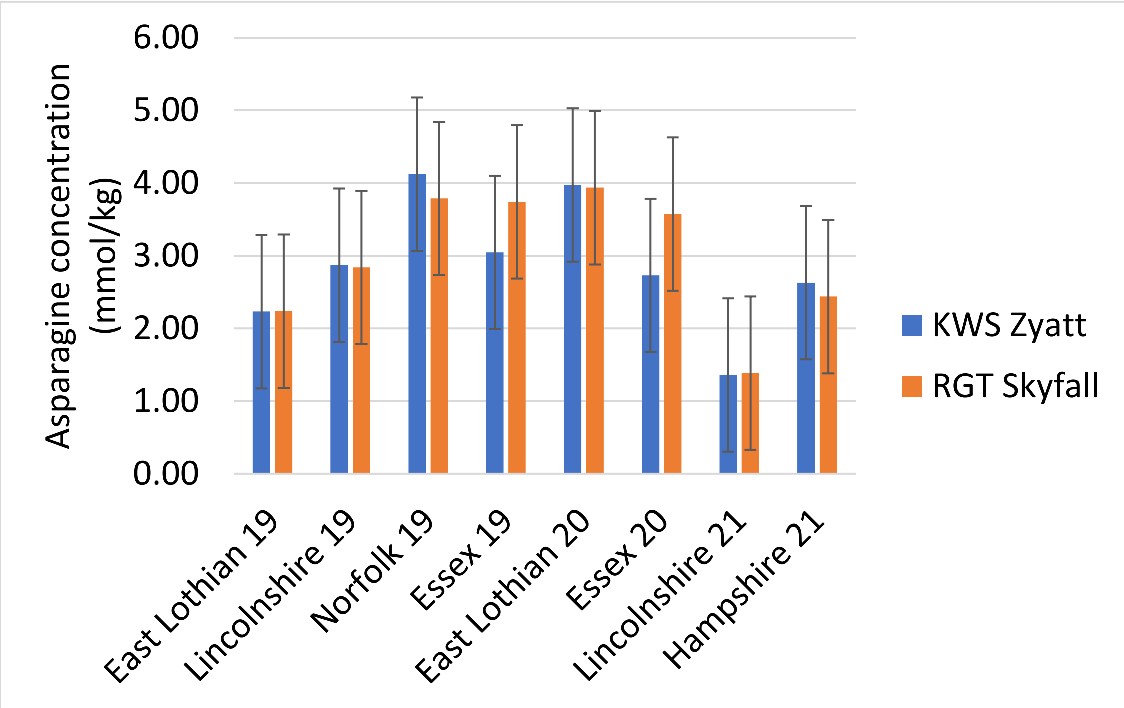

Figure 4.22: Asparagine concentration in response to Variety (Mean of S rate and timing). Error bars are least significant difference (P=0.05).

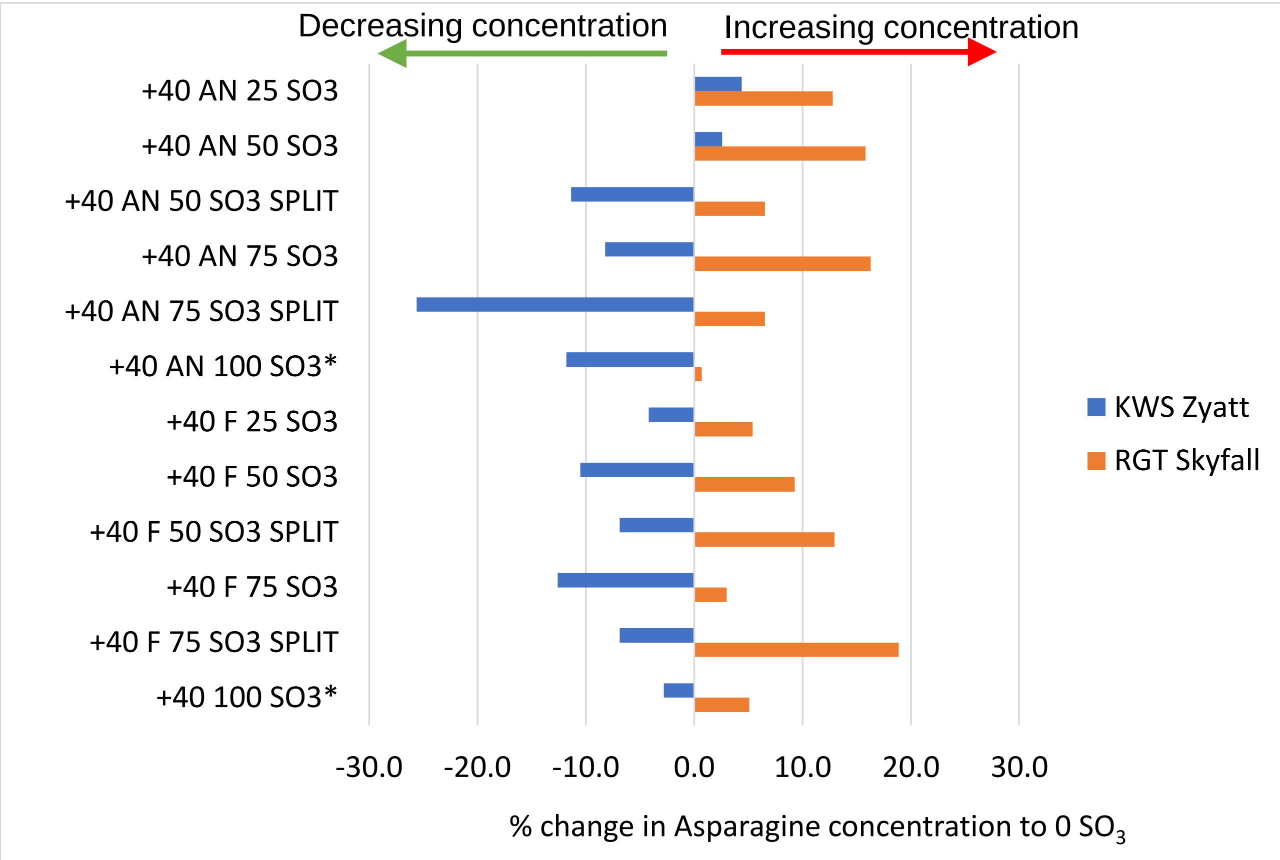

Figure 4.23: Percentage change in Asparagine concentration over 0 kg/ha SO_3. *denotes limited site data.

4.4. Objective 4. THE RELATIONSHIP BETWEEN N FERTILISER REQUIREMENT AND RHEOLOGY AND BAKING

Rheology and baking – ATC pilot milling survey

The three crop years of these trials have been challenging from an agronomic aspect and below is an overview of the commercial UK wheat crop seen from a millers' perspective (M Charlton, personal communication, 25th February, 2022).

2019

Harvesting was more protracted this season due to the rains that started 27th July and continued for some weeks, affecting more so the Midlands and Northern parts of the UK. Nationally, the moisture content of the Group 1 grain was 1.6% up on 2018 season with regional differences and grain drying required for safe storage. Protein contents were close to 2018 season as were specific weights for the four wheat groups.

From the ATC pilot milling survey, grain hardness levels were lower than seen in 2018. This had an impact on the flour water absorptions which were close to 1% lower than for 2018 season and at least 3% lower than what would be expected for hard breadmaking wheats in the UK.

Gluten strength was less than 2018 season as well as being variable resulting in some issues with weaknesses seen in the breadcrumb and loaf volumes reduced by 4.5% compared to 2018 season. It should be noted that 2018 season was an exceptional year for gluten strength.

2020

UK crop size was significantly less due to poor weather conditions for planting in the autumn of 2019, combined with some farmers reporting lower yields. The crop was estimated at 9.5mt, close to 5mt lower than normal.

Grain moisture content was the second lowest season since 2002. Grain size was small and combined with the lower moisture, specific weights were high. In the north, some wheat had higher moistures, lower specific weights and lower HFN's. Protein content was lower than 2019, but gluten quality good and like the 2019 crop. Baking quality was like the 2019 crop, but due to the smaller harvest, UK millers had to supplement their grists with imported wheat.

2021

UK crop size was significantly up on the 2020 season and back to a normal harvest year estimated at between 14.6 to 14.9mt. Harvest was protracted due to rain and most wheat had to be dried for safe storage. Protein contents were slightly lower than in 2020 with generally good gluten functionality. Grain size was smaller with increased screenings and much lower specific weights than 2020 crop. This impacted on the flour extraction rate and flour colour. Flour water absorption levels were variable and just slightly lower than 2020. Baking quality was generally good and like 2020 season.

Figure 4.24 shows the key parameters relevant to the wheat rheology and baking. The data used for these graphs was from the ATC Commercial Wheat Crop Surveys for the three crop years of this AHDB project and the three wheat varieties grown in trials.

Flour proteins are typically quoted at 'as is' moisture, but for easy comparison, with the grain protein graphs, the flour proteins have been presented at dry matter. To convert grain nitrogen to percentage protein, the values were multiplied by 5.7 (Nx5.7). In general, the Group 1 varieties, KWS Zyatt and RGT Skyfall, had higher wheat and flour proteins than Group 2 variety KWS Siskin. Of the three varieties Skyfall generally has the most resistant gluten and KWS Siskin has the weakest. Bread scores varied across seasons for each variety with the range for KWS Zyatt between 4-7; Skyfall between 5-6.5 and KWS Siskin 4-5.

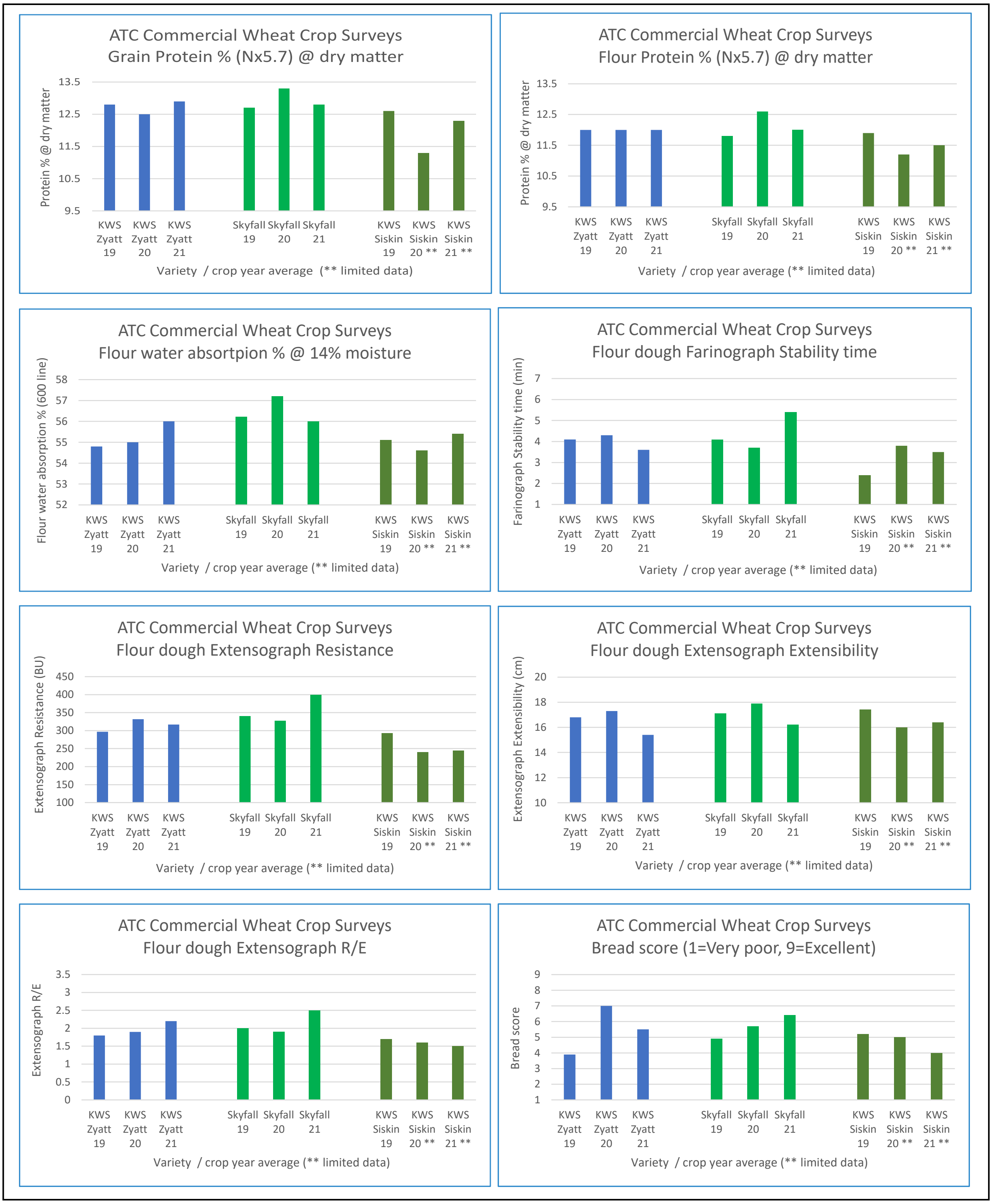

Figure 4.24: Key parameters relevant to the wheat rheology and baking. The data used for these graphs was from the ATC Commercial Wheat Crop Surveys for the 2019, 2020 and 2021 crop years.

Rheology and baking – Experimental sites

The number of experimental sites where grain samples were analysed for the rheology and baking tests are summarised in Table 4.17. This was based on the results from post harvest analysis for grain protein specific weight and HFN. In 2020, the weather conditions resulted in fewer samples attaining the UKFM specifications. Full rheology and baking datasets can be found in Appendix 3. A further dataset on additional variety and nitrogen rate and timing samples was provided by Agrii and a summary can be found in Appendix 4.

Table 4.17: Summary of samples analysed over the three crop seasons between 2019 and 2021.

Crop year	2019		2020		2021	
Varieties	No. of sites for rheology	No. of sites baked	No. of sites for rheology	No. of sites baked	No. of sites for rheology	No. of sites baked
Nitrogen rate and timing trials						
KWS Zyatt	2	2	0	0	3	2
KWS Siskin	2	2	0	0	3	2
RGT Skyfall	2	2	1	1	3	2
Sulphur rate and timing trials						
KWS Zyatt	2	2	0	0	2	2
RGT Skyfall	2	2	0	0	2	2

4.5. The effect of nitrogen fertiliser rate and timing

Grain and flour protein

It is more relevant to compare the rheology and baking performance with flour proteins, particularly at sites where low specific weights are a key feature of the crop. The protein contents (both grain and flour protein) were determined by ATC on the cleaned grain samples using a Carter-Dockage Tester prior to analysis and milling. Grain protein contents determined by ATC on the cleaned grain samples varied slightly from the post-harvest initial samplings carried out, as described previously in Section 4.2. For ease of comparison, the cleaned grain and flour proteins have been presented at dry matter.

Table 4.18 presents the mean cleaned grain and flour protein by N treatment and variety and with the percentage difference to 'RB209'). Typical protein losses during the test milling were around 1.0% for each variety. Grain proteins were significantly increased at the higher N rates (P=<0.001) and ranged from 11.4 % to 12.5 % for KWS Zyatt; 11.1 % to 12.8 % for KWS Siskin and 11.6 % to 13.0 % for RGT Skyfall. Once milled, flour proteins were significantly increased at the higher N rates

(P=<0.001) and ranged from 10.4 % to 11.6 % for KWS Zyatt; 10.2 % to 11.8 % for KWS Siskin and 10.5 to 11.9 % for RGT Skyfall.

The addition of +40 kg N/ha increased grain proteins by 0.4 % to 0.9 %. There was a small, but not significant increase, in flour protein when N was applied as Foliar N compared to AN. Greater response to Foliar N was seen in KWS Siskin and RGT Skyfall with a less marked effect in KWS Zyatt. Flour proteins peaked at between 1.2 % and 1.6 % above 'RB209' treatment when an additional 120 kg N/ha was applied. Differences between grain protein and flour protein varied between site and season (Figure 4.25). For example, in 2019, the flour protein at the Morley site ranged from 11.0 % to 12.3 % (+1.3%) compared to the Essex site the ranged from 9.8 % to 12.4 % (+2.6%).

Table 4.18: Cross site mean cleaned grain and flour protein and response to N rate and timing. Variety mean values from 5 sites except for that marked * where mean values from 6 sites.

N rate	Grain protein % @ dry matter			Difference in grain protein from 'RB209' treatment (%)			Flour protein % @ dry matter			Difference in flour protein from 'RB209' treatment (%)		
	KWS ZYATT	KWS SISKIN	RGT SKYFALL*	KWS ZYATT	KWS SISKIN	RGT SKYFALL*	KWS ZYATT	KWS SISKIN	RGT SKYFALL*	KWS ZYATT	KWS SISKIN	RGT SKYFALL*
‘RB209’	11.4	11.1	11.6	-	-	-	10.4	10.2	10.5	-	-	-
+40 AN at GS 32-35	12.0	11.6	12.0	0.5	0.5	0.4	10.9	10.7	11.0	0.5	0.5	0.4
+40 AN at GS 37-39	11.8	11.7	12.1	0.4	0.6	0.5	10.9	10.7	10.9	0.5	0.4	0.4
+40 F at GS 73	12.0	12.0	12.3	0.6	0.9	0.7	11.0	11.2	11.2	0.6	0.9	0.7
+80 AN at GS 37-39	12.0	11.9	12.3	0.6	0.9	0.7	11.2	11.1	11.2	0.8	0.9	0.7
+80 F at GS 73	12.5	12.7	12.8	1.1	1.6	1.1	11.5	11.7	11.8	1.1	1.5	1.3
+120 F at GS 73	12.5	12.8	13.0	1.1	1.7	1.4	11.6	11.8	11.9	1.2	1.6	1.3
LSD (P=<0.05)		0.59			-			0.60			-	

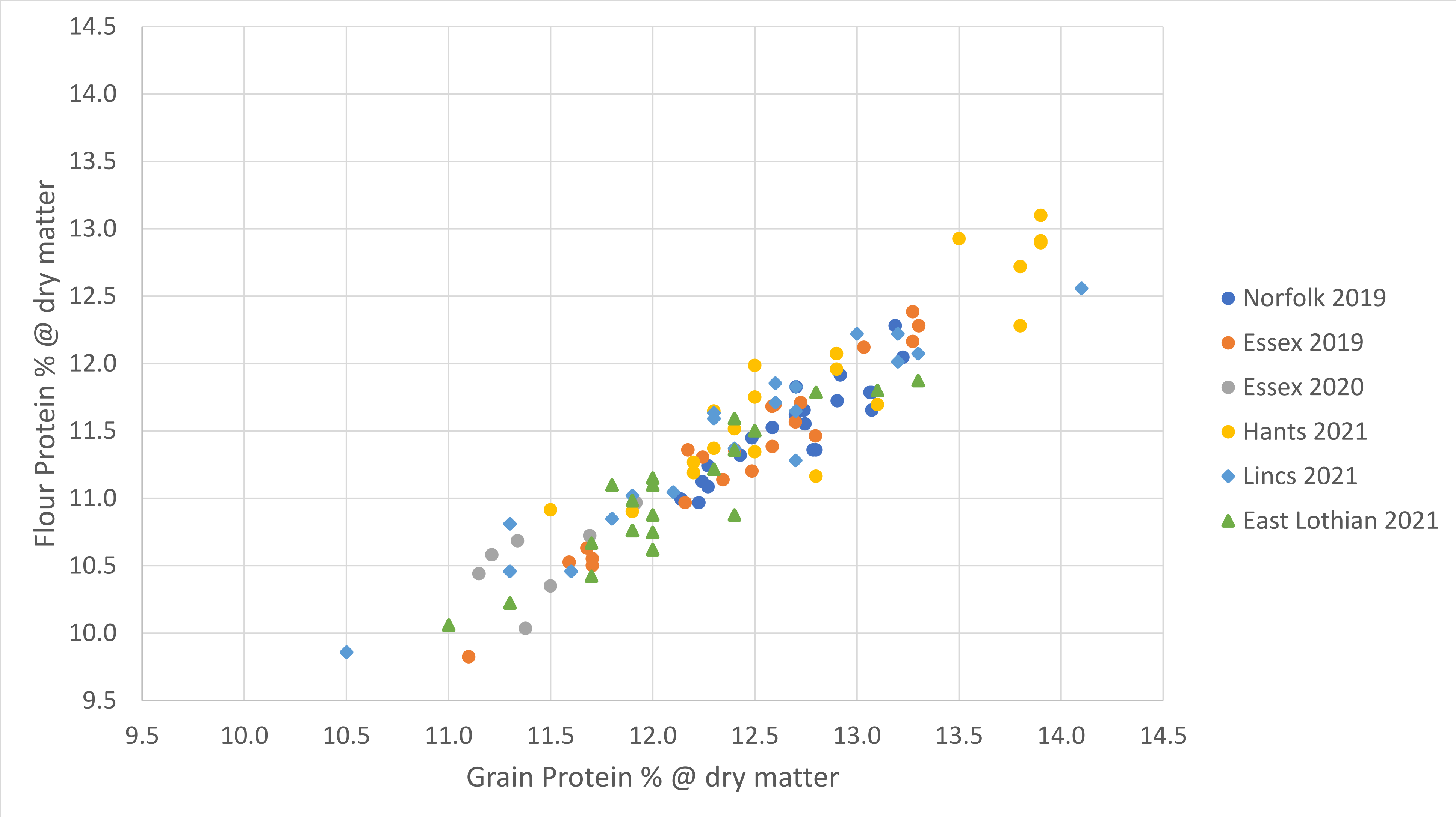

Figure 4.25: Grain protein plotted against flour protein; average values for each variety/treatment combination for all sites.

Flour extraction rate

In 2021, samples from the Essex site were tested post-harvest and the specific weights ranged from 68.8 to 73.7 kg/hl with a site mean of 71.3 kg/hl. These values were exceptionally low and were considered unsuitable for pilot milling and baking. The grain protein contents were high (14.2-14.4% @ dm) due to the low specific weights and these high protein values were more associated with the bran.

ATC made a composite sample for each variety and pilot milled them to demonstrate the impact on flour extraction and protein loss through milling. The data in Table 4.19 shows that with low specific weight, there is a reduction in flour extraction and increase in the protein loss in milling. Whilst the flour extraction rate at the Essex site in 2021 was similar (-0.1%) to that of East Lothian, in 2021, the protein percentage loss on milling was increased from 1.1 % to 1.9 % at DM. This unacceptably high protein loss on milling confirms that the grain protein was largely associated with the bran.

Table 4.19: Composite samples pilot milled to demonstrate the impact on flour extraction and protein loss through milling.

Mean site values from cleaned grain	Specific weight kg/hl (at as is moisture)	Flour extraction rate %	Protein % loss on milling @ dm
Lincolnshire, 2021	78.3	80.3	1.0
Hampshire, 2021	76.5	79.9	1.0
East Lothian, 2021	74.7	78.4	1.1
Essex, 2021	73.0	78.3	1.9

Key parameters for both rheology and test baking are presented in Figure 4.26 to report on the effect of N rate and timing (presented as the variety means from the individual trials across the three seasons). There were differences between sites and seasons and in some cases with larger differences between the two Group 1 varieties, KWS Zyatt and RGT Skyfall. For example, R/E for KWS Zyatt and RGT Skyfall ranged from 1.7 to 2.1, if the R/E values considered atypical for the crop year were discounted. KWS Siskin R/E values ranged from 1.4-1.9. Bread scores for RGT Skyfall tended to reflect the higher R/E values with a mean bread score across sites of between 4.9 and 7.0, KWS Zyatt tended to have similar bread scores whilst KWS Siskin had slightly lower scores ranging from 2.9 to 5.7.

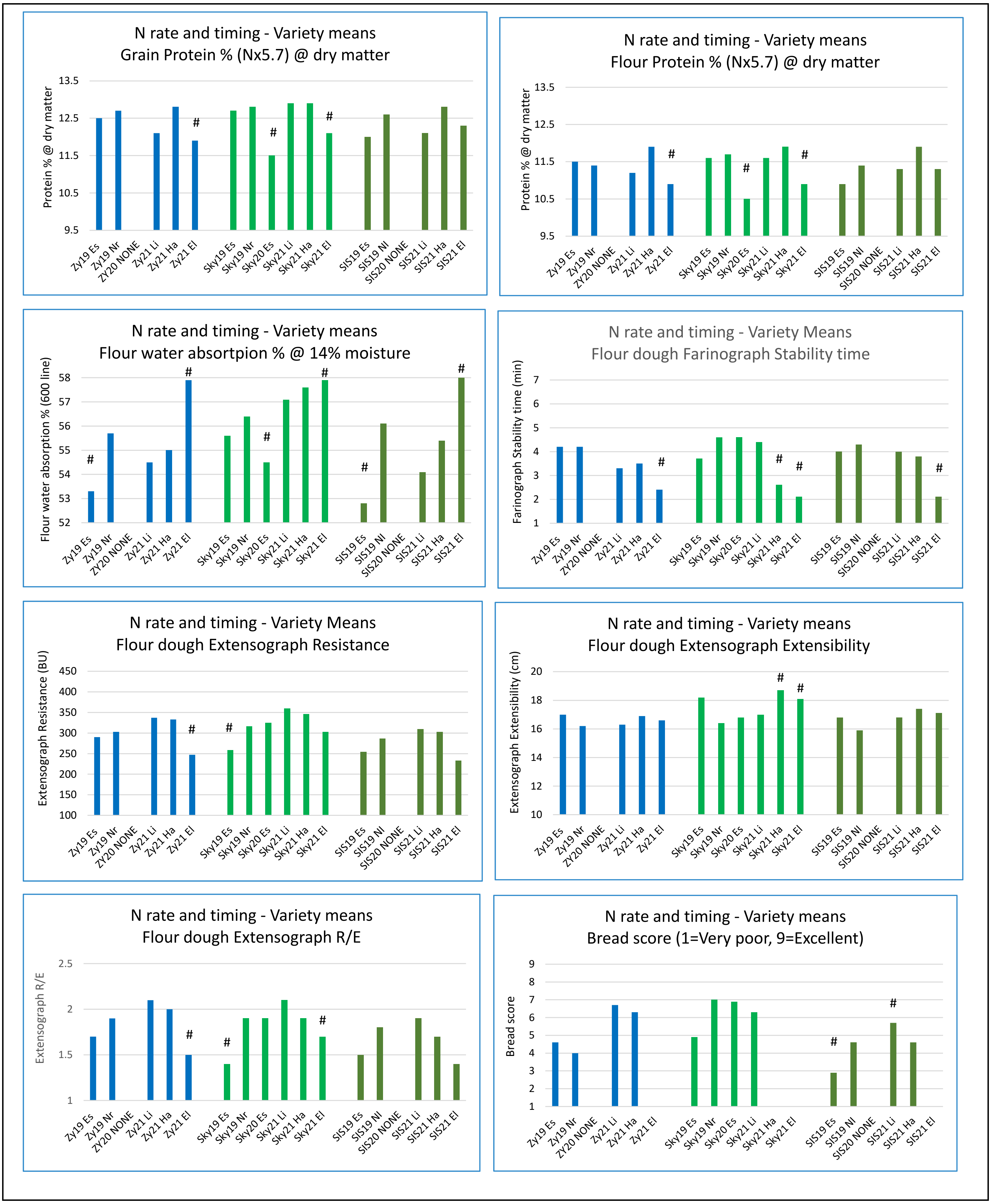

Figure 4.26: Key parameters relevant to the wheat rheology and baking for the nitrogen rate and timing. The data are presented as the mean values for each variety from the individual experiments across the three seasons. Data presented for KWS Siskin and KWS Zyatt are for 2019 and 2021. Where the mean values are significantly different for that variety and the respective crop year, then a # has been placed above the corresponding bar in the graphs.

The same rheology and baking parameters are presented in Figure 4.27 to report on the effect of N rate and timing (presented as the treatment means across the individual trials and the three seasons). KWS Siskin has shown more resistant gluten with applications of foliar urea at GS 73. Flour proteins were also higher where foliar urea had been applied compared to the comparative ammonium nitrate treatments. For example, the combined mean, across varieties, for flour protein with ammonium nitrate was 11.2 %, compared to 11.8 % with foliar urea. Higher water absorption values are required for bread making with values above 55 %. RGT Skyfall tended to have higher water absorption % compared to KWS Zyatt or KWS Siskin, but all varieties showed a response to additional N applications over 'RB209'. The mean water absorption, across varieties, was 55.1 % and this rose to 55.6 % and 56.1 % where ammonium nitrate or foliar urea had been applied. For KWS Zyatt, like that of KWS Siskin identified that foliar urea led to more resistant gluten qualities and higher R/E values. RGT Skyfall is a strong gluten variety and therefore did not show the same level of increase in gluten strength where foliar urea was applied compared to the other varieties. R/E values for RGT Skyfall were also very similar across treatments, averaging 1.8.

Across the treatments where foliar urea was applied at GS 73 there was a trend for the gluten to have more strength compared to where ammonium nitrate was applied with additional N rates of 40 or 80 kg N/ha. Likewise, the additional 120 kg N/ha treatment where 40 kg N/ha had been applied as foliar urea also showed the same characteristics as the other foliar urea treatments. The combined means of N applied as ammonium nitrate or foliar urea for some of the rheology and baking characteristics are shown in Table 4.20. There was no detrimental impact on baking quality when foliar urea was applied compared to applications of ammonium nitrate.

Table 4.20: Summary of rheology and test baking parameters for ammonium nitrate and foliar urea treatments. Combined mean values are the mean of variety and site for ammonium nitrate and foliar urea treatments.

	Farinograph	Extensograph			Baking	
	Stability time (min)	Resistance (BU)	Extensibility (cm)	R/E	Loaf volume (cm^3)	Bread Score
Mean of ammonium nitrate fertiliser trials	3.5	282	16.8	1.7	3818	5.5
Mean of foliar urea fertiliser trials	3.9	320	17.4	1.8	3783	5.5

Figure 4.27: Key parameters relevant to the wheat rheology and baking for the nitrogen rate and timing. The data are presented as the treatment means from the individual trials across the three seasons. Data presented for KWS Siskin and KWS Zyatt are for 2019 and 2021 crop years; RGT Skyfall are for the 2019, 2020 and 2021 crop years.

4.6. The effect of nitrogen and sulphur fertiliser interaction

To further understand the rheology and baking qualities from the application of sulphur fertiliser a series of eight field experiments examined the interaction of nitrogen, applied as ammonium nitrate or foliar urea, with twelve sulphur rate ranging from 0 kg/ha SO_3 (control) to 100 kg/ha SO_3 applications. The field experiments examined two, Group 1 varieties, KWS Zyatt and RGT Skyfall to look at the impact of sulphur fertiliser application on rheology and baking quality.

Key parameters for both rheology and test baking are presented in Figure 4.28 to report on the effect of S rate and timing presented as the variety means combined for all treatments from the individual trials across the two seasons (no data was available from the 2020 crop season). There were differences between sites and seasons. In particular, at the Essex site in 2019, the RGT Skyfall samples were on average, of lower resistance with a more extensible gluten resulting in a low R/E and weakness in the bread scores and this has skewed the data set slightly compared to the KWS Zyatt samples.

The same rheology and baking parameters are presented in Figure 4.29 to report on the effect of S rate and timing (presented as the treatment means combined across the individual trials and the two seasons). There are small treatment differences in some of the key parameters, but it is difficult to establish a significant trend between treatments. Some specific parameters when comparing the mean of the trials for ammonium nitrate compared to those with foliar urea appears to show higher gluten strength with the urea treated samples akin to the nitrogen rate and timing findings. These are summarised in Table 4.21.

Table 4.21: Summary of rheology and test baking parameters for the interaction of sulphur with ammonium nitrate and foliar urea treatments. Combined mean values are the mean of variety and site for ammonium nitrate and foliar urea treatments.

	Farinograph	Extensograph			Baking	
	Stability time (min)	Resistance (BU)	Extensibility (cm)	R/E	Loaf volume (cm^3)	Bread Score
Mean of ammonium nitrate fertiliser trials	3.6	281	17.0	1.7	3638	5.6
Mean of foliar urea fertiliser trials	3.9	313	17.2	1.8	3668	5.8

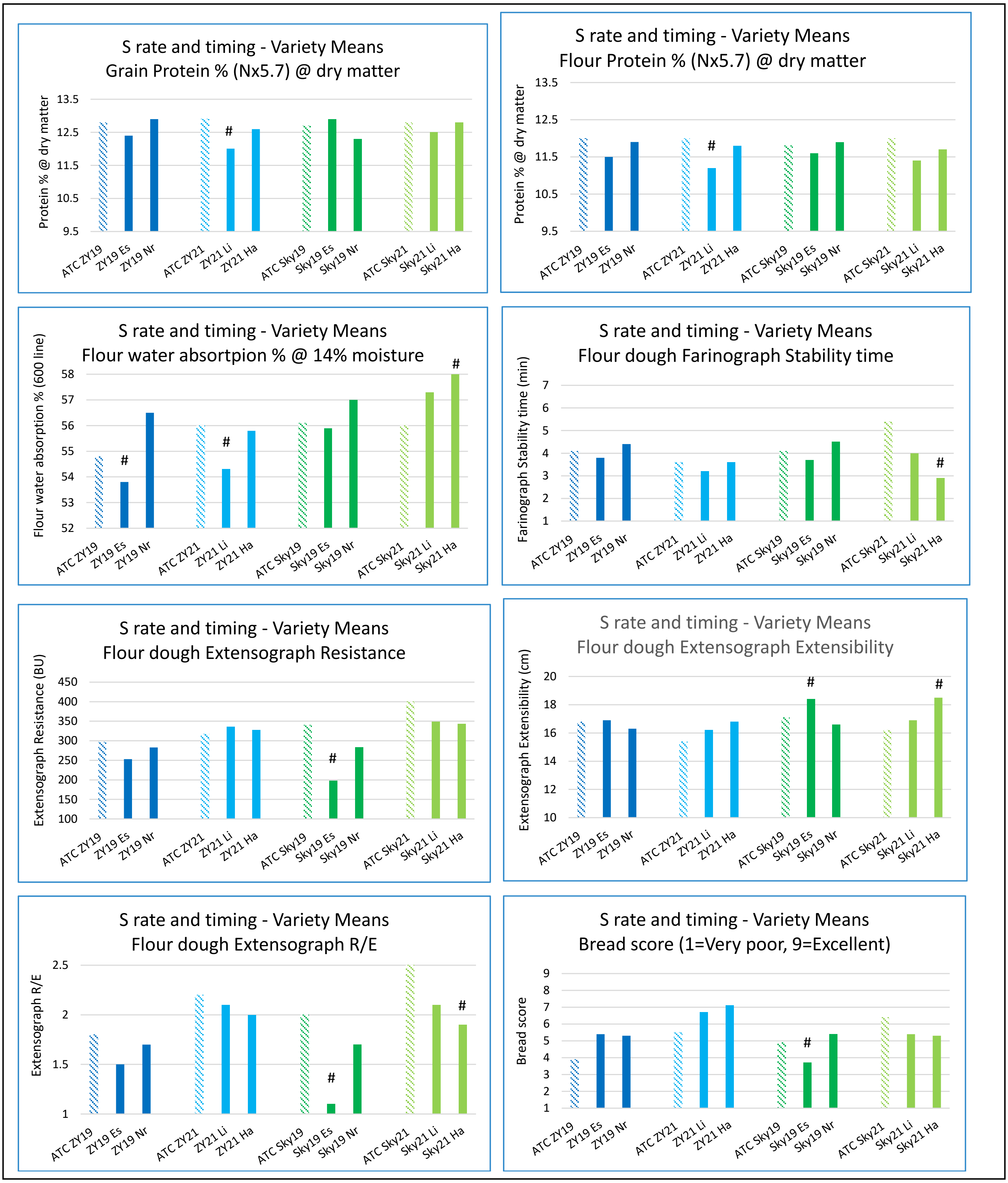

Figure 4.28: Key parameters relevant to the wheat rheology and baking for the sulphur rate and timing. The data are presented as the mean values for each variety from the individual experiments across the three seasons. Data presented for KWS Zyatt and RGT Skyfall are for 2019 and 2021. The cross-hatched bars are data from the ATC commercial crop. Where the mean values are significantly different for that variety and the respective crop year, then a # has been placed above the corresponding bar in the graphs.

Figure 4.29: Key parameters relevant to the wheat rheology and baking for the sulphur rate and timing. The data presented as the treatment means from the individual trials across the three seasons. Data presented for KWS Zyatt and RGT Skyfall are for 2019 and 2021.

5. Objectives 5 & 6: IMPLICATIONS FOR N & S FERTILISER RECOMMENDATIONS

This chapter considers how evidence from the new experiments carried out between 2019 and 2021 (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 N rate, ii) N timing and iii) suitable S rate and timing needed to achieve target grain protein and other grain quality parameters together with rheology and baking test parameters for milling wheat.

5.1. Economic considerations for N fertilisation based on current market prices

In AHDB Research Review 97, Berry *et al.* (2022) provided recommendations, based on evidence review, to support farmers in responding to expensive fertiliser nitrogen prices. Because most yield response curves have the same shape in the region of their optima, the effect of fertiliser (and grain) prices on recommendations is independent of the expected yield (and soil N supply, soil type). For example, increasing the break-even ratio from 5 to 10 results in a reduction of the economic optimum N fertiliser rate of about 50 kg N/ha and an accompanying reduction in yield of about 0.3 to 0.5 t/ha (Berry *et al.* 2022). Berry *et al*. (2022) showed that a reduction of 50 kg N/ha applied to milling wheats reduced the protein concentration on average by 1%. If the grower applied the additional 'RB209'-recommended 40 kg N/ha to achieve milling specification, then this would be likely to redress the loss but not deliver a protein content of 13% overall. Berry *et al*. (2022) concluded that in many cases it will still be economically justified to target milling quality, particularly if premiums are £30/t or more. However, if the decision is marginal on farms, for example, where proteins are not achieved consistently over seasons, or where there is a risk of low HFN or specific weight, then the recent fertiliser price increases may now move the risk/benefit balance to a point where targeting milling quality cannot be justified.

Sylvester-Bradley and Smith (2022) carried out a further detailed review of the use of late applied N for milling wheat. They concluded that if the BER was 10, and fertiliser rates were therefore reduced by 50 kg N /ha to the new economic optimum for yield, then a further 120 kg N/ha would need to be applied to meet the milling specification of 13% protein. As reported by Dampney *et al*. (2006), the same uplift in protein can be achieved with foliar urea, but there are large differences between sites in the protein level achieved with yield optimum applications. Hence extra N raised grain protein from below to above 13% in only three cases by applying 40 kg/ha extra N and in five cases by applying 120 kg/ha extra N. Sylvester-Bradley and Smith (2022) show that over much of the range over which grain protein varies, application of extra late N reduces profit because it does not affect sale price e.g. adding late N but increasing protein to only 12%. They also showed from analysis of YEN data that most farms are able to predict their grain protein levels and manage these through variety choice and N management. Sylvester-Bradley and Smith (2022) conclude that even with expensive fertiliser N it is still usually better to fertilise milling varieties to achieve 13% protein than to apply the new smaller optimum N rates for grain yield. However, they also highlight that the farms past success in meeting milling specification should be taken into account, if premiums have not been achieved consistently over seasons, or where there is a risk of low HFN or specific weight, then the recent fertiliser price increases may now have moved the risk/benefit balance to a point where targeting milling quality cannot be justified.

5.2. Nitrogen recommendations

Optimum N rate and timing

The current ‘RB209’ recommendations state that typically, application of an extra 40 kg N/ha could increase grain protein by up to 1%. Application of soil-applied additional nitrogen during stem extension may give a small yield increase, as well as an increase in grain protein. Application as a foliar urea spray during the milky ripe stage will result in a larger increase in grain protein content but cannot be expected to increase yield.

From the current experiments the additional N (rates applied of 40, 80 or 120 kg N/ha) above that required for yield, across ten experiments does not have a significant affect on yield. This is in line with the current recommendations where the ‘RB209’ N rate for maximum yield was correctly assessed. The cross-site analysis shows a 0.25 t/ha grain yield increase on average from applying 80 kg/ha of additional N applied as AN. Where the additional 80 kg/ha was split, applied as half AN and half as foliar urea, no yield response was seen across the ten experiments. There were minimal differences in yield in response to the other four N timing treatments, all of which had at least 40 kg N/ha applied. The results highlight that additional N (above that required for yield) applied after GS 32-35 has minimal impact on yield. Across the experiments, grain protein was increased on average as a result of additional N applications. On average, an additional 40 kg N/ha increased grain protein by 0.5 %, an additional 80 kg N/ha increased grain protein by 1.0 % and an additional 120 kg N/ha increased grain protein by 1.3 %.

The experiments had a range of drilling dates, from late September through to mid November and there was some evidence to suggest that late drilling date had an effect on the yield potential. This was evident particularly at the Essex site in 2020 and 2021, where due to the wet autumn delaying planting until late October / early November, low yields of around 7.0 t/ha were achieved; expected yields for this site are typically around 10.0 t/ha. However, drilling date did not clearly affect the response to specific N rate or timing treatments. Weather patterns have a significant impact on grain protein accumulation. In three experiments (Norfolk 2019, Essex 2020 and Essex 2021) dry springs would have compromised uptake of at least one N timing treatment. This rainfall pattern at least partially explains why grain protein did not respond as consistently to additional N at these three experiments. In particular, the Essex site in 2020 recorded only 47% of the 1991-2020 average rainfall during the months March through to May, this resulted in lower than expected grain protein of around 10.5 % in the ‘RB209’ treatment. A different example of dry spring conditions affecting grain protein accumulation was seen at the Essex site in 2021. In that case, grain protein in the ‘RB209’ treatment were high, averaging 13.3 %, due to the low specific weight achieved and the protein values were more associated with the bran. Higher than average rainfall in August, at Lincolnshire in 2019 and at East Lothian in all three years also had a detrimental impact on the Hagberg Falling Number which limited the number of samples being selected for rheology and baking testing.

Managing additional applied N to achieving 13 % grain protein

In summary, Figure 5.1a shows that small increases in grain yield are caused by applying extra AN at GS 39 (particularly for the more responsive Group 1 varieties (KWS Zyatt and RGT Skyfall)) but no yield increase was found where more extra N is applied as foliar urea; in fact in some instances applications of foliar urea can cause slight yield reductions. All treatments applying extra N increased grain protein (Figure 5.1b) and the responses are slightly greater with RGT Skyfall than with KWS Zyatt or KWS Siskin. Protein responses to AN continued at rates greater than 40 kg N/ha. However, protein responses to extra N applied as foliar urea were equal to or greater than the equivalent rate of AN. In these experiments, grain protein approached or achieved 13% protein only at rates of 120 kg N/ha of extra N, thus confirming the difficulty for farms to consistently achieve 13 % protein in milling wheats.

There was strong evidence that key milling parameters analysed through rheology and baking were significantly affected by N rate or timing. The different varieties (KWS Zyatt, KWS Siskin and RGT Skyfall) did not respond significantly differently to the N rate and timing treatments. Overall, it was difficult to pick out specific N rate and timing treatment differences between varieties. When all treatments where N was applied as ammonium nitrate were compared with those using foliar urea, the combined means confirmed that there was no detrimental impact on baking quality when foliar urea was applied compared with applications of ammonium nitrate.

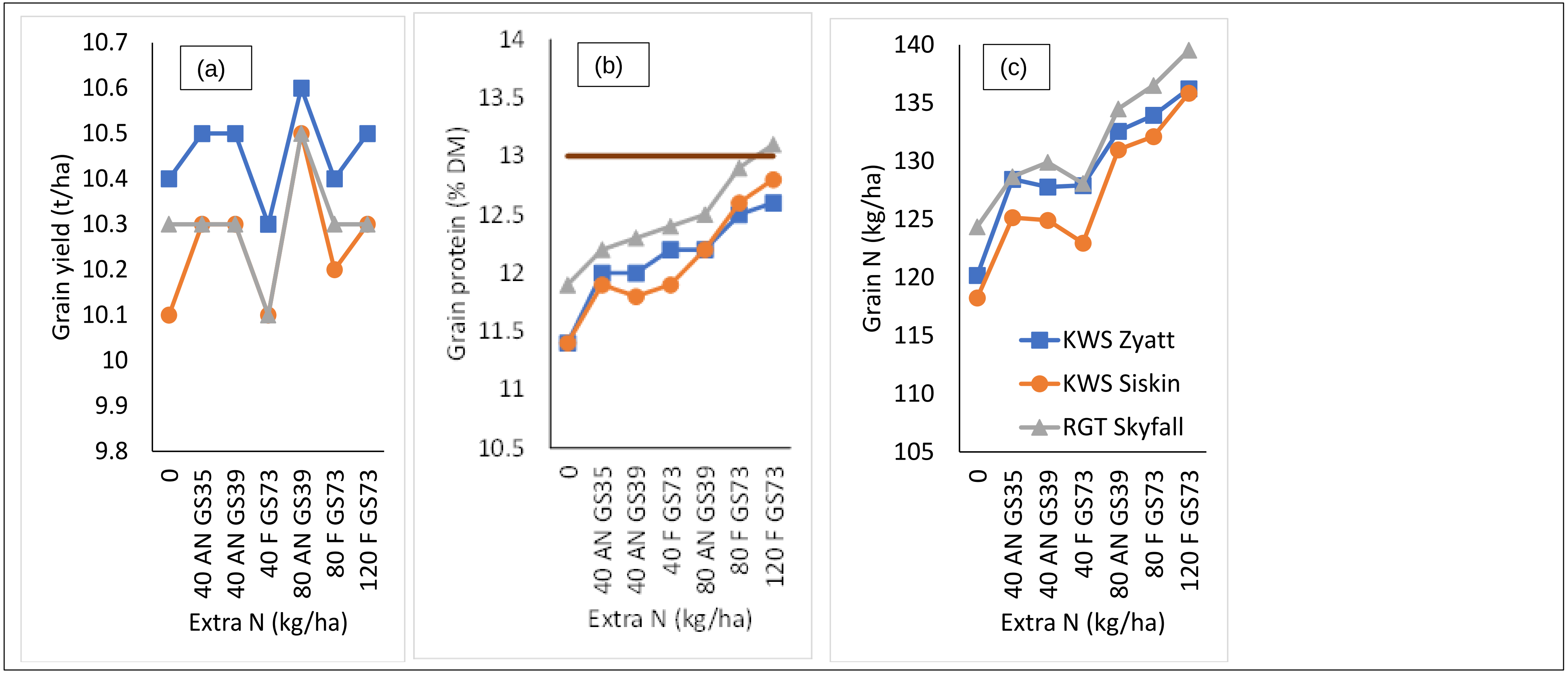

Figure 5.1: Average effects of extra N on (a) grain yield, (b) grain protein and (c) grain N offtake from ten experiments harvested from 2019 to 2021. Additional N was applied as ammonium nitrate granules (AN) or foliar urea in sprays at 20% (w/v).

As reported by Sylvester-Bradley and Clarke (2022) milling premiums are generally necessary to incentivise production of milling wheat crops. However, yields and quality premiums only need to be modest (e.g. £10/tonne) for production of milling wheat to be more profitable than production of feed wheat. However, farms often have variable success at achieving the specification for the quality premium (based on all criteria: protein, Hagberg falling number, specific weight, moisture, admixture). If premiums or the specification for milling are not achieved consistently over seasons, then the recent fertiliser price increases may alter the risk/benefit balance to a point where targeting milling quality cannot be justified.

The findings from this project and those based on the review by Sylvester-Bradley and Clarke (2022) would suggest that growers should use a decision-support approach to decide upon whether additional N is applied according to i) the premium on offer for exceeding protein threshold, ii) any delay in additional N applications due to low spring rainfall, and iii) the farm's past success in meeting the specification for premium payment, as described in Table 5.1. Additionally, it may be possible to use a protein prediction test to ascertain whether late N is required, as reported by Blake-Kalff & Blake (2022).

Table 5.1: Decision making approaches for applying additional nitrogen to milling wheat crops (modified from Sylvester-Bradley and Clarke, 2022).

Risk	Farm's past success in meeting milling specification		
	Seldom	Sometimes	Often
Grain premium offered for exceeding protein threshold	Omit additional N	Continue with usual past practice for milling wheats	Continue with usual past practice for milling wheats
Low spring rainfall	Delay additional N applications and consider using protein prediction test.	Apply late foliar N even if not usual past practice	

Recommendations for N rate and timing recommendations

- In some circumstances, an application of nitrogen may be worthwhile economically to boost the grain protein concentration. Typically, applications of an extra 40 kg N/ha could increase grain protein by up to 0.5 %. An application of an extra 80 kg N/ha may increase grain protein by up to 1.0 %. Late foliar N was better at increasing grain protein than solid applications. There was no difference between the effect of applications at GS 32 and GS 39, but due to the increase in frequency of very dry springs, the risk of no response may be considered lower where extra N is applied at GS 32.

- Application of soil-applied additional nitrogen during stem extension may give a small yield increase, as well as an increase in grain protein. Application as a foliar urea spray during the milky ripe stage will result in a larger increase in grain protein content but cannot be expected to increase yield.
- The application of foliar urea at milky ripe (GS 73) has no detrimental impact on baking quality when compared to applications of ammonium nitrate.
- The decision to apply additional N should be based on i) the premium on offer for exceeding protein threshold, ii) any delay in spring N applications due to low spring rainfall, and iii) the farm's past success in meeting the specification for premium payment.

5.3. Sulphur recommendations

Sulphur fertiliser significantly increased yield in only two of eight experiments although yield response was variable and inconsistent with increases in S rates. Sulphur at a rate of 50 kg SO_3/ha did increase grain N concentration at one of eight sites but only in the variety KWS Zyatt. However, across all eight S response experiments, there was no significant effect of sulphur fertiliser on yield or grain protein. Therefore, any impact of sulphur to increase grain protein appears to be minimal.

Application of sulphur fertiliser had a variable effect on grain asparagine concentration when comparing the two varieties. In general, increasing sulphur rates reduced asparagine concentrations in KWS Zyatt, but increased them in RGT Skyfall. There was no consistent reduction in asparagine concentrations with increasing sulphur rates. There were no detrimental effects of sulphur fertiliser on the rheology or baking parameters. 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). Therefore, even though the experiments in this study did not show a consistent statistically significant increase in yield from sulphur fertiliser, or a consistent statistically significant reduction in asparagine concentration, and hence acrylamide formation, it is concluded that current 'RB209' guidance to apply 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 for flour milling.

6. DISCUSSION

6.1. Environmental impacts and the success on achieving grain protein

One of the greatest challenges for milling wheat growers is balancing the N rates above that for yield in order to achieve 13 % grain protein given varying seasons. For example, yield at the Essex site in 2020 was particular hampered by environmental factors. A wet autumn led to late drilling and establishment was also impeded by high rainfall. This was followed by low spring rainfall (only 47% of the 1991-2020 average), it is therefore not surprising that the yields at this site averaged just 7.6 t/ha with grain protein of around 10.5 % to 11.5 %, well below the desired 13 %. The yield response to applied N was markedly different between experimental sites in this project (shown by the site N response index in Section 4.2) ranging from an N response Index of 0.2 for the Essex site in 2020 to 2.2 for the Lincolnshire experiment in 2019. However, across all sites/seasons, there was no significant difference in yield (P=1.0) between treatments where the nitrogen rate for yield alone ('RB209') was applied compared with the treatments where additional N was applied and this confirms that current N recommendations for yield alone are correct. Previous evidence (Roques *et al*., 2016) states that nitrogen fertiliser application rates should be adjusted down or up by 25 kg N/ha per 0.5% difference in grain protein. Dampney *et al*. (1995) reported that to produce grain containing 13% protein, about 60 kg N/ha above the yield optimum was required. This project has shown that grain protein can be increased from additional N applications above that for yield. On average, an additional 40 kg N/ha increased grain protein by 0.5 %, an additional 80 kg N/ha increased grain protein by 1.0 % and an additional 120 kg N/ha increased grain proteins by 1.3 %.

Previous UK experiments on the effects of late-applied N on milling wheat varieties were harvested between 2003-2005 (9 experiments) and reported by Dampney *et al*. (2006). Average responses found that small increases in yield were caused by applying extra AN at GS39 but no yield increases were found from applying more extra N than ~40 kg/ha or from later applications of foliar urea. However, they showed that multiple applications of foliar urea can cause slight yield reductions. All applications of late N increased grain protein. The use of foliar urea indicated little to increase in yield but a consistent increase in grain protein when an additional 40 kg N/ha was applied as foliar urea at GS 73. These previous findings are supported by the data collected in this project.

The variability between farms in achieving 13 % grain protein was also seen in in the ADAS Yield Enhancement Network (YEN). Between 2013 and 2020 only 40 % of milling wheats entered into YEN achieved >13 % grain protein with farms; some farms consistently met milling specification; others showed large variation from year to year. Targeting milling quality may not be justified where there is a risk of dry springs reducing nitrogen uptake or where there is a risk of low HFN or specific weight. If premiums are not achieved consistently over seasons, the imbalance between risk and benefit may not justify growing milling varieties at all.

6.2. Effects on bread making quality

High protein content is indicative of a good extensible gluten level in the grain, essential for good breadmaking dough. For breadmaking wheat, within the normal grain protein range, there should be a positive correlation between grain protein content and loaf quality (Finney et al., 1957). However, an improvement in grain protein content does not always manifest itself in an increase in breadmaking quality, particularly where other milling quality parameters (e.g. specific weight or Hagberg Falling Number tests) are not met. This project has confirmed that achieving all the milling specifications (grain protein, specific weight, and HFN) are important to ensure that they are consistent and optimum for rheology and baking. As an example, the Essex 2021 site had high grain proteins (14.2 -14.4 % @ dm) but low specific weights (68.8 to 73.7 kg/hl). A composite grain sample resulted in unacceptably high protein loss on milling, which confirms that the grain protein was largely associated with the bran. This would have serious implications for miller who would bin wheats at intake based on protein levels with an expected protein loss on milling of only c. 1.0%.

Higher water absorption values are required for breadmaking; values above 55 % are required. RGT Skyfall tended to have higher water absorption % compared to KWS Zyatt or KWS Siskin, but all varieties showed a response where extra N was applied. Where foliar urea was applied at GS 73 there was a trend for the gluten to have more strength compared with applied ammonium nitrate with extra N rates of 40 or 80 kg N/ha. Flour proteins were also higher where foliar urea had been applied compared with the ammonium nitrate treatments. For example, the combined mean, across varieties, for flour protein with ammonium nitrate was 11.2 %, compared to 11.8 % with foliar urea. Our study has therefore shown that the key parameters for both rheology and test baking were not detrimentally affected when foliar urea was applied compared with applications of ammonium nitrate.

The project has also demonstrated that achieving 13 % grain protein consistently across sites and seasons using three modern wheat varieties (KWS Zyatt, KWS Siskin and RGT Skyfall) is difficult and thus it raises the question as to whether the current requirement of 13 % grain protein content for breadmaking wheats remains valid. Provided that other quality thresholds (e.g. specific weight and HFN) were achieved, the additional N applied to achieve 12.5% grain protein made little difference to the key parameters relevant to baking rheology. Shewry *et al*. (2020) demonstrated in the AHDB funded project "**21130005** Low protein wheat for bread making" that three current UK varieties had good breadmaking quality when grown at 150 kg N/ha, with one variety (RGT Skyfall) having better quality for breadmaking when grown at 150 kg N/ha than at 250 kg N/ha, despite having a lower protein content. The opportunity to reducing nitrogen fertilisation rates to milling wheat is a major interest for farmers and processors, affecting not only the costs of grain production and food processing but also the impacts in the food supply chain on energy use and greenhouse gas (GHG) emissions. GHG emissions from fertiliser, N_2O emissions and field operations together account for more than 70% of the total GHG intensity from the Cereal YEN entries (Kindred, Sylvester-Bradley and Baxter, 2021). Overall the work in both projects, confirms that protein alone should not be the main target for milling wheat growers and that equal attention needs to be given to whether the other milling quality thresholds will be met before finalising a decision about extra N. Blake-Kalff, M. and Blake, L. (2022) used datasets from this project to help to develop a test for protein prediction in season. Later testing of crops increased the accuracy of the prediction of grain protein content (Blake-Kalff, M. and Blake, L., 2022). Their findings showed that the protein prediction test could provide an effective tool to aid farmers in their decision processes on whether to apply late N or not and how to target applications of extra N most effectively.

6.3. The management of sulphur fertilisation in milling wheat

This project found no consistent difference in sulphur fertilisation with respect to yield, grain quality (grain protein, specific weight or HFN), grain asparagine concentrations or baking performance. The accumulation of free asparagine in wheat grain is responsive to environmental and crop management factors, increasing, for example, in response to sulphur deficiency and pathogen infection (Raffan and Halford, 2019). Curtis *et al*. (2009) reported higher asparagine concentrations in grain from sulphur-deprived plants from a selection of field and pot-grown samples with a wide range of free asparagine concentrations (0.67 to 62 mmol/kg; R^2 value of 0.9945). However, Curtis *et al*. (2019) showed that there was a differential response of varieties to sulphur and a large seasonal variation in asparagine concentrations.

Within this project, responses of free asparagine concentrations to sulphur application were inconclusive, with mean free asparagine concentrations ranging from 1.36 mmol/kg to 4.12 mmol/kg. The lack of response to sulphur in this project may partially be explained by that for five out of the eight sites there was no deficiency in grain S concentrations at Nil S; at the other three sites only KWS Zyatt showed deficiency in the grain S concentration at Nil S. This is despite the very low deposition of sulphur from the atmosphere with levels measured in the UK of only 3 to 6 kg S/ha (8 to 15 kg SO_3/ha) (Webb *et al.*, 2016).

The conclusion therefore, is that current ‘RB209’ guidance to apply 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 for flour milling.

6.4. Further research requirements

- Develop breeding programmes to select varieties more efficient in nitrogen utilisation and that consequently have reduced environmental impacts whilst maintaining milling quality.
- Confirm that current N rate and timing recommendations are relevant for regenerative farming systems.
- Investigate varietal differences in asparagine concentration further and ensure outcomes are disseminated to growers and agronomists on farms to allow for crop management decisions to be made.
- Continue to support collaboration across the supply chain from breeders, growers, agronomists, researchers, millers and retailers to ensure that the guidance and best practice is updated regularly such that everyone in the supply chain benefits.

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9. APPENDIX 1. Objective 2. Quantify the effect of rate and timing of applied N fertiliser on grain quality

Effects of N Rate and Timing on Yield

Table A1.1: Yield (t/ha) for the East Lothian 2019 N rate and timing trial.

	N Fertiliser rate							
Variety	Nil N	'RB209'	+40 AN At GS 32-35	+40 AN At GS 37-39	+40 Foliar At GS 73	+80 AN At GS 37-39	+80 Foliar At GS 73	+120 Foliar At GS 73
KWS Zyatt	4.96	11.57	11.77	11.75	11.63	11.64	11.50	11.56
KWS Siskin	5.34	11.63	11.63	11.49	11.53	11.77	11.26	11.50
RGT Skyfall	5.40	11.26	11.83	11.64	11.58	11.98	11.83	11.42
	P-value	SED	LSD					
	<0.001	0.32	0.653					

Table A1.2: Yield (t/ha) for the Lincolnshire 2019 N rate and timing trial.

	N Fertiliser rate							
Variety	Nil N	'RB209'	+40 AN At GS 32-35	+40 AN At GS 37-39	+40 Foliar At GS 73	+80 AN At GS 37-39	+80 Foliar At GS 73	+120 Foliar At GS 73
KWS Zyatt	3.59	12.93	13.76	13.03	13.41	14.26	13.66	13.74
KWS Siskin	3.12	12.28	12.67	12.95	11.62	13.29	12.72	12.82
RGT Skyfall	5.27	13.05	13.37	13.52	12.60	13.72	12.86	13.60
	P-value	SED	LSD					
	<0.001	0.36	0.715					

Table A1.3: Yield (t/ha) for the Norfolk 2019 N rate and timing trial.

	N Fertiliser rate							
Variety	Nil N	'RB209'	+40 AN At GS 32-35	+40 AN At GS 37-39	+40 Foliar At GS 73	+80 AN At GS 37-39	+80 Foliar At GS 73	+120 Foliar At GS 73
KWS Zyatt	6.24	10.92	11.40	11.38	11.32	11.54	11.49	11.45
KWS Siskin	6.33	10.94	11.15	11.13	10.95	11.01	10.89	10.97
RGT Skyfall	6.15	11.06	10.86	11.18	10.79	11.30	11.05	11.40
	P-value	SED	LSD					
	<0.001	0.26	0.523					

Table A1.4: Yield (t/ha) for the Essex 2019 N rate and timing trial.

	N Fertiliser rate							
Variety	Nil N	'RB209'	+40 AN At GS 32-35	+40 AN At GS 37-39	+40 Foliar At GS 73	+80 AN At GS 37-39	+80 Foliar At GS 73	+120 Foliar At GS 73
KWS Zyatt	7.09	10.39	10.39	10.29	9.68	10.37	10.15	10.07
KWS Siskin	7.52	9.87	9.75	10.49	10.21	10.56	10.24	9.85
RGT Skyfall	7.31	10.11	9.46	9.45	9.68	9.97	9.91	9.49
	P-value	SED	LSD					
		0.38	0.764					

Table A1.5: Yield (t/ha) for the East Lothian 2020 N rate and timing trial.

	N Fertiliser rate							
Variety	Nil N	'RB209'	+40 AN At GS 32-35	+40 AN At GS 37-39	+40 Foliar At GS 73	+80 AN At GS 37-39	+80 Foliar At GS 73	+120 Foliar At GS 73
KWS Zyatt	4.46	11.02	10.97	11.12	11.02	11.04	11.15	11.73
KWS Siskin	3.77	11.03	11.35	11.34	10.76	11.07	10.63	11.15
RGT Skyfall	3.64	10.55	10.77	10.58	10.85	11.79	11.02	11.10
	P-value	SED	LSD					
	<0.001	0.36	0.728					

Table A1.6: Yield (t/ha) for the Essex 2020 N rate and timing trial.

	N Fertiliser rate							
Variety	Nil N	'RB209'	+40 AN At GS 32-35	+40 AN At GS 37-39	+40 Foliar At GS 73	+80 AN At GS 37-39	+80 Foliar At GS 73	+120 Foliar At GS 73
KWS Zyatt	5.82	7.89	7.46	7.78	7.56	7.56	7.50	7.87
KWS Siskin	6.50	7.31	7.34	7.46	7.41	7.54	7.83	8.32
RGT Skyfall	6.32	7.90	8.13	8.12	8.21	7.88	7.98	8.13
	P-value	SED	LSD					
	<0.001	0.47	0.835					

Table A1.7: Yield (t/ha) for the East Lothian 2021 N rate and timing trial.

	N Fertiliser rate							
Variety	Nil N	'RB209'	+40 AN At GS 32-35	+40 AN At GS 37-39	+40 Foliar At GS 73	+80 AN At GS 37-39	+80 Foliar At GS 73	+120 Foliar At GS 73
KWS Zyatt	6.42	12.86	13.08	12.95	13.06	13.11	12.88	13.06
KWS Siskin	6.99	12.14	12.26	12.22	12.4	12.4	11.96	12.07
RGT Skyfall	7.15	12.43	12.76	12.35	12.33	12.52	12.38	12.16
	P-value	SED	LSD					
	<0.001	0.34	0.692					

Table A1.8: Yield (t/ha) for the Lincolnshire 2021 N rate and timing trial.

	N Fertiliser rate							
Variety	Nil N	'RB209'	+40 AN At GS 32-35	+40 AN At GS 37-39	+40 Foliar At GS 73	+80 AN At GS 37-39	+80 Foliar At GS 73	+120 Foliar At GS 73
KWS Zyatt	3.92	10.12	9.95	10.31	9.89	10.33	10.31	10.30
KWS Siskin	4.00	9.63	9.82	10.23	9.83	10.21	10.09	10.31
RGT Skyfall	3.99	9.59	9.73	9.78	9.72	10.00	9.82	10.25
	P-value	SED	LSD					
	<0.001	0.22	0.437					

Table A1.9: Yield (t/ha) for the Essex 2021 N rate and timing trial.

	N Fertiliser rate							
Variety	Nil N	'RB209'	+40 AN At GS 32-35	+40 AN At GS 37-39	+40 Foliar At GS 73	+80 AN At GS 37-39	+80 Foliar At GS 73	+120 Foliar At GS 73
KWS Zyatt	4.81	6.67	6.84	6.72	6.37	6.88	6.35	6.44
KWS Siskin	5.32	7.34	7.11	6.88	7.29	7.31	7.59	7.48
RGT Skyfall	5.33	7.27	7.34	7.22	6.89	6.98	7.29	7.30
	P-value	SED	LSD					
	<0.001	0.39	0.793					

Table A1.10: Yield (t/ha) for the Hampshire 2021 N rate and timing trial.

	N Fertiliser rate							
Variety	Nil N	'RB209'	+40 AN At GS 32-35	+40 AN At GS 37-39	+40 Foliar At GS 73	+80 AN At GS 37-39	+80 Foliar At GS 73	+120 Foliar At GS 73
KWS Zyatt	6.27	11.24	11.26	11.25	10.80	11.34	11.00	10.56
KWS Siskin	6.95	10.87	11.16	10.90	10.40	11.23	10.28	10.55
RGT Skyfall	6.07	11.05	10.78	10.96	10.37	10.45	10.32	10.29
	P-value	SED	LSD					
	<0.001	0.21	0.415					

Effects of N Rate and Timing on Grain Protein

Table A1.11: Grain Protein (% DM) for the East Lothian 2019 N rate and timing trial.

	N Fertiliser rate							
Variety	Nil N	'RB209'	+40 AN At GS 32-35	+40 AN At GS 37-39	+40 Foliar At GS 73	+80 AN At GS 37-39	+80 Foliar At GS 73	+120 Foliar At GS 73
KWS Zyatt	8.9	11.2	11.8	11.8	12.4	12.3	12.5	12.8
KWS Siskin	8.1	11.2	12.0	11.8	11.8	12.5	12.8	13.1
RGT Skyfall	8.6	11.4	11.6	12.1	12.0	12.2	12.6	13.1
	P-value	SED	LSD					
	<0.001	0.26	0.52					

Table A1.12: Grain Protein (% DM) for the Lincolnshire 2019 N rate and timing trial.

	N Fertiliser rate							
Variety	Nil N	'RB209'	+40 AN At GS 32-35	+40 AN At GS 37-39	+40 Foliar At GS 73	+80 AN At GS 37-39	+80 Foliar At GS 73	+120 Foliar At GS 73
KWS Zyatt	7.4	10.4	11.5	11.7	11.8	11.9	12.5	12.7
KWS Siskin	7.2	11.1	11.7	11.5	10.9	12.3	12.4	12.8
RGT Skyfall	7.8	12.0	12.2	12.7	12.5	12.7	13.7	13.7
	P-value	SED	LSD					
	<0.001	0.55	1.11					

Table A1.13: Grain Protein (% DM) for the Norfolk 2019 N rate and timing trial.

	N Fertiliser rate							
Variety	Nil N	'RB209'	+40 AN At GS 32-35	+40 AN At GS 37-39	+40 Foliar At GS 73	+80 AN At GS 37-39	+80 Foliar At GS 73	+120 Foliar At GS 73
KWS Zyatt	11.6	12.5	12.9	12.7	12.7	12.6	12.6	12.4
KWS Siskin	11.4	12.6	12.8	12.3	12.3	12.2	13.0	13.1
RGT Skyfall	10.7	12.8	12.9	12.1	12.7	12.8	13.0	12.6
	P-value	SED	LSD					
	0.008	0.52	1.05					

Table A1.14: Grain Protein (% DM) for the Essex 2019 N rate and timing trial.

	N Fertiliser rate							
Variety	Nil N	'RB209'	+40 AN At GS 32-35	+40 AN At GS 37-39	+40 Foliar At GS 73	+80 AN At GS 37-39	+80 Foliar At GS 73	+120 Foliar At GS 73
KWS Zyatt	8.2	11.4	12.3	12.3	12.2	12.5	13.1	13.4
KWS Siskin	7.8	11.0	11.6	11.6	11.8	12.1	12.3	12.5
RGT Skyfall	8.4	11.6	12.4	12.6	12.7	12.6	13.2	13.5
	P-value	SED	LSD					
	<0.001	0.23	0.45					

Table A1.15: Grain Protein (% DM) for the East Lothian 2020 N rate and timing trial.

	N Fertiliser rate							
Variety	Nil N	'RB209'	+40 AN At GS 32-35	+40 AN At GS 37-39	+40 Foliar At GS 73	+80 AN At GS 37-39	+80 Foliar At GS 73	+120 Foliar At GS 73
KWS Zyatt	9.8	12.1	12.7	12.3	12.5	12.8	12.8	12.6
KWS Siskin	9.4	11.5	12.2	12.0	12.1	12.3	12.4	12.8
RGT Skyfall	10.1	12.4	12.8	12.7	12.7	12.9	13.1	13.4
	P-value	SED	LSD					
	<0.001	0.16	0.33					

Table A1.16: Grain Protein (% DM) for the Essex 2020 N rate and timing trial.

	N Fertiliser rate							
Variety	Nil N	'RB209'	+40 AN At GS 32-35	+40 AN At GS 37-39	+40 Foliar At GS 73	+80 AN At GS 37-39	+80 Foliar At GS 73	+120 Foliar At GS 73
KWS Zyatt	8.5	10.3	10.5	10.4	10.8	10.5	10.8	11.0
KWS Siskin	8.7	10.3	10.3	10.2	10.6	10.4	10.9	10.9
RGT Skyfall	8.8	11.0	11.0	11.1	11.3	11.2	11.5	11.5
	P-value	SED	LSD					
	<0.001	0.19	0.38					

Table A1.17: Grain Protein (% DM) for the East Lothian 2021 N rate and timing trial.

	N Fertiliser rate							
Variety	Nil N	'RB209'	+40 AN At GS 32-35	+40 AN At GS 37-39	+40 Foliar At GS 73	+80 AN At GS 37-39	+80 Foliar At GS 73	+120 Foliar At GS 73
KWS Zyatt	8.2	11.2	11.9	12.0	12.0	12.3	12.4	12.6
KWS Siskin	7.9	11.7	12.1	12.0	12.2	12.8	13.2	13.3
RGT Skyfall	8.2	11.3	11.8	12.4	11.9	12.4	12.6	13.4
	P-value	SED	LSD					
	<0.001	0.30	0.61					

Table A1.18: Grain Protein (% DM) for the Lincolnshire 2021 N rate and timing trial.

	N Fertiliser rate							
Variety	Nil N	'RB209'	+40 AN At GS 32-35	+40 AN At GS 37-39	+40 Foliar At GS 73	+80 AN At GS 37-39	+80 Foliar At GS 73	+120 Foliar At GS 73
KWS Zyatt	7.8	10.7	11.6	11.6	11.9	12.0	12.7	13.0
KWS Siskin	7.4	10.7	11.4	11.6	12.4	12.3	12.9	13.1
RGT Skyfall	7.9	11.5	12.2	12.3	12.3	12.8	13.3	13.6
	P-value	SED	LSD					
	<0.001	0.27	0.50					

Table A1.19: Grain Protein (% DM) for the Essex 2021 N rate and timing trial.

Variety	N Fertiliser rate							
	Nil N	'RB209'	+40 AN At GS 32-35	+40 AN At GS 37-39	+40 Foliar At GS 73	+80 AN At GS 37-39	+80 Foliar At GS 73	+120 Foliar At GS 73
KWS Zyatt	9.8	13.4	13.4	13.4	13.4	13.5	13.3	13.3
KWS Siskin	9.5	13.1	13.3	13.2	13.1	13.4	13.6	13.4
RGT Skyfall	10.0	13.5	13.3	13.5	13.5	13.8	13.6	13.9
	P-value	SED	LSD					
	<0.001	0.28	0.57					

Table A1.20: Grain Protein (% DM) for the Hampshire 2021 N rate and timing trial.

Variety	N Fertiliser rate							
	Nil N	'RB209'	+40 AN At GS 32-35	+40 AN At GS 37-39	+40 Foliar At GS 73	+80 AN At GS 37-39	+80 Foliar At GS 73	+120 Foliar At GS 73
KWS Zyatt	9.4	11.9	12.4	12.4	13.1	12.7	13.5	13.9
KWS Siskin	9.0	11.7	12.5	12.5	13.2	12.7	14.0	14.1
RGT Skyfall	10.1	12.1	12.5	12.6	13.0	12.9	13.9	14.0
	P-value	SED	LSD					
	<0.001	0.18	0.35					

Effects of N Rate and Timing on Specific Weight

Table A1.21:Specific Weight (kg/hl) for the East Lothian 2019 N rate and timing trial.

	N Fertiliser rate							
Variety	Nil N	'RB209'	+40 AN At GS 32-35	+40 AN At GS 37-39	+40 Foliar At GS 73	+80 AN At GS 37-39	+80 Foliar At GS 73	+120 Foliar At GS 73
KWS Zyatt	73.5	76.5	76.0	76.7	76.2	76.3	76.5	75.9
KWS Siskin	70.3	74.2	74.1	74.2	75.4	73.6	74.1	72.9
RGT Skyfall	73.5	77.9	76.9	77.6	77.8	77.8	77.9	78.0
	P-value	SED	LSD					
	<0.001	0.51	1.03					

Table A1.22: Specific Weight (kg/hl) for the Lincolnshire 2019 N rate and timing trial.

	N Fertiliser rate							
Variety	Nil N	'RB209'	+40 AN At GS 32-35	+40 AN At GS 37-39	+40 Foliar At GS 73	+80 AN At GS 37-39	+80 Foliar At GS 73	+120 Foliar At GS 73
KWS Zyatt	69.4	72.8	73.1	73.4	73.7	73.3	73.5	73.6
KWS Siskin	69.5	69.0	72.7	71.2	70.8	70.7	72.8	73.3
RGT Skyfall	70.2	73.8	73.9	73.5	73.4	73.9	73.7	74.3
	P-value	SED	LSD					
	<0.001	0.75	1.51					

Table A1.23: Specific Weight (kg/hl) for the Norfolk 2019 N rate and timing trial.

	N Fertiliser rate							
Variety	Nil N	'RB209'	+40 AN At GS 32-35	+40 AN At GS 37-39	+40 Foliar At GS 73	+80 AN At GS 37-39	+80 Foliar At GS 73	+120 Foliar At GS 73
KWS Zyatt	77.7	78.4	79.3	79.1	78.9	78.8	79.0	78.9
KWS Siskin	77.6	79.3	79.3	79.0	78.3	78.0	79.0	79.2
RGT Skyfall	77.5	80.5	79.4	79.7	79.9	79.4	80.1	78.7
	P-value	SED	LSD					
	0.035	0.77	1.56					

Table A1.24: Specific Weight (kg/hl) for the Essex 2019 N rate and timing trial.

	N Fertiliser rate							
Variety	Nil N	'RB209'	+40 AN At GS 32-35	+40 AN At GS 37-39	+40 Foliar At GS 73	+80 AN At GS 37-39	+80 Foliar At GS 73	+120 Foliar At GS 73
KWS Zyatt	73.0	76.5	76.9	76.7	77.3	76.6	77.5	77.2
KWS Siskin	72.9	76.5	76.6	76.7	76.8	76.9	76.2	77.4
RGT Skyfall	74.5	77.2	77.3	77.7	77.1	77.4	76.9	77.6
	P-value	SED	LSD					
	<0.001	0.49	0.99					

Table A1.25: Specific Weight (kg/hl) for the East Lothian 2020 N rate and timing trial.

Variety	N Fertiliser rate							
	Nil N	'RB209'	+40 AN At GS 32-35	+40 AN At GS 37-39	+40 Foliar At GS 73	+80 AN At GS 37-39	+80 Foliar At GS 73	+120 Foliar At GS 73
KWS Zyatt	73.3	76.1	75.9	76.0	75.8	76.3	76.5	76.2
KWS Siskin	73.5	75.8	75.8	75.8	76.0	76.5	75.8	75.7
RGT Skyfall	73.6	77.1	77.1	76.9	76.8	77.2	76.8	77.0
	P-value	SED	LSD					
	<0.001	0.51	1.02					

Table A1.26: Specific Weight (kg/hl) for the Essex 2020 N rate and timing trial.

Variety	N Fertiliser rate							
	Nil N	'RB209'	+40 AN At GS 32-35	+40 AN At GS 37-39	+40 Foliar At GS 73	+80 AN At GS 37-39	+80 Foliar At GS 73	+120 Foliar At GS 73
KWS Zyatt	75.1	77.1	77.4	77.2	77.4	77.5	77.1	76.9
KWS Siskin	74.0	73.9	73.7	73.9	73.9	74.9	76.0	75.3
RGT Skyfall	76.4	77.9	77.9	78.3	78.8	78.1	78.3	77.7
	P-value	SED	LSD					
	<0.001	0.64	1.29					

Table A1.27: Specific Weight (kg/hl) for the East Lothian 2021 N rate and timing trial.

Variety	N Fertiliser rate							
	Nil N	'RB209'	+40 AN At GS 32-35	+40 AN At GS 37-39	+40 Foliar At GS 73	+80 AN At GS 37-39	+80 Foliar At GS 73	+120 Foliar At GS 73
KWS Zyatt	72.1	74.1	73.2	73.9	74.4	73.2	73.6	72.9
KWS Siskin	70.7	72.1	72.5	72.1	72.7	71.4	70.5	71.1
RGT Skyfall	73.2	75.2	75.4	74.8	76.3	74.9	74.8	73.9
	P-value	SED	LSD					
	<0.001	0.50	0.10					

Table A1.28: Specific Weight (kg/hl) for the Lincolnshire 2021 N rate and timing trial.

Variety	N Fertiliser rate							
	Nil N	'RB209'	+40 AN At GS 32-35	+40 AN At GS 37-39	+40 Foliar At GS 73	+80 AN At GS 37-39	+80 Foliar At GS 73	+120 Foliar At GS 73
KWS Zyatt	74.2	77.1	77.1	77.1	77.2	76.5	77.2	77.5
KWS Siskin	74.1	75.7	76.3	76.5	76.4	76.3	77.0	76.3
RGT Skyfall	75.9	78.6	78.8	79.0	79.0	79.2	79.1	78.9
	P-value	SED	LSD					
	<0.001	0.55	1.00					

Table A1.29: Specific Weight (kg/hl) for the Essex 2021 N rate and timing trial.

Variety	N Fertiliser rate							
	Nil N	'RB209'	+40 AN At GS 32-35	+40 AN At GS 37-39	+40 Foliar At GS 73	+80 AN At GS 37-39	+80 Foliar At GS 73	+120 Foliar At GS 73
KWS Zyatt	72.7	70.7	71.1	70.9	71.3	72.3	70.1	71.4
KWS Siskin	71.4	70.4	69.3	68.8	69.0	69.9	70.6	69.6
RGT Skyfall	73.1	73.4	73.3	72.5	72.8	72.8	72.6	73.7
	P-value	SED	LSD					
	<0.001	0.94	1.89					

Table A1.30: Specific Weight (kg/hl) for the Hampshire 2021 N rate and timing trial.

Variety	N Fertiliser rate							
	Nil N	'RB209'	+40 AN At GS 32-35	+40 AN At GS 37-39	+40 Foliar At GS 73	+80 AN At GS 37-39	+80 Foliar At GS 73	+120 Foliar At GS 73
KWS Zyatt	75.3	76.6	75.5	76.2	76.0	76.0	75.6	74.9
KWS Siskin	74.7	75.6	75.4	75.5	74.5	75.5	73.6	73.5
RGT Skyfall	75.8	78.1	77.5	77.6	77.4	76.7	76.4	75.7
	P-value	SED	LSD					
	<0.001	0.45	0.91					

APPENDIX 2. Objective 3. Quantify the response to S fertiliser application rate and timing on grain quality

Effects of S Rate and Timing on Yield

Table A2.1: Yield (t/ha) for the East Lothian 2019 S rate and timing trial.

N rate	+40 AN At GS 37-39							+40 Foliar At GS 73						
S rate	0	25	50	50 split	75	75 split	100	0	25	50	50 split	75	75 split	100
KWS Zyatt	11.30	11.60	11.64	11.47	11.62	11.95	-	11.47	11.53	11.52	11.65	11.25	11.58	-
RGT Skyfall	11.31	11.38	11.64	11.42	11.65	11.57	-	11.64	11.33	11.22	11.46	11.30	10.97	-
	P-value	SED	LSD											
	0.587	0.30	0.597											

Split = Split sulphur rate

Table A2.2: Yield (t/ha) for the Lincolnshire 2019 S rate and timing trial.

N rate	+40 AN At GS 37-39							+40 Foliar At GS 73						
S rate	0	25	50	50 split	75	75 split	100	0	25	50	50 split	75	75 split	100
KWS Zyatt	12.50	13.16	13.43	13.89	13.75	13.63	-	12.01	12.90	13.35	12.97	13.35	12.75	-
RGT Skyfall	13.67	13.36	13.45	13.37	13.45	13.69	-	12.91	13.17	12.56	13.02	12.64	12.24	-
	P-value	SED	LSD											
	0.002	0.42	0.844											

Split = Split sulphur rate

Table A2.3: Yield (t/ha) for the Norfolk 2019 S rate and timing trial.

N rate	+40 AN At GS 37-39							+40 Foliar At GS 73						
S rate	0	25	50	50 split	75	75 split	100	0	25	50	50 split	75	75 split	100
KWS Zyatt	11.22	11.51	11.29	11.19	11.41	11.28	-	10.97	10.78	11.22	11.19	11.20	10.93	-
RGT Skyfall	10.91	11.10	10.90	11.10	11.13	11.16	-	10.87	10.94	10.94	10.77	10.93	10.91	-
	P-value	SED	LSD											
	0.004	0.18	0.353											

Split = Split sulphur rate

Table A2.4: Yield (t/ha) for the Essex 2019 S rate and timing trial.

N rate	+40 AN At GS 37-39							+40 Foliar At GS 73						
S rate	0	25	50	50 split	75	75 split	100	0	25	50	50 split	75	75 split	100
KWS Zyatt	10.56	10.41	10.56	10.57	10.60	10.39	-	10.54	10.45	10.44	10.55	10.55	10.10	-
RGT Skyfall	10.14	9.82	10.09	9.86	10.22	10.03	-	10.12	9.81	9.76	9.97	9.93	10.22	-
	P-value	SED	LSD											
	0.04	0.33	0.667											

Split = Split sulphur rate

Table A2.5: Yield (t/ha) for the East Lothian 2020 S rate and timing trial.

N rate	+40 AN At GS 37-39							+40 Foliar At GS 73						
S rate	0	25	50	50 split	75	75 split	100	0	25	50	50 split	75	75 split	100
KWS Zyatt	11.81	12.06	12.09	12.29	12.00	11.66	-	11.75	12.19	11.85	12.20	11.73	12.04	-
RGT Skyfall	11.89	11.69	11.35	11.56	11.89	11.62	-	11.48	11.82	11.56	11.42	11.39	11.60	-
	P-value	SED	LSD											
	0.406	0.37	0.736											

Split = Split sulphur rate

Table A2.6: Yield (t/ha) for the Essex 2020 S rate and timing trial.

N rate	+40 AN At GS 37-39							+40 Foliar At GS 73						
S rate	0	25	50	50 split	75	75 split	100	0	25	50	50 split	75	75 split	100
KWS Zyatt	7.18	7.23	7.14	7.01	7.10	7.27	-	7.06	7.25	7.32	7.08	7.09	7.10	-
RGT Skyfall	7.44	7.29	7.67	7.70	7.33	7.78	-	7.64	7.49	7.53	7.67	7.77	7.71	-
	P-value	SED	LSD											
	0.052	0.27	0.551											

Split = Split sulphur rate

Table A2.7: Yield (t/ha) for the Lincolnshire 2021 S rate and timing trial.

N rate	+40 AN At GS 37-39							+40 Foliar At GS 73						
S rate	0	25	50	50 split	75	75 split	100	0	25	50	50 split	75	75 split	100
KWS Zyatt	10.62	-	10.55	10.17	10.44	10.55	10.44	10.17	-	10.30	10.42	10.49	10.56	10.37
RGT Skyfall	9.59	-	10.06	9.98	10.09	9.94	10.15	9.98	-	9.56	9.82	9.99	10.02	10.12
	P-value	SED	LSD											
	0.021	0.41	0.826											

Split = Split sulphur rate

Table A2.8: Yield (t/ha) for the Hampshire 2021 S rate and timing trial.

N rate	+40 AN At GS 37-39							+40 Foliar At GS 73						
S rate	0	25	50	50 split	75	75 split	100	0	25	50	50 split	75	75 split	100
KWS Zyatt	10.95	-	11.22	10.94	10.88	11.05	10.94	10.45	-	10.74	10.56	10.50	10.71	10.45
RGT Skyfall	10.71	-	10.58	10.50	10.75	10.62	10.64	10.13	-	10.32	10.32	10.28	10.42	10.36
	P-value	SED	LSD											
	<0.001	0.14	0.286											

Split = Split sulphur rate

Effects of S Rate and Timing on Grain Protein.

Table A2.9: Grain Protein (% DM) for the East Lothian 2019 S rate and timing trial.

N rate	+40 AN At GS 37-39							+40 Foliar At GS 73						
S rate	0	25	50	50 split	75	75 split	100	0	25	50	50 split	75	75 split	100
KWS Zyatt	11.3	11.3	10.8	11.0	10.9	11.2	-	11.5	11.3	11.0	11.5	11.6	11.7	-
RGT Skyfall	11.6	11.0	11.4	11.5	11.3	11.1	-	11.5	11.8	11.9	11.7	11.8	11.5	-
	P-value	SED	LSD											
	0.103	0.34	0.69											

Split = Split sulphur rate

Table A2.10: Grain Protein (% DM) for the Lincolnshire 2019 S rate and timing trial.

N rate	+40 AN At GS 37-39							+40 Foliar At GS 73						
S rate	0	25	50	50 split	75	75 split	100	0	25	50	50 split	75	75 split	100
KWS Zyatt	10.7	10.8	11.3	11.1	10.9	10.9	-	10.4	10.2	10.7	10.3	10.8	10.4	-
RGT Skyfall	11.4	11.9	11.5	11.9	11.7	11.6	-	12.0	12.1	11.8	12.0	11.9	12.3	-
	P-value	SED	LSD											
	<0.001	0.52	1.04											

Split = Split sulphur rate

Table A2.11: Grain Protein (% DM) for the Norfolk 2019 S rate and timing trial.

N rate	+40 AN At GS 37-39							+40 Foliar At GS 73						
S rate	0	25	50	50 split	75	75 split	100	0	25	50	50 split	75	75 split	100
KWS Zyatt	12.1	12.1	12.2	12.2	11.9	12.1	-	12.1	12.3	11.4	12.4	12.2	12.4	-
RGT Skyfall	12.2	12.2	12.2	12.3	12.2	12.2	-	12.3	12.2	12.2	12.4	12.3	12.2	-
	P-value	SED	LSD											
	0.166	0.24	0.491											

Split = Split sulphur rate

Table A2.12: Grain Protein (% DM) for the Essex 2019 S rate and timing trial.

N rate	+40 AN At GS 37-39							+40 Foliar At GS 73						
S rate	0	25	50	50 split	75	75 split	100	0	25	50	50 split	75	75 split	100
KWS Zyatt	11.6	11.8	11.8	12.0	12.0	11.9	-	12.4	12.1	12.1	12.3	12.2	12.1	-
RGT Skyfall	12.3	12.1	12.2	12.2	12.4	12.1	-	12.0	12.1	12.6	12.4	12.2	12.3	-
	P-value	SED	LSD											
	0.003	0.20	0.40											

Split = Split sulphur rate

Table A2.13: Grain Protein (% DM) for the East Lothian 2020 S rate and timing trial.

N rate	+40 AN At GS 37-39							+40 Foliar At GS 73						
S rate	0	25	50	50 split	75	75 split	100	0	25	50	50 split	75	75 split	100
KWS Zyatt	11.6	11.5	11.6	11.6	11.6	11.6	-	11.8	11.5	11.8	11.7	11.6	11.7	-
RGT Skyfall	11.8	11.8	12.0	11.9	11.8	11.8	-	11.9	11.8	11.9	12.0	12.0	11.9	-
	P-value	SED	LSD											
	0.002	0.13	0.27											

Split = Split sulphur rate

Table A2.14: Grain Protein (% DM) for the Essex 2020 S rate and timing trial.

N rate	+40 AN At GS 37-39							+40 Foliar At GS 73						
S rate	0	25	50	50 split	75	75 split	100	0	25	50	50 split	75	75 split	100
KWS Zyatt	9.9	10.2	9.9	10.2	10.0	9.9	-	10.2	10.2	10.3	10.3	10.3	10.4	-
RGT Skyfall	10.2	10.7	10.4	10.3	10.4	10.3	-	10.7	10.5	10.7	10.7	10.3	10.9	-
	P-value	SED	LSD											
	<0.001	0.19	0.34											

Split = Split sulphur rate

Table A2.15: Grain Protein (% DM) for the Lincolnshire 2021 S rate and timing trial.

N rate	+40 AN At GS 37-39							+40 Foliar At GS 73						
S rate	0	25	50	50 split	75	75 split	100	0	25	50	50 split	75	75 split	100
KWS Zyatt	11.7	-	11.4	11.3	11.4	11.1	11.2	11.9	-	11.8	11.5	11.4	11.7	11.7
RGT Skyfall	11.7	-	12.1	12.1	11.9	12.1	11.8	12.2	-	11.8	12.4	12.0	11.8	11.4
	P-value	SED	LSD											
	<0.001	0.24	0.48											

Split = Split sulphur rate

Table A2.16: Grain Protein (% DM) for the Hampshire 2021 S rate and timing trial.

N rate	+40 AN At GS 37-39							+40 Foliar At GS 73						
S rate	0	25	50	50 split	75	75 split	100	0	25	50	50 split	75	75 split	100
KWS Zyatt	11.7	-	11.9	12.0	12.0	12.2	11.9	12.5	-	12.1	12.6	12.7	12.7	12.6
RGT Skyfall	12.2	-	12.0	12.3	12.1	12.2	12.3	12.4	-	12.6	12.6	12.4	12.4	12.5
	P-value	SED	LSD											
	<0.001	0.11	0.23											

Split = Split sulphur rate

Effects of S Rate and Timing on Specific Weight

Table A2.17: Specific Weight (kg/hl) for the East Lothian 2019 S rate and timing trial.

N rate	+40 AN At GS 37-39							+40 Foliar At GS 73						
S rate	0	25	50	50 split	75	75 split	100	0	25	50	50 split	75	75 split	100
KWS Zyatt	No Data							No Data						
RGT Skyfall	No Data							No Data						
	P-value	SED	LSD											

Split = Split sulphur rate

Table A2.18: Specific Weight (kg/hl) for the Lincolnshire 2019 S rate and timing trial.

N rate	+40 AN At GS 37-39							+40 Foliar At GS 73						
S rate	0	25	50	50 split	75	75 split	100	0	25	50	50 split	75	75 split	100
KWS Zyatt	74.5	74.6	74.4	74.7	74.1	74.3	-	74.3	73.9	74.5	73.8	74.4	74.0	-
RGT Skyfall	75.1	74.9	74.9	74.6	74.9	74.8	-	75.0	75.3	74.6	74.8	74.8	74.5	-
	P-value	SED	LSD											
	0.003	0.33	0.67											

Split = Split sulphur rate

Table A2.19: Specific Weight (kg/hl) for the Norfolk 2019 S rate and timing trial.

N rate	+40 AN At GS 37-39							+40 Foliar At GS 73						
S rate	0	25	50	50 split	75	75 split	100	0	25	50	50 split	75	75 split	100
KWS Zyatt	78.0	78.3	78.1	78.1	78.0	78.1	-	78.3	78.3	77.0	78.1	77.9	78.2	-
RGT Skyfall	78.1	78.2	78.2	78.4	78.2	78.2	-	78.5	78.3	78.7	78.7	78.0	78.4	-
	P-value	SED	LSD											
	0.425	0.45	0.91											

Split = Split sulphur rate

Table A2.20: Specific Weight (kg/hl) for the Essex 2019 S rate and timing trial.

N rate	+40 AN At GS 37-39							+40 Foliar At GS 73						
S rate	0	25	50	50 split	75	75 split	100	0	25	50	50 split	75	75 split	100
KWS Zyatt	80.2	79.8	79.7	79.5	79.8	79.8	-	79.9	79.7	79.8	79.8	80.0	79.8	-
RGT Skyfall	79.5	79.5	79.4	79.5	79.4	79.5	-	79.7	79.6	79.5	79.6	79.3	79.4	-
	P-value	SED	LSD											
	0.158	0.25	0.50											

Split = Split sulphur rate

Table A2.21: Specific Weight (kg/hl) for the East Lothian 2020 S rate and timing trial.

N rate	+40 AN At GS 37-39							+40 Foliar At GS 73						
S rate	0	25	50	50 split	75	75 split	100	0	25	50	50 split	75	75 split	100
KWS Zyatt	74.0	74.2	73.8	74.2	74.1	74.2	-	74.1	74.0	73.9	74.2	74.1	74.3	-
RGT Skyfall	75.1	75.2	75.0	75.4	75.3	75.3	-	75.0	74.9	75.4	75.2	75.6	75.3	-
	P-value	SED	LSD											
	<0.001	0.27	0.54											

Split = Split sulphur rate

Table A2.22: Specific Weight (kg/hl) for the Essex 2020 S rate and timing trial.

N rate	+40 AN At GS 37-39							+40 Foliar At GS 73						
S rate	0	25	50	50 split	75	75 split	100	0	25	50	50 split	75	75 split	100
KWS Zyatt	76.5	76.1	76.6	76.2	76.4	76.4	-	77.1	76.4	76.6	76.8	76.7	76.6	-
RGT Skyfall	76.6	76.4	76.4	76.4	76.3	75.9	-	76.7	76.4	76.7	76.4	76.2	77.1	-
	P-value	SED	LSD											
	0.745	0.51	1.03											

Split = Split sulphur rate

Table A2.23: Specific Weight (kg/hl) for the Lincolnshire 2021 S rate and timing trial.

N rate	+40 AN At GS 37-39							+40 Foliar At GS 73						
S rate	0	25	50	50 split	75	75 split	100	0	25	50	50 split	75	75 split	100
KWS Zyatt	76.6	-	77.1	76.6	77.3	77.1	77.1	77.7	-	77.4	77.5	77.3	77.6	77.4
RGT Skyfall	78.4	-	78.4	78.0	78.9	78.4	78.6	78.6	-	77.9	78.7	78.6	78.5	78.5
	P-value	SED	LSD											
	<0.001	0.38	0.77											

Split = Split sulphur rate

Table A2.24: Specific Weight (kg/hl) for the Hampshire 2021 S rate and timing trial.

N rate	+40 AN At GS 37-39							+40 Foliar At GS 73						
S rate	0	25	50	50 split	75	75 split	100	0	25	50	50 split	75	75 split	100
KWS Zyatt	75.6	-	75.0	74.1	74.9	75.0	74.9	75.7	-	75.5	75.4	75.1	74.8	75.1
RGT Skyfall	76.8	-	76.1	76.2	76.0	76.1	76.2	76.6	-	76.4	76.2	75.8	76.5	75.7
	P-value	SED	LSD											
	<0.001	0.40	0.81											

Split = Split sulphur rate

Effects of S Rate and Timing on Asparagine concentration

Table A2.25: Asparagine concentration (mmol/kg) for the East Lothian 2019 S rate and timing trial.

Variety	Sample details	Total N	Pre GS30	GS30-31	GS32-35	GS37-39	GS73	sample name	Asparagine	Asn Standard Deviation	Asn Standard error
KWS Zyatt	N1	'RB209' rec. for yield +40	0 SO_3	0 SO_3	0 SO_3	40 AN	0 Foliar N	Trt: 1	2.15	0.33	0.19
	N2		0 SO_3	25 SO_3	0 SO_3	40 AN	0 Foliar N	Trt: 2	2.46	0.65	0.37
	N3		0 SO_3	50 SO_3	0 SO_3	40 AN	0 Foliar N	Trt: 3	1.93	0.50	0.29
	N4		0 SO_3	75 SO_3	0 SO_3	40 AN	0 Foliar N	Trt: 4	1.96	0.40	0.23
	N5		0 SO_3	0 SO_3	0 SO_3	0 AN	40 Foliar N	Trt: 5	2.37	0.40	0.23
	N6		0 SO_3	25 SO_3	0 SO_3	0 AN	40 Foliar N	Trt: 6	1.85	0.61	0.35
	N7		0 SO_3	50 SO_3	0 SO_3	0 AN	40 Foliar N	Trt: 7	1.83	0.43	0.25
	N8		0 SO_3	75 SO_3	0 SO_3	0 AN	40 Foliar N	Trt: 8	2.93	1.59	0.92
	N9		0 SO_3	25 SO_3	25 SO_3	40 AN	0 Foliar N	Trt: 9	2.54	0.45	0.26
	N10		25 SO_3	25 SO_3	25 SO_3	40 AN	0 Foliar N	Trt: 10	1.99	0.21	0.12
	N11		0 SO_3	25 SO_3	25 SO_3	0 AN	40 Foliar N	Trt: 11	2.27	0.75	0.43
	N12		25 SO_3	25 SO_3	25 SO_3	0 AN	40 Foliar N	Trt: 12	2.51	0.33	0.19
	N13		0 SO_3	100 SO_3	0 SO_3	40 AN	0 Foliar N	Trt: 13			
	N14		0 SO_3	100 SO_3	0 SO_3	0 AN	40 Foliar N	Trt: 14			
RGT Skyfall	N1		0 SO_3	0 SO_3	0 SO_3	40 AN	0 Foliar N	Trt: 1	2.20	0.15	0.09
	N2		0 SO_3	25 SO_3	0 SO_3	40 AN	0 Foliar N	Trt: 2	1.95	0.33	0.19
	N3		0 SO_3	50 SO_3	0 SO_3	40 AN	0 Foliar N	Trt: 3	1.99	0.09	0.05
	N4		0 SO_3	75 SO_3	0 SO_3	40 AN	0 Foliar N	Trt: 4	2.83	0.51	0.30
	N5		0 SO_3	0 SO_3	0 SO_3	0 AN	40 Foliar N	Trt: 5	2.31	0.34	0.20
	N6		0 SO_3	25 SO_3	0 SO_3	0 AN	40 Foliar N	Trt: 6	2.12	0.49	0.28
	N7		0 SO_3	50 SO_3	0 SO_3	0 AN	40 Foliar N	Trt: 7	2.02	0.15	0.09
	N8		0 SO_3	75 SO_3	0 SO_3	0 AN	40 Foliar N	Trt: 8	2.31	0.30	0.17
	N9		0 SO_3	25 SO_3	25 SO_3	40 AN	0 Foliar N	Trt: 9	2.13	0.26	0.15
	N10		25 SO_3	25 SO_3	25 SO_3	40 AN	0 Foliar N	Trt: 10	1.92	0.04	0.02
	N11		0 SO_3	25 SO_3	25 SO_3	0 AN	40 Foliar N	Trt: 11	2.86	0.23	0.13
	N12		25 SO_3	25 SO_3	25 SO_3	0 AN	40 Foliar N	Trt: 12	2.20	0.36	0.21
	N13		0 SO_3	100 SO_3	0 SO_3	40 AN	0 Foliar N	Trt: 13			
	N14		0 SO_3	100 SO_3	0 SO_3	0 AN	40 Foliar N	Trt: 14			

Table A2.26: Asparagine concentration (mmol/kg) for the Lincolnshire 2019 S rate and timing trial.

Variety	Sample details	Total N	Pre GS30	GS30-31	GS32-35	GS37-39	GS73	sample name	Asparagine	Asn Standard Deviation	Asn Standard error
KWS Zyatt	N1	‘RB209’ rec. for yield +40	0 SO_3	0 SO_3	0 SO_3	40 AN	0 Foliar N	Trt: 1	3.35	1.20	0.70
	N2		0 SO_3	25 SO_3	0 SO_3	40 AN	0 Foliar N	Trt: 2	3.49	0.67	0.39
	N3		0 SO_3	50 SO_3	0 SO_3	40 AN	0 Foliar N	Trt: 3	3.64	0.74	0.43
	N4		0 SO_3	75 SO_3	0 SO_3	40 AN	0 Foliar N	Trt: 4	3.27	0.09	0.05
	N5		0 SO_3	0 SO_3	0 SO_3	0 AN	40 Foliar N	Trt: 5	5.09	0.95	0.55
	N6		0 SO_3	25 SO_3	0 SO_3	0 AN	40 Foliar N	Trt: 6	2.32	0.11	0.06
	N7		0 SO_3	50 SO_3	0 SO_3	0 AN	40 Foliar N	Trt: 7	2.17	0.48	0.27
	N8		0 SO_3	75 SO_3	0 SO_3	0 AN	40 Foliar N	Trt: 8	2.19	0.36	0.21
	N9		0 SO_3	25 SO_3	25 SO_3	40 AN	0 Foliar N	Trt: 9	2.81	0.57	0.33
	N10		25 SO_3	25 SO_3	25 SO_3	40 AN	0 Foliar N	Trt: 10	2.03	0.10	0.06
	N11		0 SO_3	25 SO_3	25 SO_3	0 AN	40 Foliar N	Trt: 11	2.03	0.19	0.11
	N12		25 SO_3	25 SO_3	25 SO_3	0 AN	40 Foliar N	Trt: 12	2.02	0.07	0.04
	N13		0 SO_3	100 SO_3	0 SO_3	40 AN	0 Foliar N	Trt: 13			
	N14		0 SO_3	100 SO_3	0 SO_3	0 AN	40 Foliar N	Trt: 14			
RGT Skyfall	N1		0 SO_3	0 SO_3	0 SO_3	40 AN	0 Foliar N	Trt: 1	2.57	0.76	0.44
	N2		0 SO_3	25 SO_3	0 SO_3	40 AN	0 Foliar N	Trt: 2	2.48	0.43	0.25
	N3		0 SO_3	50 SO_3	0 SO_3	40 AN	0 Foliar N	Trt: 3	2.89	0.42	0.24
	N4		0 SO_3	75 SO_3	0 SO_3	40 AN	0 Foliar N	Trt: 4	2.19	0.20	0.12
	N5		0 SO_3	0 SO_3	0 SO_3	0 AN	40 Foliar N	Trt: 5	2.75	0.34	0.20
	N6		0 SO_3	25 SO_3	0 SO_3	0 AN	40 Foliar N	Trt: 6	2.26	0.41	0.24
	N7		0 SO_3	50 SO_3	0 SO_3	0 AN	40 Foliar N	Trt: 7	2.33	0.08	0.05
	N8		0 SO_3	75 SO_3	0 SO_3	0 AN	40 Foliar N	Trt: 8	3.03	1.60	0.93
	N9		0 SO_3	25 SO_3	25 SO_3	40 AN	0 Foliar N	Trt: 9	3.53	0.55	0.32
	N10		25 SO_3	25 SO_3	25 SO_3	40 AN	0 Foliar N	Trt: 10	3.26	0.33	0.19
	N11		0 SO_3	25 SO_3	25 SO_3	0 AN	40 Foliar N	Trt: 11	3.14	0.66	0.38
	N12		25 SO_3	25 SO_3	25 SO_3	0 AN	40 Foliar N	Trt: 12	3.67	1.38	0.80
	N13		0 SO_3	100 SO_3	0 SO_3	40 AN	0 Foliar N	Trt: 13			
	N14		0 SO_3	100 SO_3	0 SO_3	0 AN	40 Foliar N	Trt: 14			

Table A2.27: Asparagine concentration (mmol/kg) for the Norfolk 2019 S rate and timing trial.

Variety	Sample details	Total N	Pre GS30	GS30-31	GS32-35	GS37-39	GS73	sample name	Asparagine	Asn Standard Deviation	Asn Standard error
KWS Zyatt	N1	'RB209' rec. for yield +40	0 SO_3	0 SO_3	0 SO_3	40 AN	0 Foliar N	Trt: 1	4.37	1.72	0.99
	N2		0 SO_3	25 SO_3	0 SO_3	40 AN	0 Foliar N	Trt: 2	4.50	0.74	0.43
	N3		0 SO_3	50 SO_3	0 SO_3	40 AN	0 Foliar N	Trt: 3	4.72	1.50	0.86
	N4		0 SO_3	75 SO_3	0 SO_3	40 AN	0 Foliar N	Trt: 4	3.15	0.95	0.55
	N5		0 SO_3	0 SO_3	0 SO_3	0 AN	40 Foliar N	Trt: 5	4.45	0.52	0.30
	N6		0 SO_3	25 SO_3	0 SO_3	0 AN	40 Foliar N	Trt: 6	5.36	1.83	1.06
	N7		0 SO_3	50 SO_3	0 SO_3	0 AN	40 Foliar N	Trt: 7	4.05	0.31	0.18
	N8		0 SO_3	75 SO_3	0 SO_3	0 AN	40 Foliar N	Trt: 8	4.27	1.56	0.90
	N9		0 SO_3	25 SO_3	25 SO_3	40 AN	0 Foliar N	Trt: 9	4.21	1.03	0.59
	N10		25 SO_3	25 SO_3	25 SO_3	40 AN	0 Foliar N	Trt: 10	3.49	0.25	0.14
	N11		0 SO_3	25 SO_3	25 SO_3	0 AN	40 Foliar N	Trt: 11	3.56	0.33	0.19
	N12		25 SO_3	25 SO_3	25 SO_3	0 AN	40 Foliar N	Trt: 12	3.34	0.60	0.35
	N13		0 SO_3	100 SO_3	0 SO_3	40 AN	0 Foliar N	Trt: 13			
	N14		0 SO_3	100 SO_3	0 SO_3	0 AN	40 Foliar N	Trt: 14			
RGT Skyfall	N1		0 SO_3	0 SO_3	0 SO_3	40 AN	0 Foliar N	Trt: 1	5.13	1.68	0.97
	N2		0 SO_3	25 SO_3	0 SO_3	40 AN	0 Foliar N	Trt: 2	4.14	1.30	0.75
	N3		0 SO_3	50 SO_3	0 SO_3	40 AN	0 Foliar N	Trt: 3	5.44	1.56	0.90
	N4		0 SO_3	75 SO_3	0 SO_3	40 AN	0 Foliar N	Trt: 4	4.94	0.77	0.45
	N5		0 SO_3	0 SO_3	0 SO_3	0 AN	40 Foliar N	Trt: 5	2.93	0.58	0.33
	N6		0 SO_3	25 SO_3	0 SO_3	0 AN	40 Foliar N	Trt: 6	3.25	0.43	0.25
	N7		0 SO_3	50 SO_3	0 SO_3	0 AN	40 Foliar N	Trt: 7	3.53	0.78	0.45
	N8		0 SO_3	75 SO_3	0 SO_3	0 AN	40 Foliar N	Trt: 8	2.48	0.55	0.32
	N9		0 SO_3	25 SO_3	25 SO_3	40 AN	0 Foliar N	Trt: 9	3.24	1.47	0.85
	N10		25 SO_3	25 SO_3	25 SO_3	40 AN	0 Foliar N	Trt: 10	3.61	0.74	0.43
	N11		0 SO_3	25 SO_3	25 SO_3	0 AN	40 Foliar N	Trt: 11	3.94	0.37	0.26
	N12		25 SO_3	25 SO_3	25 SO_3	0 AN	40 Foliar N	Trt: 12	2.98	0.52	0.30
	N13		0 SO_3	100 SO_3	0 SO_3	40 AN	0 Foliar N	Trt: 13			
	N14		0 SO_3	100 SO_3	0 SO_3	0 AN	40 Foliar N	Trt: 14			

Table A2.28: Asparagine concentration (mmol/kg) for the Essex 2019 S rate and timing trial.

Variety	Sample details	Total N	Pre GS30	GS30-31	GS32-35	GS37-39	GS73	sample name	Asparagine	Asn Standard Deviation	Asn Standard error
KWS Zyatt	N1	‘RB209’ rec. for yield +40	0 SO_3	0 SO_3	0 SO_3	40 AN	0 Foliar N	Trt: 1	3.34	0.13	0.08
	N2		0 SO_3	25 SO_3	0 SO_3	40 AN	0 Foliar N	Trt: 2	3.12	0.26	0.15
	N3		0 SO_3	50 SO_3	0 SO_3	40 AN	0 Foliar N	Trt: 3	3.42	0.76	0.44
	N4		0 SO_3	75 SO_3	0 SO_3	40 AN	0 Foliar N	Trt: 4	3.64	0.51	0.30
	N5		0 SO_3	0 SO_3	0 SO_3	0 AN	40 Foliar N	Trt: 5	3.01	0.33	0.19
	N6		0 SO_3	25 SO_3	0 SO_3	0 AN	40 Foliar N	Trt: 6	3.77	1.07	0.62
	N7		0 SO_3	50 SO_3	0 SO_3	0 AN	40 Foliar N	Trt: 7	2.71	0.42	0.24
	N8		0 SO_3	75 SO_3	0 SO_3	0 AN	40 Foliar N	Trt: 8	2.39	0.23	0.13
	N9		0 SO_3	25 SO_3	25 SO_3	40 AN	0 Foliar N	Trt: 9	3.33	0.52	0.30
	N10		25 SO_3	25 SO_3	25 SO_3	40 AN	0 Foliar N	Trt: 10	2.98	0.77	0.44
	N11		0 SO_3	25 SO_3	25 SO_3	0 AN	40 Foliar N	Trt: 11	2.30	0.35	0.20
	N12		25 SO_3	25 SO_3	25 SO_3	0 AN	40 Foliar N	Trt: 12	2.56	0.29	0.17
	N13		0 SO_3	100 SO_3	0 SO_3	40 AN	0 Foliar N	Trt: 13			
	N14		0 SO_3	100 SO_3	0 SO_3	0 AN	40 Foliar N	Trt: 14			
RGT Skyfall	N1		0 SO_3	0 SO_3	0 SO_3	40 AN	0 Foliar N	Trt: 1	3.14	1.22	0.71
	N2		0 SO_3	25 SO_3	0 SO_3	40 AN	0 Foliar N	Trt: 2	2.85	0.23	0.13
	N3		0 SO_3	50 SO_3	0 SO_3	40 AN	0 Foliar N	Trt: 3	4.25	0.25	0.15
	N4		0 SO_3	75 SO_3	0 SO_3	40 AN	0 Foliar N	Trt: 4	3.82	1.50	0.87
	N5		0 SO_3	0 SO_3	0 SO_3	0 AN	40 Foliar N	Trt: 5	3.40	0.51	0.29
	N6		0 SO_3	25 SO_3	0 SO_3	0 AN	40 Foliar N	Trt: 6	3.54	0.22	0.13
	N7		0 SO_3	50 SO_3	0 SO_3	0 AN	40 Foliar N	Trt: 7	4.13	0.30	0.17
	N8		0 SO_3	75 SO_3	0 SO_3	0 AN	40 Foliar N	Trt: 8	4.10	0.29	0.17
	N9		0 SO_3	25 SO_3	25 SO_3	40 AN	0 Foliar N	Trt: 9	4.26	0.76	0.44
	N10		25 SO_3	25 SO_3	25 SO_3	40 AN	0 Foliar N	Trt: 10	3.61	0.77	0.45
	N11		0 SO_3	25 SO_3	25 SO_3	0 AN	40 Foliar N	Trt: 11	3.71	1.77	1.02
	N12		25 SO_3	25 SO_3	25 SO_3	0 AN	40 Foliar N	Trt: 12	4.07	0.50	0.29
	N13		0 SO_3	100 SO_3	0 SO_3	40 AN	0 Foliar N	Trt: 13			
	N14		0 SO_3	100 SO_3	0 SO_3	0 AN	40 Foliar N	Trt: 14			

Table A2.29: Asparagine concentration (mmol/kg) for the East Lothian 2020 S rate and timing trial.

Variety	Sample details	Total N	Pre GS30	GS30-31	GS32-35	GS37-39	GS73	sample name	Asparagine	Asn Standard Deviation	Asn Standard error
KWS Zyatt	N1	'RB209' rec. for yield +40	0 SO_3	0 SO_3	0 SO_3	40 AN	0 Foliar N	Trt: 1	3.06	0.76	0.44
	N2		0 SO_3	25 SO_3	0 SO_3	40 AN	0 Foliar N	Trt: 2	2.73	0.38	0.22
	N3		0 SO_3	50 SO_3	0 SO_3	40 AN	0 Foliar N	Trt: 3	3.19	0.65	0.37
	N4		0 SO_3	75 SO_3	0 SO_3	40 AN	0 Foliar N	Trt: 4	3.61	0.97	0.56
	N5		0 SO_3	0 SO_3	0 SO_3	0 AN	40 Foliar N	Trt: 5	3.22	0.45	0.26
	N6		0 SO_3	25 SO_3	0 SO_3	0 AN	40 Foliar N	Trt: 6	3.53	0.85	0.49
	N7		0 SO_3	50 SO_3	0 SO_3	0 AN	40 Foliar N	Trt: 7	5.37	1.12	0.64
	N8		0 SO_3	75 SO_3	0 SO_3	0 AN	40 Foliar N	Trt: 8	4.63	0.56	0.33
	N9		0 SO_3	25 SO_3	25 SO_3	40 AN	0 Foliar N	Trt: 9	3.21	0.36	0.21
	N10		25 SO_3	25 SO_3	25 SO_3	40 AN	0 Foliar N	Trt: 10	4.20	0.49	0.28
	N11		0 SO_3	25 SO_3	25 SO_3	0 AN	40 Foliar N	Trt: 11	5.81	1.12	0.65
	N12		25 SO_3	25 SO_3	25 SO_3	0 AN	40 Foliar N	Trt: 12	5.11	0.33	0.19
	N13		0 SO_3	100 SO_3	0 SO_3	40 AN	0 Foliar N	Trt: 13			
	N14		0 SO_3	100 SO_3	0 SO_3	0 AN	40 Foliar N	Trt: 14			
RGT Skyfall	N1		0 SO_3	0 SO_3	0 SO_3	40 AN	0 Foliar N	Trt: 1	2.73	0.30	0.17
	N2		0 SO_3	25 SO_3	0 SO_3	40 AN	0 Foliar N	Trt: 2	4.21	0.34	0.20
	N3		0 SO_3	50 SO_3	0 SO_3	40 AN	0 Foliar N	Trt: 3	4.80	0.89	0.51
	N4		0 SO_3	75 SO_3	0 SO_3	40 AN	0 Foliar N	Trt: 4	4.65	0.93	0.54
	N5		0 SO_3	0 SO_3	0 SO_3	0 AN	40 Foliar N	Trt: 5	3.96	0.98	0.57
	N6		0 SO_3	25 SO_3	0 SO_3	0 AN	40 Foliar N	Trt: 6	5.27	1.04	0.60
	N7		0 SO_3	50 SO_3	0 SO_3	0 AN	40 Foliar N	Trt: 7	3.84	1.18	0.68
	N8		0 SO_3	75 SO_3	0 SO_3	0 AN	40 Foliar N	Trt: 8	4.37	0.43	0.25
	N9		0 SO_3	25 SO_3	25 SO_3	40 AN	0 Foliar N	Trt: 9	3.98	0.31	0.18
	N10		25 SO_3	25 SO_3	25 SO_3	40 AN	0 Foliar N	Trt: 10	2.92	0.67	0.39
	N11		0 SO_3	25 SO_3	25 SO_3	0 AN	40 Foliar N	Trt: 11	3.35	0.55	0.32
	N12		25 SO_3	25 SO_3	25 SO_3	0 AN	40 Foliar N	Trt: 12	3.17	0.51	0.29
	N13		0 SO_3	100 SO_3	0 SO_3	40 AN	0 Foliar N	Trt: 13			
	N14		0 SO_3	100 SO_3	0 SO_3	0 AN	40 Foliar N	Trt: 14			

Table A2.30 Asparagine concentration (mmol/kg) for the Essex 2020 S rate and timing trial.

Variety	Sample details	Total N	Pre GS30	GS30-31	GS32-35	GS37-39	GS73	sample name	Asparagine	Asn Standard Deviation	Asn Standard error
KWS Zyatt	N1	‘RB209’ rec. for yield +40	0 SO_3	0 SO_3	0 SO_3	40 AN	0 Foliar N	Trt: 1	3.75	0.65	0.37
	N2		0 SO_3	25 SO_3	0 SO_3	40 AN	0 Foliar N	Trt: 2	4.96	0.57	0.41
	N3		0 SO_3	50 SO_3	0 SO_3	40 AN	0 Foliar N	Trt: 3	4.65	0.58	0.33
	N4		0 SO_3	75 SO_3	0 SO_3	40 AN	0 Foliar N	Trt: 4	3.50	0.18	0.11
	N5		0 SO_3	0 SO_3	0 SO_3	0 AN	40 Foliar N	Trt: 5	1.61	0.43	0.25
	N6		0 SO_3	25 SO_3	0 SO_3	0 AN	40 Foliar N	Trt: 6	2.32	1.30	0.75
	N7		0 SO_3	50 SO_3	0 SO_3	0 AN	40 Foliar N	Trt: 7	2.02	3.34	1.93
	N8		0 SO_3	75 SO_3	0 SO_3	0 AN	40 Foliar N	Trt: 8	1.29	0.63	0.36
	N9		0 SO_3	25 SO_3	25 SO_3	40 AN	0 Foliar N	Trt: 9	2.31	0.92	0.53
	N10		25 SO_3	25 SO_3	25 SO_3	40 AN	0 Foliar N	Trt: 10	1.01	2.08	1.20
	N11		0 SO_3	25 SO_3	25 SO_3	0 AN	40 Foliar N	Trt: 11	2.57	1.24	0.72
	N12		25 SO_3	25 SO_3	25 SO_3	0 AN	40 Foliar N	Trt: 12	2.78	0.32	0.18
	N13		0 SO_3	100 SO_3	0 SO_3	40 AN	0 Foliar N	Trt: 13			
	N14		0 SO_3	100 SO_3	0 SO_3	0 AN	40 Foliar N	Trt: 14			
RGT Skyfall	N1		0 SO_3	0 SO_3	0 SO_3	40 AN	0 Foliar N	Trt: 1	2.25	0.68	0.39
	N2		0 SO_3	25 SO_3	0 SO_3	40 AN	0 Foliar N	Trt: 2	5.25	4.00	2.31
	N3		0 SO_3	50 SO_3	0 SO_3	40 AN	0 Foliar N	Trt: 3	3.25	1.53	0.88
	N4		0 SO_3	75 SO_3	0 SO_3	40 AN	0 Foliar N	Trt: 4	4.35	1.25	0.72
	N5		0 SO_3	0 SO_3	0 SO_3	0 AN	40 Foliar N	Trt: 5	1.94	0.55	0.32
	N6		0 SO_3	25 SO_3	0 SO_3	0 AN	40 Foliar N	Trt: 6	2.34	1.73	1.00
	N7		0 SO_3	50 SO_3	0 SO_3	0 AN	40 Foliar N	Trt: 7	3.89	0.36	0.21
	N8		0 SO_3	75 SO_3	0 SO_3	0 AN	40 Foliar N	Trt: 8	2.11	0.55	0.32
	N9		0 SO_3	25 SO_3	25 SO_3	40 AN	0 Foliar N	Trt: 9	2.80	0.85	0.49
	N10		25 SO_3	25 SO_3	25 SO_3	40 AN	0 Foliar N	Trt: 10	4.43	1.25	0.72
	N11		0 SO_3	25 SO_3	25 SO_3	0 AN	40 Foliar N	Trt: 11	3.71	0.76	0.44
	N12		25 SO_3	25 SO_3	25 SO_3	0 AN	40 Foliar N	Trt: 12	6.55	3.40	1.96
	N13		0 SO_3	100 SO_3	0 SO_3	40 AN	0 Foliar N	Trt: 13			
	N14		0 SO_3	100 SO_3	0 SO_3	0 AN	40 Foliar N	Trt: 14			

Table A2.31: Asparagine concentration (mmol/kg) for the Lincolnshire 2021 S rate and timing trial.

Variety	Sample details	Total N	Pre GS30	GS30-31	GS32-35	GS37-39	GS73	sample name	Asparagine	Asn Standard Deviation	Asn Standard error
KWS Zyatt	N1	'RB209' rec. for yield +40	0 SO_3	0 SO_3	0 SO_3	40 AN	0 Foliar N	Trt: 1	1.47	0.07	0.04
	N2		0 SO_3	25 SO_3	0 SO_3	40 AN	0 Foliar N	Trt: 2			
	N3		0 SO_3	50 SO_3	0 SO_3	40 AN	0 Foliar N	Trt: 3	1.30	0.02	0.01
	N4		0 SO_3	75 SO_3	0 SO_3	40 AN	0 Foliar N	Trt: 4	1.30	0.06	0.04
	N5		0 SO_3	0 SO_3	0 SO_3	0 AN	40 Foliar N	Trt: 5	1.47	0.04	0.02
	N6		0 SO_3	25 SO_3	0 SO_3	0 AN	40 Foliar N	Trt: 6			
	N7		0 SO_3	50 SO_3	0 SO_3	0 AN	40 Foliar N	Trt: 7	1.29	0.07	0.04
	N8		0 SO_3	75 SO_3	0 SO_3	0 AN	40 Foliar N	Trt: 8	1.20	0.03	0.02
	N9		0 SO_3	25 SO_3	25 SO_3	40 AN	0 Foliar N	Trt: 9	1.28	0.14	0.08
	N10		25 SO_3	25 SO_3	25 SO_3	40 AN	0 Foliar N	Trt: 10	1.39	0.07	0.04
	N11		0 SO_3	25 SO_3	25 SO_3	0 AN	40 Foliar N	Trt: 11	1.32	0.02	0.01
	N12		25 SO_3	25 SO_3	25 SO_3	0 AN	40 Foliar N	Trt: 12	1.53	0.05	0.03
	N13		0 SO_3	100 SO_3	0 SO_3	40 AN	0 Foliar N	Trt: 13	1.38	0.01	0.01
	N14		0 SO_3	100 SO_3	0 SO_3	0 AN	40 Foliar N	Trt: 14	1.34	0.07	0.04
RGT Skyfall	N1		0 SO_3	0 SO_3	0 SO_3	40 AN	0 Foliar N	Trt: 1	1.38	0.03	0.02
	N2		0 SO_3	25 SO_3	0 SO_3	40 AN	0 Foliar N	Trt: 2			
	N3		0 SO_3	50 SO_3	0 SO_3	40 AN	0 Foliar N	Trt: 3	1.53	0.02	0.01
	N4		0 SO_3	75 SO_3	0 SO_3	40 AN	0 Foliar N	Trt: 4	1.46	0.06	0.04
	N5		0 SO_3	0 SO_3	0 SO_3	0 AN	40 Foliar N	Trt: 5	1.28	0.01	0.01
	N6		0 SO_3	25 SO_3	0 SO_3	0 AN	40 Foliar N	Trt: 6			
	N7		0 SO_3	50 SO_3	0 SO_3	0 AN	40 Foliar N	Trt: 7	1.30	0.03	0.02
	N8		0 SO_3	75 SO_3	0 SO_3	0 AN	40 Foliar N	Trt: 8	1.34	0.04	0.02
	N9		0 SO_3	25 SO_3	25 SO_3	40 AN	0 Foliar N	Trt: 9	1.37	0.04	0.02
	N10		25 SO_3	25 SO_3	25 SO_3	40 AN	0 Foliar N	Trt: 10	1.44	0.07	0.04
	N11		0 SO_3	25 SO_3	25 SO_3	0 AN	40 Foliar N	Trt: 11	1.33	0.05	0.03
	N12		25 SO_3	25 SO_3	25 SO_3	0 AN	40 Foliar N	Trt: 12	1.27	0.03	0.02
	N13		0 SO_3	100 SO_3	0 SO_3	40 AN	0 Foliar N	Trt: 13	1.48	0.01	0.01
	N14		0 SO_3	100 SO_3	0 SO_3	0 AN	40 Foliar N	Trt: 14	1.44	0.09	0.05

Table A2.32: Asparagine concentration (mmol/kg) for the Hampshire 2021 S rate and timing trial.

Variety	Sample details	Total N	Pre GS30	GS30-31	GS32-35	GS37-39	GS73	sample name	Asparagine	Asn Standard Deviation	Asn Standard error
KWS Zyatt	N1	'RB209' rec. for yield +40	0 SO_3	0 SO_3	0 SO_3	40 AN	0 Foliar N	Trt: 1	3.27	0.19	0.11
	N2		0 SO_3	25 SO_3	0 SO_3	40 AN	0 Foliar N	Trt: 2			
	N3		0 SO_3	50 SO_3	0 SO_3	40 AN	0 Foliar N	Trt: 3	2.57	0.08	0.05
	N4		0 SO_3	75 SO_3	0 SO_3	40 AN	0 Foliar N	Trt: 4	2.51	0.22	0.13
	N5		0 SO_3	0 SO_3	0 SO_3	0 AN	40 Foliar N	Trt: 5	2.31	0.24	0.14
	N6		0 SO_3	25 SO_3	0 SO_3	0 AN	40 Foliar N	Trt: 6			
	N7		0 SO_3	50 SO_3	0 SO_3	0 AN	40 Foliar N	Trt: 7	2.79	0.16	0.09
	N8		0 SO_3	75 SO_3	0 SO_3	0 AN	40 Foliar N	Trt: 8	2.36	0.10	0.06
	N9		0 SO_3	25 SO_3	25 SO_3	40 AN	0 Foliar N	Trt: 9	2.48	0.38	0.22
	N10		25 SO_3	25 SO_3	25 SO_3	40 AN	0 Foliar N	Trt: 10	2.66	0.09	0.05
	N11		0 SO_3	25 SO_3	25 SO_3	0 AN	40 Foliar N	Trt: 11	2.60	0.03	0.02
	N12		25 SO_3	25 SO_3	25 SO_3	0 AN	40 Foliar N	Trt: 12	2.74	0.02	0.01
	N13		0 SO_3	100 SO_3	0 SO_3	40 AN	0 Foliar N	Trt: 13	2.65	0.10	0.06
	N14		0 SO_3	100 SO_3	0 SO_3	0 AN	40 Foliar N	Trt: 14	2.64	0.07	0.04
RGT Skyfall	N1		0 SO_3	0 SO_3	0 SO_3	40 AN	0 Foliar N	Trt: 1	2.83	0.07	0.04
	N2		0 SO_3	25 SO_3	0 SO_3	40 AN	0 Foliar N	Trt: 2			
	N3		0 SO_3	50 SO_3	0 SO_3	40 AN	0 Foliar N	Trt: 3	2.12	0.05	0.03
	N4		0 SO_3	75 SO_3	0 SO_3	40 AN	0 Foliar N	Trt: 4	2.17	0.06	0.03
	N5		0 SO_3	0 SO_3	0 SO_3	0 AN	40 Foliar N	Trt: 5	2.27	0.05	0.03
	N6		0 SO_3	25 SO_3	0 SO_3	0 AN	40 Foliar N	Trt: 6			
	N7		0 SO_3	50 SO_3	0 SO_3	0 AN	40 Foliar N	Trt: 7	2.69	0.16	0.09
	N8		0 SO_3	75 SO_3	0 SO_3	0 AN	40 Foliar N	Trt: 8	2.47	0.10	0.06
	N9		0 SO_3	25 SO_3	25 SO_3	40 AN	0 Foliar N	Trt: 9	2.27	0.08	0.05
	N10		25 SO_3	25 SO_3	25 SO_3	40 AN	0 Foliar N	Trt: 10	2.38	0.10	0.06
	N11		0 SO_3	25 SO_3	25 SO_3	0 AN	40 Foliar N	Trt: 11	2.43	0.10	0.06
	N12		25 SO_3	25 SO_3	25 SO_3	0 AN	40 Foliar N	Trt: 12	2.59	0.27	0.15
	N13		0 SO_3	100 SO_3	0 SO_3	40 AN	0 Foliar N	Trt: 13	2.62	0.04	0.03
	N14		0 SO_3	100 SO_3	0 SO_3	0 AN	40 Foliar N	Trt: 14	2.37	0.04	0.02

APPENDIX 3. Objective 4. To assess the impact of N and S fertiliser rate and timing on dough rheology and baking performance.

Table A3.1: Rheology and baking for the Norfolk 2019 N rate and timing trial.

Norfolk 2019 - N rate and timing			Wheat analysis							Flour						Farinograph				Extensograph				Minolta colour			CBP test baking $						Loaf volume for unit level of protein (dm)	
ATC sample no.	Variety	Treatmen No.	Moist. %	Prot. % at DM	Prot	Sp.wt. (kg/hl)	Sp wht	Hard-ness	Ext.rate %	Moist. %	Prot. %	Prot. % at DM	Prot % loss on milling	Water Abs. %	W.abs @ 14% moist	Arr. mins	Peak mins	Stab. mins	Tol. BU	Res. BU	Ext. cm	Area cm2	R/E	L*	b*	L*-b*	Loaf vol. cm3	Bread quality	Crumb Structure	Crumb texture	Crumb colour	Quality Score 1-9		
ATC method			NIT07 $	NIT08	Post harvest	GRN09	Post harvest	MIS43$	PRP04	NIT07 $	NIT08	Cal.$	Cal.$	RHE01	Calculated	RHE02				RHE03				MIS44$			MIS37$	MIS07$					Wheat Prot.	Flour Prot.
LA20.00750	KWS Zyatt	T2	14.4	12.8	12.5	79.5	78.4	47	80.8	14.6	9.7	11.4	1.4	54.6	55.7	1.5	2.0	4.0	80	380	15.8	65	2.4	81.86	12.52	69.34	3650	Moderate to good	Slightly Weak	Fine	White	5	285	321
LA20.00751	KWS Zyatt	T3	14.5	13.1	12.9	79.3	79.3	47	81.0	14.2	10.0	11.7	1.4	55.6	56.0	1.0	2.0	4.0	70	270	17.0	64	1.6	82.27	12.47	69.80	3580	Moderate to poor	Weak	Fine	White	3	274	307
LA20.00752	KWS Zyatt	T4	14.5	12.6	12.7	79.2	79.1	48	81.4	14.1	9.9	11.5	1.1	56.1	56.2	1.0	2.0	4.0	60	270	17.5	70	1.5	81.39	12.68	68.71	3660	Moderate	Slightly Weak	Slightly coarse	White	4	291	318
LA20.00753	KWS Zyatt	T5	14.5	12.8	12.7	79.2	78.9	50	81.0	14.6	9.7	11.4	1.4	54.8	55.9	1.0	2.0	4.5	60	300	16.1	70	1.9	81.78	12.54	69.24	3690	Moderate	Slightly Weak	Slightly coarse	White	4	289	325
LA20.00754	KWS Zyatt	T6	14.5	12.4	12.6	79.1	78.8	47	80.9	14.3	9.7	11.3	1.1	54.2	54.7	1.0	2.0	4.5	60	300	15.3	65	2.0	81.62	12.61	69.01	3760	Moderate to good	Resilient	Slightly coarse	White	5	303	332
LA20.00755	KWS Zyatt	T7	14.5	12.7	12.6	79.1	79.0	50	81.1	14.2	10.0	11.7	1.1	55.6	56.0	1.5	2.0	4.5	60	290	15.8	63	1.8	82.49	12.43	70.06	3740	Moderate	Doughy / Weak	Fine	White	4	294	321
LA20.00756	KWS Zyatt	T8	14.6	12.2	12.4	79.2	78.9	45	80.7	14.6	9.5	11.1	1.1	54.6	55.7	1.0	1.5	4.0	60	310	16.0	63	1.9	81.67	12.08	69.59	3690	Moderate to poor	Weak	Fine	White	3	301	332
LA20.00757	KWS Siskin	T2	14.5	12.5	12.6	79.3	79.3	49	80.9	14.4	9.8	11.4	1.0	55.3	56.0	1.5	2.5	4.5	70	290	15.7	64	1.8	81.52	12.32	69.20	3760	Moderate to good	Slightly Weak	Slightly coarse	White	5	301	328
LA20.00758	KWS Siskin	T3	14.4	12.7	12.8	79.6	79.3	48	81.2	14.3	9.9	11.6	1.2	56.3	56.8	1.0	2.0	4.0	60	270	16.2	64	1.7	81.38	12.53	68.85	3800	Good to moderate	Slightly Weak	Fine	White	6	298	329
LA20.00759	KWS Siskin	T4	14.4	12.3	12.3	79.3	79.0	48	80.8	14.6	9.6	11.2	1.0	54.6	55.7	1.5	2.5	4.0	70	270	15.8	61	1.7	81.61	12.42	69.19	3730	Moderate to poor	Doughy / Weak	Fine	White	3	304	332
LA20.00760	KWS Siskin	T5	14.6	12.3	12.3	78.7	78.3	49	80.7	14.3	9.5	11.1	1.2	55.4	55.9	1.0	2.0	4.0	80	290	14.1	59	2.1	81.49	12.65	68.84	3610	Moderate	Doughy / Weak	Fine	White	4	294	326
LA20.00761	KWS Siskin	T6	14.6	12.2	12.2	78.0	78.0	48	81.1	14.3	9.4	11.0	1.3	54.7	55.2	1.0	2.0	4.0	70	270	15.0	59	1.8	82.09	12.42	69.67	3800	Moderate to good	Slightly Weak	Fine	White	5	311	346
LA20.00762	KWS Siskin	T7	14.6	12.9	13.0	79.6	79.0	53	80.4	14.7	10.0	11.7	1.2	55.1	56.4	1.5	2.0	4.5	40	310	16.8	70	1.8	81.37	12.49	68.88	3760	Moderate	Slightly Weak	Slightly coarse	White	4	291	321
LA20.00763	KWS Siskin	T8	14.7	13.2	13.1	80.0	79.2	54	80.4	14.5	10.3	12.0	1.2	56.1	57.0	1.5	4.0	5.0	80	310	17.5	77	1.8	81.53	12.61	68.92	3740	Moderate to good	Slightly Weak	Fine	White	5	283	310
LA20.00764	RGT Skyfall	T2	14.4	12.9	12.8	80.3	80.5	45	80.5	14.4	10.2	11.9	1.0	56.7	57.4	1.5	2.0	4.5	50	310	16.1	70	1.9	80.76	11.96	68.80	3800	Good	Resilient	Fine	White	7	294	319
LA20.00765	RGT Skyfall	T3	14.6	12.7	12.9	79.3	79.4	51	81.0	14.6	10.1	11.8	0.9	55.3	56.4	1.5	2.0	4.5	60	300	16.4	70	1.8	81.02	12.21	68.81	3790	Good to moderate	Slightly Weak	Fine	White	6	298	320
LA20.00766	RGT Skyfall	T4	14.7	12.1	12.1	79.5	79.7	43	80.0	14.5	9.4	11.0	1.1	53.8	54.7	1.0	2.0	4.0	70	310	16.2	71	1.9	82.06	11.77	70.29	3920	Good	Resilient	Fine	White	7	323	357
LA20.00767	RGT Skyfall	T5	14.6	13.1	12.7	79.5	79.9	54	80.6	14.3	10.1	11.8	1.3	56.4	56.9	1.5	2.0	4.5	50	320	17.0	76	1.9	81.91	12.19	69.72	3730	Good to moderate	Slightly Weak	Fine	White	6	286	316
LA20.00768	RGT Skyfall	T6	14.5	12.7	12.8	79.8	79.4	49	80.7	14.8	9.9	11.6	1.1	55.0	56.4	1.0	2.0	5.0	50	310	16.4	72	1.9	80.75	12.56	68.19	3850	Good	Resilient	Fine	White	7	303	331
LA20.00769	RGT Skyfall	T7	14.5	13.2	13.0	80.2	80.1	47	80.2	14.5	10.5	12.3	0.9	56.2	57.1	1.0	2.0	5.0	50	330	16.7	81	2.0	81.31	12.34	68.97	3830	Very good	Resilient	Fine	White	8	290	312
LA20.00770	RGT Skyfall	T8	14.6	13.1	12.6	78.8	78.7	45	80.9	14.3	10.1	11.8	1.3	55.3	55.8	1.0	2.0	5.0	30	330	16.0	73	2.1	81.15	12.32	68.83	3900	Very good	Resilient	Fine	White	8	298	331
All sample Mean			14.5	12.7	12.6	79.4	79.2	48	80.8	14.4	9.9	11.5	1.2	55.3	56.1	1.2	2.1	4.4	61	302	16.2	68	1.9	81.57	12.39	69.19	3752					5.2	296	325
All sample Max			14.7	13.2	13.1	80.3	80.5	54	81.4	14.8	10.5	12.3	1.4	56.7	57.4	1.5	4.0	5.0	80	380	17.5	81	2.4	82.49	12.68	70.29	3920					8.0	323	357
All sample Min			14.4	12.1	12.1	78.0	78.0	43	80.0	14.1	9.4	11.0	0.9	53.8	54.7	1.0	1.5	4.0	30	270	14.1	59	1.5	80.75	11.77	68.19	3580					3.0	274	307
T2 mean			14.4	12.7	12.6	79.7	79.4	47	80.7	14.5	9.9	11.6	1.1	55.5	56.4	1.5	2.2	4.3	67	327	15.9	66	2.0	81.38	12.27	69.11	3737					5.7	293	323
T3 mean			14.5	12.8	12.9	79.4	79.3	49	81.1	14.4	10.0	11.7	1.1	55.7	56.4	1.2	2.0	4.2	63	280	16.5	66	1.7	81.56	12.40	69.15	3723					5.0	290	319
T4 mean			14.5	12.3	12.4	79.3	79.3	46	80.7	14.4	9.6	11.3	1.0	54.8	55.5	1.2	2.2	4.0	67	283	16.5	67	1.7	81.69	12.29	69.40	3770					4.7	306	335
T5 Mean			14.6	12.7	12.6	79.1	79.0	51	80.8	14.4	9.8	11.4	1.3	55.5	56.2	1.2	2.0	4.3	63	303	15.7	68	2.0	81.73	12.46	69.27	3677					4.7	289	322
T6 mean			14.5	12.5	12.5	79.0	78.7	48	80.9	14.5	9.7	11.3	1.2	54.6	55.4	1.0	2.0	4.5	60	293	15.6	65	1.9	81.49	12.53	68.96	3803					5.7	305	337
T7 mean			14.5	12.9	12.9	79.6	79.4	50	80.6	14.5	10.2	11.9	1.0	55.6	56.5	1.3	2.0	4.7	50	310	16.4	71	1.9	81.72	12.42	69.30	3777					5.3	292	318
T8 mean			14.6	12.8	12.7	79.3	78.9	48	80.7	14.5	10.0	11.7	1.1	55.3	56.2	1.2	2.5	4.7	57	317	16.5	71	1.9	81.45	12.34	69.11	3777					5.3	294	324
KWS Zyatt Mean			14.5	12.7	12.6	79.2	78.9	48	81.0	14.4	9.8	11.4	1.3	55.1	55.7	1.1	1.9	4.2	64	303	16.2	66	1.9	81.87	12.48	69.39	3681					4.0	291	322
KWS Siskin Mean			14.5	12.6	12.6	79.2	78.9	50	80.8	14.4	9.8	11.4	1.2	55.4	56.1	1.3	2.4	4.3	67	287	15.9	65	1.8	81.57	12.49	69.08	3743					4.6	297	327
RGT Skyfall Mean			14.6	12.8	12.7	79.6	79.7	48	80.6	14.5	10.0	11.7	1.1	55.5	56.4	1.2	2.0	4.6	51	316	16.4	73	1.9	81.28	12.19	69.09	3831					7.0	299	327

Table A3.2: Rheology and baking for the Essex 2019 N rate and timing trial.

Essex 2019 - N rate and timing			Wheat analysis							Flour						Farinograph				Extensograph				CBP test baking $										
ATC sample no.	Variety	Treatment No.	Moist. %	Prot. % at DM	Prot	Sp.wt. (kg/hl)	Sp wht	Hard-ness	Ext.rate %	Moist. %	Prot. %	Prot. % at DM	Prot % loss on milling	Water Abs. %	W.abs @ 14% moist	Arr. mins	Peak. mins	Stab. mins	Tol. BU	Res. BU	Ext. cm	Area cm2	R/E	Minolta colour L*	b*	L*-b*	Loaf vol. cm3	Bread quality	Crumb Structure	Crumb texture	Crumb colour	Quality Score 1-9	Loaf volume for unit level of protein (dm)	
ATC method			NIT07 $	NIT08	Post Harvest	GRN09	Post Harvest	MIS43$	PRP04	NIT07 $	NIT08	Cal.	Cal.$	RHE01	Calculated	RHE02				RHE03				MIS44$			MIS37$	MIS07$					Wheat Prot.	Flour Prot.
LA20.00729	KWS Zyatt	T2	12.4	11.6	11.4	77.8	76.5	39	82.0	14.5	9.0	10.5	1.1	51.1	52.0	1.0	1.5	4.5	60	290	16.3	68	1.8	82.39	12.47	69.92	3780	Moderate to poor	Weak	Slightly coarse	White	3	326	359
LA20.00730	KWS Zyatt	T3	11.9	12.5	12.3	77.8	76.9	42	82.2	14.3	9.6	11.2	1.3	53.0	53.5	1.5	3.5	3.0	100	250	16.5	58	1.5	82.42	12.55	69.87	3700	Moderate	Slightly Weak	Slightly coarse	White	4	296	330
LA20.00731	KWS Zyatt	T4	12.1	12.2	12.3	78.3	76.7	40	82.2	14.2	9.7	11.3	0.9	52.6	53.0	1.5	4.0	4.0	80	270	16.7	62	1.6	82.60	12.37	70.23	3780	Moderate to good	Slightly Weak	Fine	White	5	309	334
LA20.00732	KWS Zyatt	T5	12.1	12.4	12.2	78.6	77.3	42	82.2	14.6	9.7	11.4	1.0	51.8	52.9	1.0	2.0	5.0	40	350	16.8	82	2.1	83.15	11.88	71.27	3850	Moderate to good	Slightly Weak	Fine	White	5	310	339
LA20.00733	KWS Zyatt	T6	12.0	12.6	12.5	77.9	76.6	41	82.2	14.4	10.0	11.7	0.9	52.9	53.6	1.0	3.5	4.0	80	260	17.4	65	1.5	82.39	12.67	69.72	3840	Good to moderate	Resilient	Fine	White	6	305	329
LA20.00734	KWS Zyatt	T7	12.2	13.0	13.1	78.5	77.5	43	82.8	14.2	10.4	12.1	0.9	53.6	54.0	1.5	4.0	5.0	70	300	16.9	73	1.8	82.98	12.54	70.44	3730	Moderate to good	Slightly Weak	Fine	White	5	286	308
LA20.00735	KWS Zyatt	T8	12.1	13.3	13.4	78.3	77.2	42	82.5	14.5	10.4	12.2	1.1	53.3	54.2	1.5	3.5	4.0	70	310	18.1	83	1.7	82.01	13.03	68.98	3780	Moderate	Slightly Weak	Slightly coarse	White	4	285	311
LA20.00736	KWS Siskin	T2	12.2	11.1	11.0	77.6	76.5	45	82.5	14.5	8.4	9.8	1.3	51.5	52.4	1.0	2.0	4.0	70	250	16.7	63	1.5	83.07	12.83	70.24	3780	Moderate to poor	Firm/Weak	Slightly coarse	White	3	341	385
LA20.00737	KWS Siskin	T3	12.3	11.7	11.6	78.1	76.6	45	82.7	14.3	9.0	10.5	1.2	51.7	52.2	1.0	2.0	4.0	60	240	17.1	58	1.4	82.58	12.86	69.72	3810	Moderate	Slightly Weak	Slightly coarse	White	4	326	363
LA20.00738	KWS Siskin	T4	12.1	11.7	11.6	77.8	76.7	47	82.8	14.7	9.0	10.6	1.2	51.2	52.5	1.0	3.0	4.0	80	220	16.3	49	1.3	81.52	13.13	68.39	3770	Poor	Weak / Dense	Slightly coarse	White	2	322	357
LA20.00739	KWS Siskin	T5	12.2	12.2	11.8	77.8	76.8	48	82.7	14.6	9.7	11.4	0.8	51.7	52.8	1.0	3.5	4.5	80	250	16.5	58	1.5	82.04	12.89	69.15	3810	Moderate to poor	Firm/Weak	Slightly coarse	White	3	313	335
LA20.00740	KWS Siskin	T6	12.4	12.2	12.1	77.5	76.9	47	82.8	14.3	9.4	11.0	1.2	52.7	53.2	1.5	3.5	3.0	110	230	16.9	56	1.4	81.53	13.20	68.33	3670	Poor	Weak / Dense	Fine	White	2	302	335
LA20.00741	KWS Siskin	T7	12.3	12.6	12.3	78.0	76.2	49	82.6	14.8	9.7	11.4	1.2	51.8	53.2	1.5	3.5	4.0	90	280	17.3	67	1.6	81.77	13.01	68.76	3860	Moderate to poor	Firm/Weak	Slightly coarse	White	3	307	339
LA20.00742	KWS Siskin	T8	12.5	12.6	12.5	78.2	77.4	50	83.2	14.5	10.0	11.7	0.9	52.4	53.3	1.5	3.5	4.5	80	310	16.9	72	1.8	81.70	13.16	68.54	3730	Moderate to poor	Firm	Slightly coarse	White	3	296	319
LA20.00743	RGT Skyfall	T2	12.3	11.7	11.6	77.7	77.2	38	80.7	14.4	9.1	10.6	1.0	54.2	54.9	1.5	3.0	3.5	90	210	17.1	52	1.2	81.39	12.53	68.86	3810	Moderate	Slightly Weak	Slightly coarse	White	4	326	358
LA20.00744	RGT Skyfall	T3	12.1	12.3	12.4	78.3	77.3	40	81.1	14.7	9.5	11.1	1.2	53.7	55.0	1.5	3.5	4.0	90	260	17.6	67	1.5	81.06	12.52	68.54	3800	Moderate	Slightly Weak	Slightly coarse	White	4	308	341
LA20.00745	RGT Skyfall	T4	12.3	12.7	12.6	78.2	77.7	39	81.2	14.4	9.9	11.6	1.1	55.0	55.7	1.5	3.5	4.0	80	250	18.2	64	1.4	80.41	12.70	67.71	3790	Moderate to good	Slightly Weak	Fine	White	5	298	328
LA20.00746	RGT Skyfall	T5	12.3	12.8	12.7	77.9	77.1	39	81.0	14.5	9.8	11.5	1.3	54.6	55.5	1.5	3.5	3.5	80	270	18.2	71	1.5	81.07	12.53	68.54	3840	Moderate	Firm	Slightly coarse	White	4	300	335
LA20.00747	RGT Skyfall	T6	12.0	12.7	12.6	78.2	77.4	38	81.6	14.6	10.0	11.7	1.0	54.8	55.9	1.5	3.5	3.5	100	250	18.7	66	1.3	81.04	12.83	68.21	3790	Good to moderate	Resilient	Fine	White	6	298	324
LA20.00748	RGT Skyfall	T7	12.0	13.3	13.2	78.2	76.9	42	81.2	14.5	10.5	12.3	1.0	55.0	55.9	2.0	3.5	3.5	80	280	18.9	75	1.5	80.82	12.73	68.09	3820	Good	Resilient	Fine	White	7	287	311
LA20.00749	RGT Skyfall	T8	12.1	13.3	13.5	78.4	77.6	41	81.5	14.4	10.6	12.4	0.9	55.7	56.4	1.5	4.0	4.0	90	290	18.5	75	1.6	80.03	12.75	67.28	3790	Moderate	Firm	Slightly coarse	White	4	286	306
All sample Mean			12.2	12.4	12.3	78.1	77.0	43	82.1	14.5	9.7	11.3	1.1	53.1	53.9	1.4	3.2	4.0	80	268	17.3	66	1.5	81.81	12.72	69.09	3787					4.1	306	336
All sample Max			12.5	13.3	13.5	78.6	77.7	50	83.2	14.8	10.6	12.4	1.3	55.7	56.4	2.0	4.0	5.0	110	350	18.9	83	2.1	83.15	13.20	71.27	3860					7.0	341	385
All sample Min			11.9	11.1	11.0	77.5	76.2	38	80.7	14.2	8.4	9.8	0.8	51.1	52.0	1.0	1.5	3.0	40	210	16.3	49	1.2	80.03	11.88	67.28	3670					2.0	285	306
T2 mean			12.3	11.5	11.3	77.7	76.7	41	81.7	14.5	8.8	10.3	1.2	52.3	53.1	1.2	2.2	4.0	73	250	16.7	61	1.5	82.28	12.61	69.67	3790					3.3	331	367
T3 mean			12.1	12.2	12.1	78.1	76.9	42	82.0	14.4	9.4	10.9	1.3	52.8	53.6	1.3	3.0	3.7	83	250	17.1	61	1.5	82.02	12.64	69.38	3770					4.0	310	345
T4 mean			12.2	12.2	12.2	78.1	77.0	42	82.1	14.4	9.5	11.1	1.1	52.9	53.7	1.3	3.5	4.0	80	247	17.1	58	1.4	81.51	12.73	68.78	3780					4.0	310	340
T5 Mean			12.2	12.5	12.2	78.1	77.1	43	82.0	14.6	9.7	11.4	1.1	52.7	53.7	1.2	3.0	4.3	67	290	17.2	70	1.7	82.09	12.43	69.65	3833					4.0	308	336
T6 mean			12.1	12.5	12.4	77.9	77.0	42	82.2	14.4	9.8	11.5	1.0	53.5	54.2	1.3	3.5	3.5	97	247	17.7	62	1.4	81.65	12.90	68.75	3767					4.7	302	329
T7 mean			12.2	13.0	12.9	78.2	76.9	45	82.2	14.5	10.2	11.9	1.1	53.5	54.4	1.7	3.7	4.2	80	287	17.7	72	1.6	81.86	12.76	69.10	3803					5.0	293	319
T8 mean			12.2	13.0	13.1	78.3	77.4	44	82.4	14.5	10.3	12.1	0.9	53.8	54.6	1.5	3.7	4.2	80	303	17.8	77	1.7	81.25	12.98	68.27	3767					3.7	289	312
KWS Zyatt Mean			12.1	12.5	12.5	78.2	77.0	41	82.3	14.4	9.8	11.5	1.0	52.6	53.3	1.3	3.1	4.2	71	290	17.0	70	1.7	82.56	12.50	70.06	3780					4.6	303	330
KWS Siskin Mean			12.3	12.0	11.8	77.9	76.7	47	82.8	14.5	9.3	10.9	1.1	51.9	52.8	1.2	3.0	4.0	81	254	16.8	60	1.5	82.03	13.01	69.02	3776					2.9	315	348
RGT Skyfall Mean			12.2	12.7	12.7	78.1	77.3	40	81.2	14.5	9.9	11.6	1.1	54.7	55.6	1.6	3.5	3.7	87	259	18.2	67	1.4	80.83	12.66	68.18	3806					4.9	300	329

Table A3.3: Rheology and baking for the Norfolk 2019 N and S rate and timing trial.

Norfolk 2019 - N & S timing			Wheat analysis							Flour						Farinograph				Extensograph				CBP test baking $										
ATC sample no.	Variety	Treatment No.	Moist. %	Prot. % at DM	Prot	Sp.wt. (kg/hl)	Sp wht	Hard- ness	Ext.rate %	Moist. %	Prot. %	Prot. % at DM	Prot % loss on milling	Water Abs. %	W.abs @ 14% moist	Arr. mins	Peak. mins	Stab. mins	Tol. BU	Res. BU	Ext. cm	Area cm2	R/E	Minolta colour L*	b*	L*-b*	Loaf vol. cm3	Bread quality	Crumb Structure	Crumb texture	Crumb colour	Quality Score 1-9	Loaf volume for unit level of protein	
ATC method			NIT07 $	NIT08	Post harvest	GRN09	Post harvest	MIS43$	PRP04	NIT07 $	NIT08	Cal.	Cal.$	RHE01	Calculated	RHE02				RHE03				MIS44$			MIS37$		MIS07$				Wheat Prot.	Flour Prot.
LA20.01808	KWS Zyatt	1	14.2	12.8	12.1	79.8	79.2	48	81.7	14.6	10.2	11.9	0.9	54.8	55.9	1.0	2.0	4.0	70	290	15.4	64	1.9	82.30	13.02	69.28	3690	Good	Resilient	Fine	White	7	287	309
LA20.01809	KWS Zyatt	2	14.2	13.2	12.1	80.4	79.4	47	81.1	14.2	10.3	12.0	1.2	56.7	57.1	1.0	2.0	4.0	70	280	17.0	68	1.6	81.97	12.88	69.09	3640	Good to moderate	Slightly Weak	Fine	White	6	276	303
LA20.01810	KWS Zyatt	3	14.2	13.3	12.2	79.7	79.2	45	81.3	14.1	10.2	11.9	1.4	57.0	57.2	1.0	2.0	4.0	60	250	16.5	60	1.5	81.03	12.99	68.04	3680	Good to moderate	Slightly Weak	Fine	White	6	276	310
LA20.01811	KWS Zyatt	4	14.1	12.7	11.9	79.8	79.2	49	81.0	14.8	9.8	11.5	1.2	53.9	55.3	1.0	2.0	4.5	50	310	15.7	68	2.0	81.98	12.81	69.17	3670	Moderate	Weak	Slightly coarse	White	4	290	319
LA20.01812	KWS Zyatt	5	14.1	12.9	12.1	80.2	79.4	47	81.2	14.4	10.2	11.9	1.0	56.1	56.8	1.0	2.0	4.0	50	290	16.4	67	1.8	82.01	12.86	69.15	3690	Good to moderate	Slightly Weak	Fine	White	6	286	310
LA20.01813	KWS Zyatt	6	14.2	12.9	12.3	80.0	79.5	47	81.2	14.1	10.4	12.1	0.8	57.0	57.2	1.5	2.5	4.5	50	290	15.9	67	1.8	81.68	12.68	69.00	3700	Moderate to good	Weak	Slightly coarse	White	5	286	306
LA20.01814	KWS Zyatt	7	14.2	11.8	11.4	78.3	78.9	45	81.3	14.8	9.4	11.0	0.8	54.0	55.4	1.5	2.0	4.0	70	290	15.4	64	1.9	82.42	12.80	69.62	3770	Moderate to good	Weak	Fine	White	5	319	342
LA20.01815	KWS Zyatt	8	14.2	12.9	12.2	80.2	79.1	47	81.4	14.2	10.2	11.9	1.0	56.2	56.6	1.0	2.0	4.5	70	300	17.4	73	1.7	80.87	13.00	67.87	3600	Moderate to good	Resilient	Slightly coarse	Creamy	5	280	303
LA20.01816	KWS Zyatt	9	14.2	13.0	12.2	80.2	79.2	49	81.2	14.2	10.3	12.0	1.0	56.4	57.0	1.5	2.0	5.0	50	280	16.0	66	1.8	81.99	12.72	69.27	3680	Moderate to good	Weak	Fine	White	5	283	307
LA20.01817	KWS Zyatt	10	14.2	13.0	12.1	79.8	79.3	45	81.8	14.7	10.0	11.7	1.3	54.8	56.1	1.0	2.0	4.5	60	250	16.4	56	1.5	82.05	12.64	69.41	3750	Moderate	Weak	Slightly coarse	White	4	288	320
LA20.01818	KWS Zyatt	11	14.3	13.2	12.4	80.0	79.3	46	81.1	14.4	10.4	12.1	1.1	55.8	56.5	1.5	2.5	5.0	50	300	17.0	74	1.8	82.28	12.38	69.90	3820	Good	Resilient	Fine	White	7	288	314
LA20.01819	KWS Zyatt	12	14.2	13.4	12.4	80.2	79.3	50	81.5	14.0	10.5	12.2	1.2	56.9	56.9	1.5	2.5	4.5	70	260	16.7	61	1.6	81.09	12.92	68.17	3580	Moderate	Spongy	Slightly coarse	White	4	268	293
LA20.01820	RGT Skyfall	1	14.4	13.2	12.2	79.9	79.3	48	81.3	14.6	10.1	11.8	1.3	55.5	56.6	1.0	2.0	5.0	50	280	16.4	67	1.7	81.11	12.64	68.47	3790	Moderate to good	Weak	Fine	White	5	288	320
LA20.01821	RGT Skyfall	2	14.4	13.1	12.2	79.9	79.3	46	80.8	14.4	10.1	11.8	1.3	56.2	56.9	1.0	2.0	4.0	70	250	16.6	61	1.5	81.46	12.51	68.95	3660	Moderate	Weak	Slightly coarse	Creamy	4	280	310
LA20.01822	RGT Skyfall	3	14.4	13.0	12.2	79.9	79.4	47	81.5	14.3	10.2	11.9	1.1	56.7	57.2	1.5	2.0	4.0	70	260	17.5	66	1.5	80.69	12.68	68.01	3740	Moderate to good	Resilient	Slightly coarse	White	5	288	314
LA20.01823	RGT Skyfall	4	14.3	13.2	12.2	80.3	79.4	46	81.3	14.7	10.1	11.8	1.4	55.3	56.6	1.0	1.5	4.5	50	290	16.5	65	1.8	81.43	12.54	68.89	3740	Moderate to good	Slightly Weak	Slightly coarse	White	5	283	316
LA20.01824	RGT Skyfall	5	14.3	13.1	12.3	80.5	79.7	47	81.1	14.4	10.1	11.8	1.3	56.2	56.9	1.5	3.5	4.5	80	290	15.7	64	1.8	81.98	12.65	69.33	3720	Good to moderate	Resilient	Fine	White	6	283	315
LA20.01825	RGT Skyfall	6	14.3	13.1	12.2	80.3	79.4	47	80.8	14.4	10.1	11.8	1.3	56.3	57.0	1.0	2.0	5.0	50	280	16.3	66	1.7	81.37	12.43	68.94	3840	Good	Resilient	Fine	White	7	292	325
LA20.01826	RGT Skyfall	7	14.2	13.3	12.2	80.7	79.8	47	80.7	14.8	10.2	12.0	1.4	55.2	56.6	1.0	2.0	5.0	30	310	16.5	73	1.9	81.73	12.31	69.42	3740	Good	Resilient	Fine	White	7	280	312
LA20.01827	RGT Skyfall	8	14.3	13.1	12.3	80.1	79.2	47	81.0	14.5	10.2	11.9	1.2	56.2	57.1	1.0	2.0	4.5	60	300	17.0	73	1.8	80.97	12.82	68.15	3820	Moderate to good	Slightly Weak	Slightly coarse	White	5	291	320
LA20.01828	RGT Skyfall	9	14.2	13.1	12.3	80.6	79.5	49	81.3	14.4	10.2	11.9	1.2	56.6	57.3	1.0	2.0	4.5	60	280	16.7	67	1.7	81.37	12.75	68.62	3790	Good to moderate	Resilient	Slightly coarse	Creamy	6	288	318
LA20.01829	RGT Skyfall	10	14.3	13.1	12.2	79.9	79.3	47	81.2	14.7	10.0	11.7	1.4	55.4	56.7	1.0	2.0	4.5	60	270	16.5	64	1.6	80.81	12.84	67.97	3700	Moderate	Slightly Weak	Slightly coarse	White	4	281	316
LA20.01830	RGT Skyfall	11	14.3	13.2	12.4	80.6	79.8	46	80.8	14.5	10.1	11.8	1.4	56.5	57.4	1.5	2.0	4.5	40	290	16.6	71	1.7	81.23	12.52	68.71	3700	Moderate to good	Weak	Slightly coarse	White	5	280	313
LA20.01831	RGT Skyfall	12	14.3	13.2	12.4	80.3	79.5	49	81.1	14.4	10.3	12.0	1.2	56.7	57.4	1.5	2.0	4.5	70	310	16.4	71	1.9	81.44	12.60	68.84	3810	Good to moderate	Slightly Weak	Slightly coarse	White	6	288	317
2019 Series 2 NIAB - All Sample Mea			14.3	13.0	12.2	80.1	79.5	47	81.2	14.4	10.2	11.9	1.1	55.9	56.7	1.2	2.1	4.5	59	283	16.4	67	1.7	81.55	12.71	68.84	3722					5.4	285	314
2019 Series 2 NIAB - All Sample Max			14.4	13.4	12.4	80.7	79.8	50	81.8	14.8	10.5	12.2	1.4	57.0	57.4	1.5	3.5	5.0	80	310	17.5	74	2.0	82.42	13.02	69.90	3840					7.0	319	342
2019 Series 2 NIAB - All Sample Min			14.1	11.8	11.4	78.3	79.2	45	80.7	14.0	9.4	11.0	0.8	53.9	55.3	1.0	1.5	4.0	30	250	15.4	56	1.5	80.69	12.31	67.87	3580					4.0	268	293
2019 Series 2 - NIAB - T1 mean			14.3	13.0	12.2	79.9	79.3	48	81.5	14.6	10.2	11.9	1.1	55.2	56.3	1.0	2.0	4.5	60	285	15.9	66	1.8	81.71	12.83	68.88	3740					6.0	288	315
2019 Series 2 - NIAB - T2 mean			14.3	13.1	12.2	80.2	79.4	47	81.0	14.3	10.2	11.9	1.2	56.5	57.0	1.0	2.0	4.0	70	265	16.8	65	1.6	81.72	12.70	69.02	3650					5.0	278	307
2019 Series 2 - NIAB - T3 mean			14.3	13.2	12.2	79.8	79.3	46	81.4	14.2	10.2	11.9	1.3	56.9	57.2	1.3	2.0	4.0	65	255	17.0	63	1.5	80.86	12.84	68.03	3710					5.5	282	312
2019 Series 2 - NIAB - T4 mean			14.2	12.9	12.1	80.1	79.3	48	81.2	14.8	10.0	11.7	1.2	54.6	56.0	1.0	1.8	4.5	50	300	16.1	67	1.9	81.71	12.68	69.03	3705					4.5	286	317
2019 Series 2 - NIAB - T5 mean			14.2	13.0	12.2	80.4	79.6	47	81.2	14.4	10.2	11.9	1.1	56.2	56.9	1.3	2.8	4.3	65	290	16.1	66	1.8	82.00	12.76	69.24	3705					6.0	284	312
2019 Series 2 - NIAB - T6 mean			14.3	13.0	12.3	80.2	79.5	47	81.0	14.3	10.3	12.0	1.0	56.7	57.1	1.3	2.3	4.8	50	285	16.1	67	1.8	81.53	12.56	68.97	3770					6.0	289	315
2019 Series 2 - NIAB - T7 mean			14.2	12.6	11.8	79.5	79.4	46	81.0	14.8	9.8	11.5	1.1	54.6	56.0	1.3	2.0	4.5	50	300	16.0	69	1.9	82.08	12.56	69.52	3755					6.0	298	326
2019 Series 2 - NIAB - T8 mean			14.3	13.0	12.3	80.2	79.2	47	81.2	14.4	10.2	11.9	1.1	56.2	56.9	1.0	2.0	4.5	65	300	17.2	73	1.8	80.92	12.91	68.01	3710					5.0	285	312
2019 Series 2 - NIAB - T9 mean			14.2	13.1	12.3	80.4	79.4	49	81.3	14.3	10.3	12.0	1.0	56.5	57.2	1.3	2.0	4.8	55	280	16.4	67	1.8	81.68	12.74	68.95	3735					5.5	286	312
2019 Series 2 - NIAB - T10 mean			14.3	13.1	12.2	79.9	79.3	46	81.5	14.7	10.0	11.7	1.4	55.1	56.4	1.0	2.0	4.5	60	260	16.5	60	1.6	81.43	12.74	68.69	3725					4.0	285	318
2019 Series 2 - NIAB - T11 mean			14.3	13.2	12.4	80.3	79.6	46	81.0	14.5	10.3	12.0	1.2	56.2	57.0	1.5	2.3	4.8	45	295	16.8	73	1.8	81.76	12.45	69.31	3760					6.0	284	314
2019 Series 2 - NIAB - T12 mean			14.3	13.3	12.4	80.3	79.4	50	81.3	14.2	10.4	12.1	1.1	56.8	57.2	1.5	2.3	4.5	70	285	16.6	66	1.8	81.27	12.76	68.51	3695					5.0	278	305
2019 Series 2 - NIAB - KWS Zyatt me			14.2	12.9	12.1	79.9	79.3	47	81.3	14.4	10.2	11.9	1.1	55.8	56.5	1.2	2.1	4.4	60	283	16.3	####	1.7	81.81	12.81	69.00	3689					5.3	286	311
2019 Series 2 - NIAB - RGT Skyfall me			14.3	13.2	12.3	80.3	79.5	47	81.1	14.5	10.1	11.9	1.3	56.1	57.0	1.2	2.1	4.5	58	284	16.6	####	1.7	81.30	12.61	68.69	3754					5.4	285	316

Table A3.4: Rheology and baking for the Essex 2019 N and S rate and timing trial.

Essex 2019 - N & S timing			Wheat analysis							Flour						Farinograph				Extensograph				CBP test baking $										
ATC sample no.	Variety	Treatment No.	Moist. %	Prot. % at DM	Prot	Sp.wt. (kg/hl)	Sp wht	Hard-ness	Ext.rate %	Moist. %	Prot. %	Prot. % at DM	Prot % loss on milling	Water Abs. %	W.abs @ 14% moist	Arr. mins	Peak mins	Stab. mins	Tol. BU	Res. BU	Ext. cm	Area cm2	R/E	Minolta colour L*	b*	L*-b*	Loaf vol. cm3	Bread quality	Crumb Structure	Crumb texture	Crumb colour	Quality Score 1-9	Loaf volume for unit level of protein	
ATC method			NIT07 $	NIT08	Post harvest	GRN09	Post harvest	MIS43$	PRP04	NIT07 $	NIT08	Cal.	Cal.$	RHE01	Calculated	RHE02				RHE03				MIS44$				MIS37$	MIS07$				Wheat Prot.	Flour Prot.
LA20.01784	KWS Zyatt	1	12.1	12.2	11.6	77.5	80.2	42	81.9	14.7	9.3	10.9	1.3	52.4	53.7	1.0	3.0	3.5	100	250	16.3	57	1.5	82.50	12.63	69.87	3730	Good to moderate	Slightly Weak	Fine	White	6	307	342
LA20.01785	KWS Zyatt	2	12.0	12.3	11.8	78.3	79.8	40	82.9	14.3	9.4	11.0	1.3	53.1	53.6	1.0	3.5	3.5	100	250	17.2	60	1.5	81.96	12.91	69.05	3690	Good to moderate	Slightly Weak	Fine	White	6	300	336
LA20.01786	KWS Zyatt	3	12.1	12.2	11.8	77.2	79.7	43	82.1	14.7	9.4	11.0	1.2	52.2	53.5	1.5	3.5	4.0	80	240	17.0	59	1.4	81.67	12.59	69.08	3780	Good to moderate	Slightly Weak	Fine	White	6	310	343
LA20.01787	KWS Zyatt	4	11.7	12.5	12.0	77.9	79.8	40	82.6	14.8	9.9	11.6	0.9	52.5	53.9	1.5	3.5	3.0	100	220	16.3	50	1.3	81.59	12.73	68.86	3690	Good to moderate	Slightly Weak	Fine	White	6	296	318
LA20.01788	KWS Zyatt	5	11.8	12.7	12.4	77.9	79.9	44	82.6	14.5	10.1	11.8	0.9	52.9	53.8	1.0	3.5	4.0	80	270	16.2	63	1.7	82.40	12.57	69.83	3830	Good to moderate	Slightly Weak	Fine	White	6	301	324
LA20.01789	KWS Zyatt	6	11.8	12.6	12.1	78.5	79.7	43	83.0	14.3	10.2	11.9	0.7	53.5	54.2	1.0	3.5	3.5	90	270	17.1	65	1.6	81.65	13.01	68.64	3750	Moderate to good	Slightly Weak	Fine	White	5	297	315
LA20.01790	KWS Zyatt	7	11.8	12.4	12.1	78.3	79.8	43	82.5	14.7	9.9	11.6	0.8	52.5	53.8	1.5	3.5	4.0	80	290	16.5	64	1.8	82.02	12.73	69.29	3710	Good to moderate	Slightly Weak	Fine	White	6	300	320
LA20.01791	KWS Zyatt	8	11.6	12.3	12.2	77.6	80.0	43	82.5	14.3	10.0	11.7	0.6	53.1	53.6	1.5	3.5	4.0	80	270	16.4	61	1.6	81.72	12.78	68.94	3790	Moderate to good	Weak	Fine	White	5	309	325
LA20.01792	KWS Zyatt	9	11.8	12.4	12.0	77.2	79.5	41	82.6	14.3	9.8	11.4	1.0	53.2	53.7	1.5	3.5	4.0	90	240	17.6	58	1.4	82.15	12.78	69.37	3760	Moderate to good	Weak	Fine	White	5	304	329
LA20.01793	KWS Zyatt	10	11.7	12.4	11.9	77.6	79.8	41	82.2	14.7	9.8	11.5	0.9	52.4	53.7	1.5	3.5	3.5	90	200	17.3	52	1.2	81.84	12.78	69.06	3660	Moderate	Weak	Slightly coarse	White	4	295	319
LA20.01794	KWS Zyatt	11	11.7	12.6	12.3	77.5	79.8	43	82.5	14.6	10.1	11.8	0.8	53.2	54.3	1.5	3.5	4.0	90	270	17.3	69	1.6	81.77	12.89	68.88	3830	Moderate to good	Weak	Fine	White	5	303	324
LA20.01795	KWS Zyatt	12	11.6	12.5	12.1	77.7	79.8	43	82.9	14.3	10.1	11.8	0.7	53.5	54.0	1.5	3.5	4.0	90	270	17.2	63	1.6	82.09	12.71	69.38	3740	Moderate to good	Weak	Fine	White	5	299	317
LA20.01796	RGT Skyfall	1	12.1	12.9	12.3	78.1	79.5	40	81.3	14.4	10.0	11.7	1.2	54.8	55.5	1.5	3.0	3.5	80	200	17.5	52	1.1	80.51	12.63	67.88	3660	Moderate	Weak	Slightly coarse	White	4	284	313
LA20.01797	RGT Skyfall	2	11.9	13.0	12.1	78.0	79.5	40	81.8	14.5	10.0	11.7	1.3	55.0	55.9	1.5	3.0	4.0	70	180	17.8	48	1.0	80.61	12.65	67.96	3630	Moderate	Slightly Weak	Slightly coarse	Creamy	4	279	310
LA20.01798	RGT Skyfall	3	11.8	13.0	12.2	77.7	79.5	40	81.8	14.5	10.0	11.7	1.3	54.8	55.5	1.0	2.5	3.5	70	170	17.9	43	0.9	80.08	12.68	67.40	3650	Moderate to good	Slightly Weak	Slightly coarse	White	5	281	312
LA20.01799	RGT Skyfall	4	12.0	12.9	12.4	77.9	79.4	39	81.2	14.7	9.9	11.6	1.3	54.9	56.2	1.5	3.5	3.5	90	170	18.4	45	0.9	80.65	12.71	67.94	3480	Moderate to good	Weak	Slightly coarse	White	5	270	300
LA20.01800	RGT Skyfall	5	12.0	12.7	12.0	77.5	79.7	39	81.2	14.5	9.8	11.5	1.2	54.5	55.4	1.0	3.5	4.0	80	220	17.5	57	1.3	81.32	12.17	69.15	3760	Good	Resilient	Fine	White	7	296	328
LA20.01801	RGT Skyfall	6	12.2	12.8	12.1	77.9	79.6	39	81.7	14.3	9.8	11.4	1.4	55.1	55.6	1.0	3.5	4.0	90	240	17.6	63	1.4	80.80	12.48	68.32	3730	Moderate to good	Slightly Weak	Fine	Creamy	5	291	326
LA20.01802	RGT Skyfall	7	11.8	13.0	11.6	78.0	79.5	40	81.6	14.2	10.1	11.8	1.2	55.8	56.1	2.0	3.5	3.5	80	220	20.5	64	1.1	80.23	12.92	67.31	3650	Moderate to good	Resilient	Slightly coarse	White	5	282	310
LA20.01803	RGT Skyfall	8	11.8	12.6	12.2	77.8	79.3	40	81.6	14.5	9.8	11.5	1.2	54.8	55.7	1.5	3.5	4.0	80	240	18.4	62	1.3	80.65	12.36	68.29	3780	Good	Resilient	Fine	White	7	299	330
LA20.01804	RGT Skyfall	9	11.8	13.0	12.2	77.9	79.5	41	81.5	14.4	10.0	11.7	1.3	55.8	56.5	1.5	3.0	3.5	90	170	17.9	43	0.9	79.98	12.24	67.74	3590	Moderate to poor	Spongy	Slightly coarse	White	3	276	307
LA20.01805	RGT Skyfall	10	11.6	12.7	12.1	78.0	79.5	40	81.3	14.6	9.8	11.5	1.2	54.8	55.9	1.5	3.0	4.0	80	190	18.7	52	1.0	80.04	12.71	67.33	3590	Moderate to poor	Weak	Slightly coarse	Creamy	3	282	313
LA20.01806	RGT Skyfall	11	11.7	13.0	12.4	77.8	79.6	41	81.7	14.3	10.3	12.0	0.9	55.7	56.2	1.5	3.0	3.5	90	190	19.7	54	1.0	80.09	12.95	67.14	3650	Moderate to good	Slightly Weak	Slightly coarse	White	5	282	304
LA20.01807	RGT Skyfall	12	11.8	13.1	12.3	78.0	79.4	41	81.4	14.2	10.1	11.8	1.3	56.0	56.4	1.5	2.5	3.5	70	180	18.4	47	1.0	80.35	12.74	67.61	3610	Moderate	Slightly Weak	Fine	White	4	276	307
2019 Series 2 Agrii - All Sample Mea			11.8	12.7	12.1	77.8	79.5	41	82.0	14.5	9.9	11.6	1.1	54.0	54.9	1.4	3.3	3.7	85	225	17.6	56	1.3	81.19	12.68	68.51	3698					5.1	292	320
2019 Series 2 Agrii - All Sample Max			12.2	13.1	12.4	78.5	79.7	44	83.0	14.8	10.3	12.0	1.4	56.0	56.5	2.0	3.5	4.0	100	290	20.5	69	1.8	82.50	13.01	69.87	3830					7.0	310	343
2019 Series 2 Agrii - All Sample Min			11.6	12.2	11.6	77.2	79.3	39	81.2	14.2	9.3	10.9	0.6	52.2	53.5	1.0	2.5	3.0	70	170	16.2	43	0.9	79.98	12.17	67.14	3480					3.0	270	300
2019 Series 2 - Agrii - T1 mean			12.1	12.5	12.0	77.8	79.9	41	81.6	14.6	9.7	11.3	1.2	53.6	54.6	1.3	3.0	3.5	90	225	16.9	55	1.3	81.51	12.63	68.88	3695					5.0	295	327
2019 Series 2 - Agrii - T2 mean			12.0	12.6	12.0	78.2	79.7	40	82.4	14.4	9.7	11.3	1.3	54.1	54.8	1.3	3.3	3.8	85	215	17.5	54	1.3	81.29	12.78	68.51	3660					5.0	290	323
2019 Series 2 - Agrii - T3 mean			12.0	12.6	12.0	77.5	79.6	42	82.0	14.6	9.7	11.4	1.2	53.5	54.5	1.3	3.0	3.8	75	205	17.5	51	1.2	80.88	12.64	68.24	3715					5.5	295	327
2019 Series 2 - Agrii - T4 mean			11.9	12.7	12.2	77.9	79.6	40	81.9	14.8	9.9	11.6	1.1	53.7	55.1	1.5	3.5	3.3	95	195	17.4	48	1.1	81.12	12.72	68.40	3585					5.5	282	309
2019 Series 2 - Agrii - T5 mean			11.9	12.7	12.2	77.7	79.8	42	81.9	14.5	10.0	11.6	1.1	53.7	54.6	1.0	3.5	4.0	80	245	16.9	60	1.5	81.86	12.37	69.49	3795					6.5	299	326
2019 Series 2 - Agrii - T6 mean			12.0	12.7	12.1	78.2	79.7	41	82.4	14.3	10.0	11.7	1.1	54.3	54.9	1.0	3.5	3.8	90	255	17.4	64	1.5	81.23	12.75	68.48	3740					5.0	294	321
2019 Series 2 - Agrii - T7 mean			11.8	12.7	11.9	78.2	79.7	42	82.1	14.5	10.0	11.7	1.0	54.2	55.0	1.8	3.5	3.8	80	255	18.5	64	1.5	81.13	12.83	68.30	3680					5.5	291	315
2019 Series 2 - Agrii - T8 mean			11.7	12.5	12.2	77.7	79.7	42	82.1	14.4	9.9	11.6	0.9	54.0	54.7	1.5	3.5	4.0	80	255	17.4	62	1.5	81.19	12.57	68.62	3785					6.0	304	327
2019 Series 2 - Agrii - T9 mean			11.8	12.7	12.1	77.6	79.5	41	82.1	14.4	9.9	11.6	1.1	54.5	55.1	1.5	3.3	3.8	90	205	17.8	51	1.2	81.07	12.51	68.56	3675					4.0	290	318
2019 Series 2 - Agrii - T10 mean			11.7	12.6	12.0	77.8	79.7	41	81.8	14.7	9.8	11.5	1.1	53.6	54.8	1.5	3.3	3.8	85	195	18.0	52	1.1	80.94	12.75	68.20	3625					3.5	288	316
2019 Series 2 - Agrii - T11 mean			11.7	12.8	12.4	77.7	79.7	42	82.1	14.5	10.2	11.9	0.9	54.5	55.3	1.5	3.3	3.8	90	230	18.5	62	1.3	80.93	12.92	68.01	3740					5.0	292	314
2019 Series 2 - Agrii - T12 mean			11.7	12.8	12.2	77.9	79.6	42	82.2	14.3	10.1	11.8	1.0	54.8	55.2	1.5	3.0	3.8	80	225	17.8	55	1.3	81.22	12.73	68.50	3675					4.5	287	312
2019 Series 2 - Agrii - KWS Zyatt mea			11.8	12.4	12.0	77.8	79.8	42	82.5	14.5	9.8	11.5	0.9	52.9	53.8	1.3	3.5	3.8	89	253	16.9	####	1.5	81.95	12.76	69.19	3747					5.4	302	326
2019 Series 2 - Agrii - RGT Skyfall me			11.9	12.9	12.2	77.9	79.5	40	81.5	14.4	10.0	11.6	1.2	55.2	55.9	1.4	3.1	3.7	81	198	18.4	####	1.1	80.44	12.60	67.84	3648					4.8	283	313

Table A3.5: Rheology and baking for the Essex 2020 N rate and timing trial.

Essex 2020 - N rate and timing			Wheat analysis							Flour					
ATC sample no.	Variety	Treatment No.	Moist. %	Prot. % at DM	Prot	Sp.wt. (kg/hl)	Sp wht	Hard-ness	Ext.rate %	Moist. %	Prot. %	Prot. % at DM	Prot % loss on milling	Water Abs. %	W.abs @ 14% moist
ATC method			NIT07 $	NIT08	Post Harvest	GRN09	Post Harvest	MIS43$	PRP04	MIS48	NIT08	Cal.	Cal.$	RHE01	Calculated
LA21.00105	RGT Skyfall	1	12.5	9.0	8.8	77.0	76.4	44	80.5	14.2	6.9	8.0	0.9	51.6	52.0
LA21.00106	RGT Skyfall	2	12.5	11.4	11.0	78.5	77.9	51	79.9	14.3	8.6	10.0	1.3	53.3	53.8
LA21.00107	RGT Skyfall	3	12.6	11.5	11.0	78.4	77.9	51	81.8	14.0	8.9	10.3	1.3	55.1	55.1
LA21.00108	RGT Skyfall	4	12.5	11.2	11.1	78.2	78.3	50	80.9	14.0	9.1	10.6	0.6	54.6	54.6
LA21.00109	RGT Skyfall	5	12.3	11.3	11.3	79.0	78.8	54	81.6	13.9	9.2	10.7	0.7	56.2	56.0
LA21.00110	RGT Skyfall	6	12.5	11.1	11.2	78.8	78.1	55	80.2	13.8	9.0	10.4	0.7	55.4	55.0
LA21.00111	RGT Skyfall	7	12.4	11.9	11.5	78.8	78.3	54	80.8	14.3	9.4	11.0	0.9	54.8	55.3
LA21.00112	RGT Skyfall	8	12.4	11.7	11.5	77.9	77.7	54	80.0	14.2	9.2	10.7	1.0	53.8	54.2
All sample Mean			12.5	11.1	10.9	78.3	77.9	52	80.7	14.1	8.8	10.2	0.9	54.4	54.5
All sample Max			12.6	11.9	11.5	79.0	78.8	55	81.8	14.3	9.4	11.0	1.3	56.2	56.0
All sample Min			12.3	9.0	8.8	77.0	76.4	44	79.9	13.8	6.9	8.0	0.6	51.6	52.0

	Farinograph				Extensograph				CBP test baking $										
									Minolta colour										
ATC sample no.	Arr. mins	Peak. mins	Stab. mins	Tol. BU	Res. BU	Ext. cm	Area cm2	R/E	L*	b*	L*-b*	Loaf vol. cm3	Bread quality	Crumb Structure	Crumb texture	Crumb colour	Quality Score 1-9	Loaf volume for unit level of protein (dm)	
ATC method	RHE02				RHE03				MIS44$			MIS37$	MIS07$					Wheat Prot.	Flour Prot.
LA21.00105	1.0	1.5	3.5	80	300	13.1	58	2.3	82.12	12.81	69.31	3780	Moderate	Slightly Weak	Coarse	Creamy	4	421	470
LA21.00106	1.0	2.0	4.5	50	350	17.0	84	2.1	82.38	13.64	68.74	3880	Good	Resilient	Fine	White	7	341	387
LA21.00107	1.0	2.0	4.5	70	300	16.9	75	1.8	83.58	13.03	70.55	3860	Good	Resilient	Fine	White	7	336	373
LA21.00108	1.0	2.0	4.5	60	310	16.9	76	1.8	81.93	13.17	68.76	3880	Very good	Resilient	Fine	White	8	346	367
LA21.00109	1.5	2.5	4.0	70	310	16.2	73	1.9	81.88	13.72	68.16	3780	Good to moderate	Resilient	Slightly coarse	Creamy	6	333	354
LA21.00110	1.0	1.5	4.5	50	340	16.4	80	2.1	83.08	13.72	69.36	3870	Good to moderate	Resilient	Fine	White	6	347	371
LA21.00111	1.0	2.0	5.0	40	310	17.1	79	1.8	82.27	14.27	68.00	3830	Good to moderate	Resilient	Slightly coarse	White	6	321	349
LA21.00112	1.0	2.0	5.0	40	360	17.2	89	2.1	82.72	13.87	68.85	3800	Very good	Resilient	Fine	White	8	325	354
All sample Mean	1.1	1.9	4.4	58	323	16.4	77	2.0	82.50	13.53	68.97	3835					6.5	346	378
All sample Max	1.5	2.5	5.0	80	360	17.2	89	2.3	83.58	14.27	70.55	3880					8.0	421	470
All sample Min	1.0	1.5	3.5	40	300	13.1	58	1.8	81.88	12.81	68.00	3780					4.0	321	349

Table A3.6: Rheology and baking for the East Lothian 2021 N rate and timing trial.

East Lothian 2021 - N rate and timing				Wheat analysis						Flour								Farinograph				Extensograph			
ATC sample no.	Variety	Treatmen No.	Plot No.	Moist. %	Prot. % at DM	Prot	Sp.wt. (kg/hl)	Sp wht	Ext.rate %	Moist. %	Prot. %	Prot. % at DM	Prot % loss on milling	Water Abs. %	W.abs @ 14% moist	Starch damage %	HFN	Arr. mins	Peak mins	Stab. mins	Tol. BU	Res. BU	Ext. cm	Area cm2	R/E
ATC method				NIT07 $	NIT07	NIAB	GRN09	NIAB	PRP04	MIS48	MIS48	Cal.	Cal.$	RHE01	Calculated	MIS48 $	CHO01	RHE02				RHE03			
LA22.00352	KWS Zyatt	T2		12.5	11.0	11.2	74.9	74.1	80.0	14.5	8.6	10.1	0.9	56.5	57.4	33	168	1.0	1.5	2.0	120	240	15.0	53	1.6
LA22.00353	KWS Zyatt	T3		13.0	12.0	11.9	74.6	73.2	80.0	14.3	9.1	10.6	1.4	57.4	57.9	33	181	1.5	2.0	2.0	110	220	16.7	54	1.3
LA22.00354	KWS Zyatt	T4		12.7	11.9	12.0	74.8	73.9	80.0	14.5	9.2	10.8	1.1	57.0	57.9	35	180	1.5	2.0	2.5	110	230	17.1	55	1.3
LA22.00355	KWS Zyatt	T5		12.2	11.9	12.0	75.4	74.4	77.7	14.5	9.2	10.8	1.1	55.9	56.8	33	179	1.0	2.0	2.5	90	300	16.4	73	1.8
LA22.00356	KWS Zyatt	T6		13.1	12.0	12.3	74.4	73.2	79.7	14.4	9.5	11.1	0.9	57.9	58.6	34	189	1.5	2.0	2.5	100	230	16.9	59	1.4
LA22.00357	KWS Zyatt	T7		12.6	12.3	12.4	74.6	73.6	77.5	14.4	9.6	11.2	1.1	57.2	57.9	34	189	1.5	2.0	3.0	80	280	17.2	69	1.6
LA22.00358	KWS Zyatt	T8		12.8	12.5	12.6	74.9	72.9	78.1	14.8	9.8	11.5	1.0	57.3	58.7	34	183	1.5	2.0	2.5	100	230	16.6	56	1.4
LA22.00344	KWS Siskin	T2		12.8	11.7	11.7	73.7	72.1	80.3	14.7	9.1	10.7	1.0	56.3	57.6	26	170	1.5	2.0	2.0	130	220	16.4	53	1.3
LA22.00345	KWS Siskin	T3		12.8	11.8	12.1	73.6	72.5	80.3	14.4	9.5	11.1	0.7	57.5	58.2	29	178	1.5	2.0	2.5	110	200	16.4	48	1.2
LA22.00346	KWS Siskin	T4		13.1	11.9	12.0	73.4	72.1	77.8	14.4	9.4	11.0	0.9	57.5	58.2	26	174	1.0	2.0	2.5	120	230	17.0	54	1.4
LA22.00347	KWS Siskin	T5		13.4	12.0	12.2	73.8	72.7	77.6	14.8	9.5	11.2	0.8	56.1	57.5	29	180	1.0	1.5	1.5	120	270	17.1	69	1.6
LA22.00348	KWS Siskin	T6		13.1	12.4	12.8	72.7	71.4	79.7	14.6	9.9	11.6	0.8	57.5	58.6	30	169	1.5	2.0	2.5	130	200	16.6	48	1.2
LA22.00349	KWS Siskin	T7		13.1	12.8	13.2	73.1	70.5	77.1	14.3	10.1	11.8	1.0	58.1	58.6	31	171	1.5	2.5	2.0	120	260	18.3	67	1.4
LA22.00350	KWS Siskin	T8		12.2	13.3	13.3	72.4	71.1	77.0	14.1	10.2	11.9	1.4	58.9	59.1	30	163	1.5	2.0	2.0	110	250	18.0	65	1.4
LA22.00336	RGT Skyfall	T2		13.5	11.3	11.3	76.4	75.2	77.2	14.9	8.7	10.2	1.1	55.3	56.9	28	170	1.0	1.5	1.5	130	250	17.6	64	1.4
LA22.00337	RGT Skyfall	T3		12.5	11.7	11.8	76.8	75.4	77.7	14.6	8.9	10.4	1.3	55.5	56.6	28	189	1.5	2.0	2.0	110	310	16.6	75	1.9
LA22.00338	RGT Skyfall	T4		13.4	12.4	12.4	75.9	74.8	77.4	14.5	9.3	10.9	1.5	56.8	57.7	31	174	1.5	2.0	2.5	100	310	18.4	83	1.7
LA22.00339	RGT Skyfall	T5		13.4	12.0	11.9	77.1	76.3	77.5	14.4	9.2	10.7	1.3	57.2	57.9	32	175	1.5	2.0	2.0	120	340	18.8	94	1.8
LA22.00340	RGT Skyfall	T6		13.3	12.0	13.4	75.7	74.9	77.6	14.5	9.3	10.9	1.1	56.6	57.5	30	152	1.5	2.0	2.5	110	290	17.9	78	1.6
LA22.00341	RGT Skyfall	T7		12.8	12.4	12.6	75.5	74.8	78.8	14.6	9.7	11.4	1.0	58.1	59.2	34	172	1.5	2.5	2.5	110	310	17.5	79	1.8
LA22.00342	RGT Skyfall	T8		12.4	13.1	13.4	75.3	73.9	76.8	14.4	10.1	11.8	1.3	58.5	59.2	33	176	1.5	2.0	2.0	110	310	20.2	91	1.5
2021 Series 1 SRUC - All sample Mean				12.9	12.1	12.3	74.7	73.5	78.4	14.5	9.4	11.0	1.1	57.1	58.0	31	175	1.4	2.0	2.2	111	261	17.3	66	1.5
2021 Series 1 SRUC - All sample Max				13.5	13.3	13.4	77.1	76.3	80.3	14.9	10.2	11.9	1.5	58.9	59.2	35	189	1.5	2.5	3.0	130	340	20.2	94	1.9
2021 Series 1 SRUC - All sample Min				12.2	11.0	11.2	72.4	70.5	76.8	14.1	8.6	10.1	0.7	55.3	56.6	26	152	1.0	1.5	1.5	80	200	15.0	48	1.2
2021 Series 1 SRUC - T2 mean				12.9	11.3	11.4	75.0	73.8	79.2	14.7	8.8	10.3	1.0	56.0	57.3	29	178	1.2	1.7	1.8	127	237	16.3	57	1.4
2021 Series 1 SRUC - T3 mean				12.8	11.8	11.9	75.0	73.7	79.3	14.4	9.2	10.7	1.1	56.8	57.6	30	176	1.5	2.0	2.2	110	243	16.6	59	1.5
2021 Series 1 SRUC -T4 mean				13.1	12.1	12.1	74.7	73.6	78.4	14.5	9.3	10.9	1.2	57.1	57.9	31	178	1.3	2.0	2.5	110	257	17.5	64	1.5
2021 Series 1 SRUC - T5 Mean				13.0	12.0	12.0	75.4	74.5	77.6	14.6	9.3	10.9	1.1	56.4	57.4	31	167	1.2	1.8	2.0	110	303	17.4	79	1.7
2021 Series 1 SRUC - T6 mean				13.2	12.1	12.8	74.3	73.2	79.0	14.5	9.6	11.2	0.9	57.3	58.2	31	177	1.5	2.0	2.5	113	240	17.1	62	1.4
2021 Series 1 SRUC - T7 mean				12.8	12.5	12.7	74.4	73.0	77.8	14.4	9.8	11.5	1.0	57.8	58.6	33	176	1.5	2.3	2.5	103	283	17.7	72	1.6
2021 Series 1 SRUC - T8 mean				12.5	13.0	13.1	74.2	72.6	77.3	14.4	10.0	11.7	1.3	58.2	59.0	32	174	1.5	2.0	2.2	107	263	18.3	71	1.4
2021 Series 1 SRUC - KWS Zyatt Mean				12.7	11.9	12.1	74.8	73.6	79.0	14.5	9.3	10.9	1.0	57.0	57.9	34	180	1.4	1.9	2.4	101	247	16.6	60	1.5
2021 Series 1 SRUC - KWS Siskin Mean				12.9	12.3	12.5	73.2	71.8	78.5	14.5	9.7	11.3	1.0	57.4	58.3	29	172	1.4	2.0	2.1	120	233	17.1	58	1.4
2021 Series 1 SRUC - RGT Skyfall Mean				13.0	12.1	12.4	76.1	75.0	77.6	14.6	9.3	10.9	1.2	56.9	57.9	31	173	1.4	2.0	2.1	113	303	18.1	81	1.7

Table A3.7: Rheology and baking for the Lincolnshire 2021 N rate and timing trial.

Lincolnshire 2021 - N rate and timing				Wheat analysis						Flour								Farinograph				Extensograph				CBP test baking $										
ATC sample no.	Variety	Treatment No.	Plot No.	Moist. %	Prot. % at DM	Prot	Sp.wt. (kg/hl)	Sp wht	Ext.rate %	Moist. %	Prot. %	Prot. % at DM	Prot % loss on milling	Water Abs. %	W.abs @ 14% moist	Starch damage %	HFN	Arr. mins	Peak. mins	Stab. mins	Tol. BU	Res. BU	Ext. cm	Area cm2	R/E	Minolta colour L*	Minolta colour b*	Minolta colour L*-b*	Loaf vol. cm3	Bread quality	Crumb Structure	Crumb texture	Crumb colour	Quality Score 1-9	Loaf volume for unit level of protein (dm) Wheat Prot.	Loaf volume for unit level of protein (dm) Flour Prot.
ATC method				NIT07 $	NIT07	NIAB	GRN09	NIAB	PRP04	MIS48	MIS48	Cal.	Cal.$	RHE01	Calculated	MIS48 $	CHO01	RHE02				RHE03				MIS44$			MIS37$	MIS07$					Wheat Prot.	Flour Prot.
LA21.08736	KWS Zyatt	T2	2	14.7	11.3	10.7	78.2	77.1	81.7	14.9	8.9	10.5	0.8	52.7	54.3	28	282	1.5	2.0	3.5	70	290	15.0	62	1.9	81.70	12.49	69.30	3850	Good to moderate	Slightly Weak	Fine	White	6	341	368
LA21.08737	KWS Zyatt	T3	3	14.6	11.8	11.6	78.1	77.1	79.6	15.2	9.2	10.8	1.0	51.1	53.3	25	309	1.0	1.5	3.0	70	310	16.8	74	1.8	82.75	12.18	70.57	3880	Good to moderate	Slightly Weak	Fine	White	6	329	358
LA21.08738	KWS Zyatt	T4	4	14.9	11.9	11.6	78.3	77.2	81.2	14.7	9.4	11.0	0.9	53.7	55.0	31	312	1.0	1.5	3.5	70	310	16.1	72	1.9	82.16	12.46	69.70	3880	Very good	Resilient	Fine	White	8	326	352
LA21.08739	KWS Zyatt	T5	5	15.3	12.1	11.9	78.3	77.3	79.9	14.9	9.4	11.0	1.1	52.5	54.1	27	322	1.0	2.0	2.5	80	390	16.3	91	2.4	82.81	12.29	70.52	3940	Very good	Resilient	Fine	White	8	326	357
LA21.08740	KWS Zyatt	T6	6	15.0	12.3	12.0	77.3	76.5	81.4	14.9	9.9	11.6	0.7	53.2	54.8	29	323	1.0	2.0	4.0	50	320	16.1	72	2.0	82.26	12.65	69.61	3920	Good to moderate	Slightly Weak	Fine	Creamy	6	319	337
LA21.08741	KWS Zyatt	T7	7	15.5	12.6	12.7	78.0	77.2	79.9	14.8	10.1	11.9	0.7	52.5	53.9	28	316	1.0	2.0	3.0	60	400	17.5	98	2.3	82.51	12.17	70.34	3850	Good to moderate	Slightly Weak	Fine	White	6	306	325
LA21.08742	KWS Zyatt	T8	8	14.9	12.7	13.0	78.0	77.5	80.4	14.6	10.1	11.8	0.9	54.9	56.0	30	320	1.0	2.0	3.5	60	340	16.5	79	2.1	82.01	12.38	69.63	3790	Good	Resilient	Fine	White	7	298	320
LA21.08743	KWS Siskin	T2	10	13.9	10.5	10.7	77.1	75.7	80.0	14.8	8.4	9.9	0.6	50.7	52.1	17	317	1.0	1.5	2.0	80	280	16.0	64	1.8	82.81	11.98	70.83	3910	Moderate to poor	Weak	Fine	White	3	372	397
LA21.08744	KWS Siskin	T3	11	14.0	11.3	11.4	77.5	76.3	81.5	14.9	9.2	10.8	0.5	52.8	54.4	23	353	1.0	1.5	3.5	70	270	15.4	61	1.8	81.26	12.31	68.95	3890	Moderate	Firm	Fine	White	4	344	360
LA21.08745	KWS Siskin	T4	12	14.5	11.8	11.6	77.3	76.5	80.1	15.2	9.2	10.8	1.0	50.9	53.1	22	335	1.0	1.5	3.5	60	300	16.8	73	1.8	82.16	12.13	70.03	3870	Good to moderate	Slightly Weak	Fine	White	6	328	357
LA21.08746	KWS Siskin	T5	13	13.9	12.6	12.4	78.0	76.4	80.2	14.6	10.0	11.7	0.9	53.4	54.5	26	339	1.0	2.0	4.5	40	330	17.0	77	1.9	82.12	11.91	70.21	3910	Good to moderate	Slightly Weak	Fine	White	6	310	334
LA21.08747	KWS Siskin	T6	14	14.1	12.3	12.3	77.4	76.3	81.5	14.6	9.9	11.6	0.7	53.7	54.8	24	348	1.0	1.5	4.5	60	300	16.8	71	1.8	82.13	11.78	70.35	4140	Good	Resilient	Fine	White	7	337	357
LA21.08748	KWS Siskin	T7	15	13.9	13.2	12.9	77.2	77.0	79.4	14.9	10.4	12.2	1.0	52.8	54.4	26	333	1.0	1.5	5.0	40	350	18.7	94	1.9	82.42	11.89	70.53	3980	Good	Resilient	Fine	White	7	302	326
LA21.08749	KWS Siskin	T8	16	13.8	13.0	13.1	77.2	76.3	81.0	14.9	10.4	12.2	0.8	54.1	55.7	29	350	1.0	2.0	5.0	50	340	17.0	82	2.0	81.83	12.23	69.60	3850	Good	Resilient	Fine	White	7	296	315
LA21.08750	RGT Skyfall	T2	18	14.0	11.6	11.5	79.3	78.6	78.8	14.9	8.9	10.5	1.1	54.3	55.9	26	332	1.0	2.0	3.0	50	350	16.4	81	2.1	82.68	11.17	71.51	3790	Moderate	Firm	Fine	White	4	327	362
LA21.08751	RGT Skyfall	T3	19	14.3	12.4	12.2	79.6	78.8	80.9	14.7	9.7	11.4	1.0	56.2	57.5	30	350	1.5	2.0	5.5	40	320	16.4	77	2.0	81.52	11.63	69.89	3870	Good to moderate	Slightly Weak	Fine	White	6	312	340
LA21.08752	RGT Skyfall	T4	20	14.5	12.7	12.3	79.1	79.0	78.5	14.9	9.6	11.3	1.4	55.3	56.9	27	319	1.0	2.0	3.5	60	320	16.2	86	2.0	81.77	11.30	70.47	3860	Good	Resilient	Fine	White	7	304	342
LA21.08753	RGT Skyfall	T5	21	14.4	12.7	12.3	79.1	79.0	80.6	15.0	9.9	11.6	1.1	55.6	57.4	30	372	1.5	2.0	5.0	40	350	17.2	86	2.0	80.89	11.62	69.27	3800	Good	Resilient	Fine	White	7	299	326
LA21.08754	RGT Skyfall	T6	22	13.9	13.2	12.8	79.5	79.2	79.3	15.1	10.2	12.0	1.2	54.5	56.5	27	372	1.0	2.0	4.0	50	400	16.8	94	2.4	81.30	11.44	69.86	3840	Good	Resilient	Fine	White	7	291	320
LA21.08755	RGT Skyfall	T7	23	14.3	13.3	13.3	79.7	79.2	80.4	14.7	10.3	12.1	1.2	57.2	58.5	30	336	1.5	2.5	5.0	50	350	17.5	87	2.0	80.27	11.58	68.69	3760	Good	Resilient	Fine	White	7	283	311
LA21.08756	RGT Skyfall	T8	24	13.7	14.1	13.6	79.7	78.9	79.2	14.8	10.7	12.6	1.5	55.8	57.2	27	340	1.5	2.0	4.5	40	430	18.4	107	2.3	81.30	11.46	69.84	3770	Good to moderate	Slightly Weak	Fine	White	6	267	300

2021 Series 1 NIAB (BE) - All sample Mean				14.4	12.4	12.2	78.3	77.5	80.3	14.9	9.7	11.4	1.0	53.7	55.3	27	332	1.1	1.9	3.9	57	336	16.7	80	2.0	81.94	11.95	69.99	3874					6.2	315	341
2021 Series 1 NIAB (BE) - All sample Max				15.5	14.1	13.6	79.7	79.2	81.7	15.2	10.7	12.6	1.5	57.2	58.5	31	372	1.5	2.5	5.5	80	430	18.7	107	2.4	82.81	12.65	71.51	4140					8.0	372	397
2021 Series 1 NIAB (BE) - All sample Min				13.7	10.5	10.7	77.1	75.7	78.5	14.6	8.4	9.9	0.5	50.7	52.1	17	282	1.0	1.5	2.0	40	270	15.0	61	1.8	80.27	11.17	68.69	3760					3.0	267	300
2021 Series 1 NIAB (BE) - T2 mean				14.2	11.1	11.0	78.2	77.1	80.2	14.9	8.7	10.3	0.8	52.6	54.1	24	310	1.2	1.8	2.8	67	307	15.8	69	1.9	82.40	11.88	70.55	3850					4.3	347	376
2021 Series 1 NIAB (BE) - T3 mean				14.3	11.8	11.7	78.4	77.4	80.7	14.9	9.4	11.0	0.8	53.4	55.0	26	337	1.2	1.7	4.0	60	300	16.2	71	1.9	81.84	12.04	69.80	3880					5.3	328	353
2021 Series 1 NIAB (BE) - T4 mean				14.6	12.1	11.8	78.2	77.6	79.9	14.9	9.4	11.0	1.1	53.3	55.0	27	322	1.0	1.7	3.5	63	310	16.4	77	1.9	82.03	11.96	70.07	3870					7.0	319	350
2021 Series 1 NIAB (BE) - T5 Mean				14.5	12.5	12.2	78.5	77.6	80.2	14.8	9.8	11.5	1.0	53.8	55.3	28	344	1.2	2.0	4.0	53	357	16.8	85	2.1	81.94	11.94	70.00	3883					7.0	312	339
2021 Series 1 NIAB (BE) - T6 mean				14.3	12.6	12.4	78.1	77.3	80.7	14.9	10.0	11.7	0.9	53.8	55.4	27	348	1.0	1.8	4.2	53	340	16.6	79	2.1	81.90	11.96	69.94	3967					6.7	315	338
2021 Series 1 NIAB (BE) - T7 mean				14.6	13.0	13.0	78.3	77.8	79.9	14.8	10.3	12.1	0.9	54.2	55.6	28	328	1.2	2.0	4.3	50	367	17.9	93	2.1	81.73	11.88	69.85	3863					6.7	297	321
2021 Series 1 NIAB (BE) - T8 mean				14.1	13.3	13.2	78.3	77.6	80.2	14.8	10.4	12.2	1.1	54.9	56.3	29	337	1.2	2.0	4.3	50	370	17.3	89	2.1	81.71	12.02	69.69	3803					6.7	287	312
2021 Series 1 NIAB (BE) - KWS Zyatt Mean				15.0	12.1	11.9	78.0	77.1	80.6	14.9	9.6	11.2	0.9	52.9	54.5	28	312	1.1	1.9	3.3	66	337	16.3	78	2.1	82.31	12.37	69.95	3873					6.7	321	345
2021 Series 1 NIAB (BE) - KWS Siskin Mear				14.0	12.1	12.1	77.4	76.4	80.5	14.8	9.6	11.3	0.8	52.6	54.1	24	339	1.0	1.6	4.0	57	310	16.8	75	1.9	82.10	12.03	70.07	3936					5.7	327	349
2021 Series 1 NIAB (BE) - RGT Skyfall Mean				14.2	12.9	12.6	79.4	79.0	79.7	14.9	9.9	11.6	1.3	55.6	57.1	28	346	1.3	2.1	4.4	47	360	17.0	88	2.1	81.39	11.46	69.93	3813					6.3	298	329

Table A3.8: Rheology and baking for the Essex 2021 N rate and timing trial.

Essex 2021 - N rate and timing				Wheat analysis					Flour									Farinograph				Extensograph			
ATC sample no.	Variety	Treatment No.	Plot No.	Moist. %	Prot. % at DM	Prot	Sp.wt. (kg/hl)	Sp wht	Ext.rate %	Moist. %	Prot. %	Prot. % at DM	Prot % loss on milling	Water Abs. %	W.abs @ 14% moist	Starch damage %	HFN	Arr. mins	Peak. mins	Stab. mins	Tol. BU	Res. BU	Ext. cm	Area cm2	R/E
ATC method				NIT07 $	NIT07	Agrii	GRN09	Agrii	PRP04	MIS48	MIS48	Cal.	Cal.$	RHE01	Calculated	MIS48 $	CHO01	RHE02				RHE03			
LA22.00475	KWS Zyatt	T2					71.8	70.7																	
LA22.00476	KWS Zyatt	T3					72.5	71.1																	
LA22.00477	KWS Zyatt	T4					71.6	70.9																	
LA22.00478	KWS Zyatt	T5					71.9	71.3																	
LA22.00479	KWS Zyatt	T6					72.6	72.3																	
LA22.00480	KWS Zyatt	T7					70.6	70.1																	
LA22.00481	KWS Zyatt	T8					71.8	71.4																	
LA22.00482	KWS Siskin	T2					70.7	70.4																	
LA22.00483	KWS Siskin	T3					70.0	69.3																	
LA22.00484	KWS Siskin	T4					69.2	68.8																	
LA22.00485	KWS Siskin	T5					69.7	69.0																	
LA22.00486	KWS Siskin	T6					70.2	69.9																	
LA22.00487	KWS Siskin	T7					70.6	70.6																	
LA22.00488	KWS Siskin	T8					70.1	69.6																	
LA22.00489	RGT Skyfall	T2					74.1	73.4																	
LA22.00490	RGT Skyfall	T3					73.3	73.3																	
LA22.00491	RGT Skyfall	T4					73.0	72.5																	
LA22.00492	RGT Skyfall	T5					73.1	72.8																	
LA22.00493	RGT Skyfall	T6					73.6	72.8																	
LA22.00494	RGT Skyfall	T7					73.4	72.6																	
LA22.00495	RGT Skyfall	T8					74.2	73.7																	
2021 Series 1 Agrii - All sample Mean							71.8	71.3																	
2021 Series 1 Agrii - All sample Max							74.2	73.7																	
2021 Series 1 Agrii - All sample Min							69.2	68.8																	
2021 Series 1 Agrii - T2 mean							72.2	71.5																	
2021 Series 1 Agrii - T3 mean							71.9	71.2																	
2021 Series 1 Agrii - T4 mean							71.3	70.7																	
2021 Series 1 Agrii - T5 Mean							71.6	71.0																	
2021 Series 1 Agrii - T6 mean							72.1	71.7																	
2021 Series 1 Agrii - T7 mean							71.5	71.1																	
2021 Series 1 Agrii - T8 mean							72.0	71.6																	
2021 Series 1 Agrii - KWS Zyatt Composite				11.2	14.3		72.7		78.5	14.9	10.6	12.5	1.8	52.7	54.3	25	296	1.0	2.0	6.5	20	370	19.1	102	1.9
2021 Series 1 Agrii - KWS Siskin Composi				11.7	14.2		71.5		78.3	14.6	10.5	12.3	1.9	53.1	54.2	22	337	1.5	2.5	6.0	30	350	19.4	97	1.8
2021 Series 1 Agrii - RGT Skyfall Composi				11.9	14.4		74.7		78.3	14.4	10.5	12.3	2.1	56.5	57.2	24	301	1.5	2.0	6.0	30	400	17.2	98	2.3

Table A3.9: Rheology and baking for the Hampshire 2021 N rate and timing trial.

Hampshire 2021 - N rate and timing				Wheat analysis						Flour								Farinograph				Extensograph				CBP test baking $												
ATC sample no.	Variety	Treatment No.	Plot No.	Moist. %	Prot. % at DM	Prot	Sp.wt. (kg/hl)	Sp wht	Ext.rate %	Moist. %	Prot. %	Prot. % at DM	Prot % loss on milling	Water Abs. %	W.abs @ 14% moist	Starch damage %	HFN	Arr. mins	Peak. mins	Stab. mins	Tol. BU	Res. BU	Ext. cm	Area cm2	R/E	Minolta colour L*	b*	L*-b*	Loaf vol. cm3	Bread quality	Crumb Structure	Crumb texture	Crumb colour	Quality Score 1-9	Loaf volume for unit level of protein (dm)	
ATC method				NIT07 $	NIT07	NIAB	GRN09	NIAB	PRP04	MIS48	MIS48	Cal.	Cal.$	RHE01	Calculated	MIS48 $	CHO01	RHE02				RHE03				MIS44$			MIS37$	MIS07$					Wheat Prot.	Flour Prot.
LA21.09099	KWS Zyatt	T2	2	13.6	12.2	11.9	77.0	76.6	79.8	15.1	9.5	11.2	1.0	52.1	54.1	28	270	1.0	2.0	2.0	90	310	16.6	73	1.9	81.85	11.51	70.34	3850	Moderate	Firm	Fine	White	4	316	344
LA21.09100	KWS Zyatt	T3	3	13.7	12.3	12.4	76.1	75.5	80.5	15.0	9.9	11.6	0.7	54.2	56.0	30	281	1.0	2.0	3.5	70	280	16.1	66	1.7	80.81	11.85	68.96	3790	Good	Resilient	Fine	White	7	308	325
LA21.09101	KWS Zyatt	T4	4	13.9	12.3	12.4	76.4	76.2	80.1	14.7	9.7	11.4	0.9	53.4	54.7	29	265	1.0	1.5	2.5	80	290	17.5	74	1.7	81.53	11.57	69.96	3700	Good	Resilient	Fine	White	7	301	325
LA21.09102	KWS Zyatt	T5	5	13.3	12.9	13.1	76.5	76	80.8	14.7	10.3	12.1	0.8	54.4	55.7	29	270	1.5	2.0	3.5	60	360	17.0	86	2.1	81.06	11.81	69.25	3800	Good	Resilient	Fine	White	7	295	315
LA21.09103	KWS Zyatt	T6	6	13.5	12.5	12.7	76.1	76	79.5	14.9	10.0	11.8	0.7	52.0	53.6	25	258	1.0	2.0	3.5	60	350	16.4	82	2.1	81.90	12.05	69.85	3790	Moderate	Weak	Fine	Creamy	4	303	323
LA21.09104	KWS Zyatt	T7	7	13.6	13.8	13.5	75.9	75.6	79.0	14.5	10.5	12.3	1.5	53.5	54.4	30	280	1.0	2.0	4.5	50	400	17.0	99	2.4	81.93	11.84	70.09	3860	Very good	Resilient	Fine	White	8	280	314
LA21.09105	KWS Zyatt	T8	8	13.5	13.9	13.9	75.3	74.9	80.6	14.5	11.2	13.1	0.8	56.0	56.9	35	290	1.0	2.0	5.0	40	340	17.8	84	1.9	80.71	12.34	68.37	3790	Good	Resilient	Fine	White	7	273	289
LA21.09106	KWS Siskin	T2	10	13.4	11.5	11.7	76.2	75.6	81.0	14.8	9.3	10.9	0.6	53.6	55.0	24	314	1.0	1.5	2.0	80	250	16.6	63	1.5	80.06	12.53	67.53	3860	Moderate	Slightly Weak	Slightly coarse	White	4	336	354
LA21.09107	KWS Siskin	T3	11	13.8	12.2	12.5	75.6	75.4	79.7	14.8	9.6	11.3	0.9	52.6	54.0	22	293	1.0	2.0	3.0	60	310	17.7	81	1.8	81.56	12.19	69.37	3930	Good to moderate	Slightly Weak	Fine	White	6	322	349
LA21.09108	KWS Siskin	T4	12	13.5	12.5	12.5	76.5	75.5	81.1	14.5	9.7	11.3	1.2	54.6	55.5	24	293	1.5	2.0	3.0	70	270	16.8	65	1.6	80.43	12.50	67.93	3800	Good to moderate	Slightly Weak	Fine	Creamy	6	304	335
LA21.09109	KWS Siskin	T5	13	13.3	12.9	13.2	75.1	74.5	79.2	14.7	10.3	12.1	0.8	54.1	55.4	24	290	1.5	2.0	3.0	70	350	17.2	85	2.0	80.18	12.44	67.74	3710	Moderate to poor	Weak	Slightly coarse	White	3	288	307
LA21.09110	KWS Siskin	T6	14	12.7	12.5	12.7	76.1	75.5	81.4	14.9	10.2	12.0	0.5	54.2	55.8	27	305	1.0	2.0	4.0	50	290	17.0	71	1.7	79.56	12.76	66.80	3840	Good to moderate	Resilient	Slightly coarse	White	6	307	320
LA21.09111	KWS Siskin	T7	15	12.9	13.9	14.0	75.0	73.6	78.5	14.8	11.0	12.9	1.0	53.9	55.3	23	321	1.5	2.5	6.5	30	350	18.8	96	1.9	79.62	12.77	66.85	3730	Moderate	Slightly Weak	Slightly coarse	White	4	268	289
LA21.09112	KWS Siskin	T8	16	13.0	13.8	14.1	74.4	73.5	80.5	14.3	10.9	12.7	1.1	56.4	56.9	29	309	1.0	1.5	5.0	30	300	18.0	79	1.7	78.56	13.05	65.51	3700	Moderate to poor	Weak	Slightly coarse	Dull	3	268	291
LA21.09113	RGT Skyfall	T2	18	13.3	11.9	11.9	78.0	78.1	78.9	14.7	9.3	10.9	1.0	55.2	56.5	27	213	1.0	2.0	2.5	80	350	16.8	88	2.1											
LA21.09114	RGT Skyfall	T3	19	13.5	12.4	12.5	78.0	77.5	80.8	14.9	9.8	11.5	0.9	56.4	58.0	29	206	1.0	2.0	3.0	70	290	18.1	73	1.6											
LA21.09115	RGT Skyfall	T4	20	13.8	12.8	12.5	78.0	77.6	77.9	14.9	9.5	11.2	1.6	55.3	56.9	23	210	1.0	2.0	2.0	100	350	18.4	89	1.9											
LA21.09116	RGT Skyfall	T5	21	13.4	12.9	13.1	77.8	77.4	80.7	14.7	10.2	12.0	0.9	57.3	58.6	30	212	1.5	2.0	3.0	80	320	19.8	89	1.6											
LA21.09117	RGT Skyfall	T6	22	13.3	13.1	12.8	77.7	76.7	78.9	14.5	10.0	11.7	1.4	56.1	57.0	27	211	1.0	2.0	2.0	90	370	18.1	95	2.0											
LA21.09118	RGT Skyfall	T7	23	13.1	13.5	13.8	77.7	76.4	79.9	14.9	11.0	12.9	0.6	56.4	58.0	28	204	1.5	2.0	3.0	70	370	20.0	106	1.9											
LA21.09119	RGT Skyfall	T8	24	12.8	13.9	14.0	77.6	75.7	79.2	14.7	11.0	12.9	1.0	56.9	58.2	29	211	1.5	2.0	3.0	70	370	19.8	107	1.9											
2021 Series 1 NIAB (SS) - All sample Mean				13.4	12.8	12.9	76.5	75.9	79.9	14.7	10.1	11.9	1.0	54.7	56.0	27	262	1.2	2.0	3.3	67	327	17.7	83	1.9	80.70	12.23	68.47	3796					5.4	298	320
2021 Series 1 NIAB (SS) - All sample Max				13.9	13.9	14.1	78.0	78.1	81.4	15.1	11.2	13.1	1.6	57.3	58.6	35	321	1.5	2.5	6.5	100	400	20.0	107	2.4	81.93	13.05	70.34	3930					8.0	336	354
2021 Series 1 NIAB (SS) - All sample Min				12.7	11.5	11.7	74.4	73.5	77.9	14.3	9.3	10.9	0.5	52.0	53.6	22	204	1.0	1.5	2.0	30	250	16.1	63	1.5	78.56	11.51	65.51	3700					3.0	268	289
2021 Series 1 NIAB (SS) - T2 mean				13.4	11.9	11.8	77.1	76.8	79.9	14.9	9.4	11.0	0.9	53.6	55.2	26	266	1.0	1.8	2.2	83	303	16.7	75	1.8	80.96	12.02	68.94	3855					4.0	326	349
2021 Series 1 NIAB (SS) - T3 mean				13.7	12.3	12.5	76.6	76.1	80.3	14.9	9.8	11.5	0.8	54.4	56.0	27	260	1.0	2.0	3.2	67	293	17.3	73	1.7	81.19	12.02	69.17	3860					6.5	315	337
2021 Series 1 NIAB (SS) - T4 mean				13.7	12.5	12.5	77.0	76.4	79.7	14.7	9.6	11.3	1.2	54.4	55.7	25	256	1.2	1.8	2.5	83	303	17.6	76	1.7	80.98	12.04	68.95	3750					6.5	302	330
2021 Series 1 NIAB (SS) - T5 Mean				13.3	12.9	13.1	76.5	76.0	80.2	14.7	10.3	12.0	0.9	55.3	56.5	28	257	1.5	2.0	3.2	70	343	18.0	87	1.9	80.62	12.13	68.50	3755					5.0	291	311
2021 Series 1 NIAB (SS) - T6 mean				13.2	12.7	12.7	76.6	76.1	79.9	14.8	10.1	11.8	0.9	54.1	55.5	26	258	1.0	2.0	3.2	67	337	17.2	83	1.9	80.73	12.41	68.33	3815					5.0	305	321
2021 Series 1 NIAB (SS) - T7 mean				13.2	13.7	13.8	76.2	75.2	79.1	14.7	10.8	12.7	1.0	54.6	55.9	27	268	1.3	2.2	4.7	50	373	18.6	100	2.1	80.78	12.31	68.47	3795					6.0	274	302
2021 Series 1 NIAB (SS) - T8 mean				13.1	13.9	14.0	75.8	74.7	80.1	14.5	11.0	12.9	1.0	56.4	57.3	31	270	1.2	1.8	4.3	47	337	18.5	90	1.8	79.64	12.70	66.94	3745					5.0	270	290
2021 Series 1 NIAB (SS) - KWS Zyatt Mear				13.6	12.8	12.8	76.2	75.8	80.0	14.8	10.2	11.9	0.9	53.7	55.0	29	273	1.1	1.9	3.5	64	333	16.9	81	2.0	81.40	11.85	69.55	3797					6.3	296	319
2021 Series 1 NIAB (SS) - KWS Siskin Mea				13.2	12.8	13.0	75.6	74.8	80.2	14.7	10.1	11.9	0.9	54.2	55.4	25	304	1.2	1.9	3.8	56	303	17.4	77	1.7	80.00	12.61	67.39	3796					4.6	299	321
2021 Series 1 NIAB (SS) - RGT Skyfall Mea				13.3	12.9	12.9	77.8	77.1	79.5	14.8	10.1	11.9	1.1	56.2	57.6	28	210	1.2	2.0	2.6	80	346	18.7	92	1.9											

Table A3.10: Rheology and baking for cross site / year N rate and timing trials.

Cross site / year mean values - N rate and timing					Wheat					Flour			Farino		Extensograph			Baking	
Crop year	No. of samples	No. of samples baked	Variety	Treatment No.	Prot. % at DM	Prot	Sp.wt. (kg/hl)	Sp wht	Ext.rate %	Prot. %	Prot. % at DM	W.abs @ 14% moist	Stab. mins	Tol. BU	Res. BU	Ext. cm	R/E	Loaf vol. cm3	Quality Score 1-9
					NIT07	NIAB	GRN09	NIAB	PRP04	MIS48	Cal.	Calculated			RHE03			MIS37$	
2019 & 2021	5	4	Siskin	T2	11.5	11.5	76.8	75.8	80.9	9.0	10.5	54.6	2.9	86	258	16.3	1.6	3828	3.8
2019 & 2021	5	4	Siskin	T3	12.0	12.1	76.9	76.0	81.1	9.4	11.0	55.1	3.4	72	258	16.6	1.6	3858	5.0
2019 & 2021	5	4	Siskin	T4	12.0	12.0	76.9	76.0	80.5	9.4	11.0	55.0	3.4	80	258	16.5	1.6	3793	4.3
2019 & 2021	5	4	Siskin	T5	12.4	12.4	76.7	75.7	80.1	9.8	11.5	55.2	3.5	78	298	16.4	1.8	3760	4.0
2019 & 2021	5	4	Siskin	T6	12.3	12.4	76.3	75.6	81.3	9.8	11.4	55.5	3.6	84	258	16.5	1.6	3863	5.0
2019 & 2021	5	4	Siskin	T7	13.1	13.1	76.6	75.3	79.6	10.2	12.0	55.6	4.4	64	310	18.0	1.7	3833	4.5
2019 & 2021	5	4	Siskin	T8	13.2	13.2	76.4	75.5	80.4	10.4	12.1	56.4	4.3	70	302	17.5	1.7	3755	4.5
2019 & 2021	5	4	Zyatt	T2	11.8	11.5	77.5	76.5	80.9	9.1	10.7	54.7	3.2	84	302	15.7	1.9	3783	4.5
2019 & 2021	5	4	Zyatt	T3	12.3	12.2	77.2	76.4	80.7	9.6	11.2	55.3	3.1	84	266	16.6	1.6	3738	5.0
2019 & 2021	5	4	Zyatt	T4	12.2	12.2	77.4	76.6	81.0	9.6	11.2	55.3	3.3	80	274	17.0	1.6	3755	6.0
2019 & 2021	5	4	Zyatt	T5	12.4	12.4	77.6	76.8	80.3	9.7	11.3	55.1	3.6	66	340	16.5	2.1	3820	6.0
2019 & 2021	5	4	Zyatt	T6	12.4	12.4	77.0	76.2	80.7	9.8	11.5	55.1	3.7	70	292	16.4	1.8	3828	5.3
2019 & 2021	5	4	Zyatt	T7	12.9	12.9	77.2	76.6	80.1	10.1	11.8	55.3	4.0	64	334	16.9	2.0	3795	5.8
2019 & 2021	5	4	Zyatt	T8	12.9	13.1	77.1	76.3	80.5	10.2	11.9	56.3	3.8	66	306	17.0	1.8	3763	5.3
19, 20 & 21	5	4	Skyfall	T2	11.8	11.7	78.4	77.9	79.3	9.1	10.7	55.9	3.3	75	303	16.8	1.8	3820	5.5
19, 20 & 21	5	4	Skyfall	T3	12.2	12.1	78.4	77.7	80.6	9.5	11.1	56.4	3.9	73	297	17.0	1.8	3830	5.8
19, 20 & 21	5	4	Skyfall	T4	12.3	12.2	78.2	77.9	79.3	9.5	11.1	56.1	3.4	78	308	17.4	1.8	3863	6.8
19, 20 & 21	5	4	Skyfall	T5	12.5	12.3	78.4	78.1	80.3	9.7	11.4	57.1	3.7	73	318	17.9	1.8	3788	5.8
19, 20 & 21	5	4	Skyfall	T6	12.5	12.6	78.3	77.6	79.7	9.7	11.4	56.4	3.6	75	327	17.4	1.9	3838	6.5
19, 20 & 21	5	4	Skyfall	T7	12.9	12.9	78.4	77.6	80.2	10.2	12.0	57.3	4.0	67	325	18.0	1.8	3810	7.0
19, 20 & 21	5	4	Skyfall	T8	13.2	13.1	78.0	77.1	79.6	10.3	12.0	56.8	3.9	63	348	18.4	1.9	3815	6.5

Table A3.11: Rheology and baking for the Lincolnshire 2021 N and S rate and timing trial.

Lincolnshire 2021 - N & S timing			Wheat analysis						Flour								Farinograph				Extensograph				CBP test baking $										
ATC sample no.	Variety	Treatment No.	Moist. %	Prot. % at DM	Prot	Sp.wt. (kg/hl)	Sp wht	Ext.rate %	Moist. %	Prot. %	Prot. % at DM	Prot % loss on milling	Water Abs. %	W.abs @ 14% moist	Starch damage %	HFN	Arr. mins	Peak. mins	Stab. mins	Tol. BU	Res. BU	Ext. cm	Area cm2	R/E	Minolta colour L*	Minolta colour b*	Minolta colour L*-b*	Loaf vol. cm3	Bread quality	Crumb Structure	Crumb texture	Crumb colour	Quality Score 1-9	Loaf volume for unit level of protein: Wheat Prot.	Loaf volume for unit level of protein: Flour Prot.
ATC method			NIT07 $	NIT07	NIAB	GRN09	NIAB	PRP04	MIS48	MIS48	Cal.	Cal.$	RHE01	Calculated	MIS48 $	CHO01	RHE02				RHE03				MIS44$			MIS37$		MIS07$				Wheat Prot.	Flour Prot.
LA21.09315	KWS Zyatt	1	12.5	12.0	11.7	78.6	76.6	80.8	14.7	9.6	11.3	0.7	52.6	53.9	27	315	1.0	1.5	3.0	70	330	16.8	79	2.0	81.94	12.22	69.72	3850	Good	Resilient	Fine	White	7	321	342
LA21.08738	KWS Zyatt	2	14.9	11.9	11.4	78.3	77.1	81.2	14.7	9.4	11.0	0.9	53.7	55.0	31	312	1.0	1.5	3.5	70	310	16.1	72	1.9	82.16	12.46	69.70	3880	Very good	Resilient	Fine	White	8	326	352
LA21.09316	KWS Zyatt	3	12.2	11.6	11.4	78.3	77.3	79.4	14.8	9.3	10.9	0.7	51.7	53.1	25	311	1.0	2.0	3.0	70	320	15.7	77	2.0	81.81	12.23	69.58	3910	Very good	Resilient	Fine	White	8	337	358
LA21.09317	KWS Zyatt	4	12.1	11.8	11.2	78.5	77.1	80.7	14.6	9.4	11.0	0.8	52.9	54.0	28	316	1.0	1.5	3.0	70	300	15.8	69	1.9	81.42	12.25	69.17	3790	Good to moderate	Resilient	Fine	Creamy	6	321	344
LA21.09318	KWS Zyatt	5	12.2	12.6	11.9	79.1	77.7	79.7	14.5	9.8	11.5	1.1	53.8	54.7	29	324	1.0	2.0	3.0	60	390	17.2	95	2.3	81.73	12.51	69.22	3670	Good to moderate	Resilient	Slightly coarse	White	6	291	320
LA21.08739	KWS Zyatt	6	15.3	12.1	11.8	78.3	77.4	79.9	14.9	9.4	11.0	1.1	52.5	54.1	27	322	1.0	2.0	2.5	80	390	16.3	91	2.4	82.81	12.29	70.52	3940	Very good	Resilient	Fine	White	8	326	357
LA21.09319	KWS Zyatt	7	12.6	11.9	11.4	78.9	77.3	81.4	14.7	9.7	11.4	0.5	54.2	55.5	30	309	1.5	2.0	3.0	70	310	16.0	72	1.9	80.71	12.61	68.10	3660	Good to moderate	Slightly Weak	Slightly coarse	Creamy	6	308	322
LA21.09320	KWS Zyatt	8	12.6	12.0	11.7	78.6	77.4	79.6	14.3	9.5	11.1	0.9	53.5	54.0	28	318	1.0	2.0	3.5	50	350	15.8	81	2.2	82.20	12.17	70.03	3610	Good to moderate	Resilient	Fine	White	6	301	326
LA21.09321	KWS Zyatt	9	12.6	11.7	11.3	77.8	76.6	81.2	14.8	9.5	11.2	0.5	53.3	54.7	29	351	1.0	2.0	3.5	60	260	16.0	61	1.6	80.61	13.04	67.57	3500	Moderate to good	Slightly Weak	Fine	Creamy	5	299	314
LA21.09322	KWS Zyatt	10	12.1	11.3	11.1	78.5	77.1	79.3	15.0	9.0	10.6	0.7	51.0	52.8	23	324	1.0	1.5	3.0	70	370	15.6	82	2.4	82.47	12.32	70.15	3580	Good to moderate	Slightly Weak	Fine	White	6	317	338
LA21.09323	KWS Zyatt	11	12.8	12.4	11.5	78.7	77.5	79.0	14.6	9.8	11.5	0.9	53.0	54.1	29	335	1.0	2.0	3.0	60	370	16.5	82	2.2	82.06	12.45	69.61	3710	Good	Resilient	Fine	White	7	299	323
LA21.09324	KWS Zyatt	12	12.8	12.4	11.7	78.9	77.6	81.1	14.5	9.9	11.6	0.8	54.7	55.6	32	335	1.5	2.0	4.5	40	330	16.5	78	2.0	80.62	13.07	67.55	3860	Good	Resilient	Fine	White	7	311	333
LA21.09325	RGT Skyfall	1	13.0	12.3	11.7	79.6	78.4	80.5	14.7	9.8	11.5	0.8	56.1	57.4	28	349	1.0	2.0	4.5	50	350	15.7	77	2.2	79.73	12.71	67.02	3510	Moderate to good	Slightly Weak	Fine	Creamy	5	285	306
LA21.08752	RGT Skyfall	2	14.5	12.7	12.1	79.1	78.4	78.5	14.9	9.6	11.3	1.4	55.3	56.9	27	319	1.0	2.0	3.5	60	320	16.2	86	2.0	81.77	11.30	70.47	3860	Good	Resilient	Fine	White	7	304	342
LA21.09326	RGT Skyfall	3	12.8	12.7	11.9	79.9	78.9	78.4	14.8	9.7	11.4	1.3	54.7	56.1	24	335	1.0	1.5	3.0	60	360	17.0	86	2.1	81.25	12.16	69.09	3500	Good to moderate	Resilient	Fine	White	6	276	307
LA21.09327	RGT Skyfall	4	12.7	12.5	11.8	79.6	78.0	80.7	14.6	9.8	11.5	1.0	57.0	58.1	30	362	1.0	2.0	5.0	40	300	17.1	73	1.8	80.00	12.45	67.55	3480	Moderate to good	Slightly Weak	Fine	White	5	278	303
LA21.09328	RGT Skyfall	5	12.6	12.3	12.2	80.1	78.6	78.2	14.8	9.6	11.3	1.0	55.2	56.6	25	356	1.5	2.0	3.0	70	440	18.1	110	2.4	81.15	12.26	68.89	3520	Good to moderate	Slightly Weak	Fine	White	6	286	312
LA21.08753	RGT Skyfall	6	14.4	12.7	11.8	79.1	77.9	80.9	14.7	9.7	11.4	1.3	56.2	57.5	30	372	1.5	2.0	5.5	40	320	16.4	77	2.0	81.52	11.63	69.89	3870	Good to moderate	Slightly Weak	Fine	White	6	305	340
LA21.09329	RGT Skyfall	7	12.8	12.1	12.0	79.9	78.6	81.4	14.5	9.7	11.3	0.8	57.6	58.5	30	348	1.0	2.0	5.0	50	320	17.0	81	1.9	79.61	12.75	66.86	3500	Moderate to good	Slightly Weak	Fine	White	5	289	309
LA21.09330	RGT Skyfall	8	12.5	12.5	11.4	79.5	78.5	78.6	14.4	9.6	11.2	1.3	55.8	56.5	27	336	1.0	2.0	4.0	50	380	16.7	91	2.3	80.66	12.54	68.12	3640	Moderate to good	Resilient	Slightly coarse	White	5	291	325
LA21.09331	RGT Skyfall	9	12.8	12.6	12.1	79.6	78.0	80.3	15.0	9.9	11.6	1.0	55.8	57.6	27	351	1.0	1.5	4.0	60	310	16.8	75	1.8	80.38	12.81	67.57	3470	Moderate to good	Slightly Weak	Fine	White	5	275	298
LA21.09332	RGT Skyfall	10	12.8	12.2	12.1	80	78.4	78.7	15.1	9.7	11.4	0.8	54.4	56.4	25	315	1.0	1.5	3.5	50	360	17.5	90	2.1	80.67	12.48	68.19	3580	Moderate to good	Slightly Weak	Fine	White	5	293	313
LA21.09333	RGT Skyfall	11	12.8	12.7	12.4	79.2	78.7	80.5	14.7	10.1	11.8	0.9	57.4	58.7	29	362	1.5	2.5	4.5	50	340	16.8	81	2.0	78.70	12.95	65.75	3670	Moderate to good	Resilient	Slightly coarse	Dull	5	289	310
LA21.09334	RGT Skyfall	12	12.8	12.6	11.8	79.4	78.5	79.7	14.7	9.9	11.6	1.0	55.8	57.1	26	351	1.5	2.0	3.0	60	390	17.8	97	2.2	79.89	12.59	67.30	3640	Moderate to good	Slightly Weak	Slightly coarse	Creamy	5	289	314
2021 Series 2 NIAB (BE) - All Sample Mean			13.0	12.2	11.7	79.1	78.4	80.0	14.7	9.6	11.3	0.9	54.5	55.8	28	335	1.1	1.9	3.6	59	343	16.6	82	2.1	81.08	12.43	68.65	3675					6.0	301	325
2021 Series 2 NIAB (BE) - All Sample Max			15.3	12.7	12.4	80.1	78.9	81.4	15.1	10.1	11.8	1.4	57.6	58.7	32	372	1.5	2.5	5.5	80	440	18.1	110	2.4	82.81	13.07	70.52	3940					8.0	337	358
2021 Series 2 NIAB (BE) - All Sample Min			12.1	11.3	11.1	77.8	77.9	78.2	14.3	9.0	10.6	0.5	51.0	52.8	23	309	1.0	1.5	2.5	40	260	15.6	61	1.6	78.70	11.30	65.75	3470					5.0	275	298
2021 Series 2 NIAB (BE) - T1 mean			12.8	12.2	11.7	79.1	77.5	80.7	14.7	9.7	11.4	0.8	54.4	55.6	28	332	1.0	1.8	3.8	60	340	16.3	78	2.1	80.84	12.47	68.37	3680					6.0	303	324
2021 Series 2 NIAB (BE) - T2 mean			14.7	12.3	11.8	78.7	77.8	79.9	14.8	9.5	11.2	1.1	54.5	55.9	29	316	1.0	1.8	3.5	65	315	16.2	79	2.0	81.97	11.88	70.09	3870					7.5	315	347
2021 Series 2 NIAB (BE) - T3 mean			12.5	12.2	11.7	79.1	78.1	78.9	14.8	9.5	11.2	1.0	53.2	54.6	25	323	1.0	1.8	3.0	65	340	16.4	82	2.1	81.53	12.20	69.34	3705					7.0	306	333
2021 Series 2 NIAB (BE) - T4 mean			12.4	12.2	11.5	79.1	77.6	80.7	14.6	9.6	11.2	1.0	55.0	56.0	29	339	1.0	1.8	4.0	55	300	16.5	71	1.9	80.71	12.35	68.36	3635					5.5	300	324
2021 Series 2 NIAB (BE) - T5 mean			12.4	12.5	12.1	79.6	78.2	79.0	14.7	9.7	11.4	1.1	54.5	55.7	27	340	1.3	2.0	3.0	65	415	17.7	103	2.4	81.44	12.39	69.06	3595					6.0	289	316
2021 Series 2 NIAB (BE) - T6 mean			14.9	12.4	11.8	78.7	77.7	80.4	14.8	9.6	11.2	1.2	54.4	55.8	29	347	1.3	2.0	4.0	60	355	16.4	84	2.2	82.17	11.96	70.21	3905					7.0	315	349
2021 Series 2 NIAB (BE) - T7 mean			12.7	12.0	11.7	79.4	78.0	81.4	14.6	9.7	11.4	0.6	55.9	57.0	30	329	1.3	2.0	4.0	60	315	16.5	77	1.9	80.16	12.68	67.48	3580					5.5	298	315
2021 Series 2 NIAB (BE) - T8 mean			12.6	12.3	11.6	79.1	78.0	79.1	14.4	9.6	11.2	1.1	54.7	55.3	28	327	1.0	2.0	3.8	50	365	16.3	86	2.3	81.43	12.36	69.08	3625					5.5	296	325
2021 Series 2 NIAB (BE) - T9 mean			12.7	12.2	11.7	78.7	77.3	80.8	14.9	9.7	11.4	0.8	54.6	56.2	28	351	1.0	1.8	3.8	60	285	16.4	68	1.7	80.50	12.93	67.57	3485					5.0	287	306
2021 Series 2 NIAB (BE) - T10 mean			12.5	11.8	11.6	79.3	77.8	79.0	15.1	9.4	11.0	0.8	52.7	54.6	24	320	1.0	1.5	3.3	60	365	16.6	86	2.3	81.57	12.40	69.17	3580					5.5	305	326
2021 Series 2 NIAB (BE) - T11 mean			12.8	12.6	12.0	79.0	78.1	79.8	14.7	10.0	11.7	0.9	55.2	56.4	29	349	1.3	2.3	3.8	55	355	16.7	82	2.1	80.38	12.70	67.68	3690					6.0	294	317
2021 Series 2 NIAB (BE) - T12 mean			12.8	12.5	11.8	79.2	78.1	80.4	14.6	9.9	11.6	0.9	55.3	56.3	29	343	1.5	2.0	3.8	50	360	17.2	88	2.1	80.26	12.83	67.43	3750					6.0	300	323
2021 Series 2 NIAB (BE) - KWS Zyatt mear			12.9	12.0	11.5	78.5	77.2	80.3	14.7	9.5	11.2	0.8	53.1	54.3	28	323	1.1	1.8	3.2	64	336	16.2	78	2.1	81.71	12.47	69.24	3747					6.7	313	336
2021 Series 2 NIAB (BE) - RGT Skyfall mea			13.0	12.5	11.9	79.6	78.4	79.7	14.7	9.8	11.4	1.1	55.9	57.3	27	346	1.2	1.9	4.0	53	349	16.9	85	2.1	80.44	12.39	68.06	3603					5.4	288	315

Table A3.12: Rheology and baking for the Hampshire 2021 N and S rate and timing trial.

Hampshire 2021 - N & S timing			Wheat analysis						Flour								Farinograph				Extensograph					CBP test baking $										
ATC sample no.	Variety	Treatment No.	Moist. %	Prot. % at DM	Prot	Sp.wt. (kg/hl)	Sp wht	Ext.rate %	Moist. %	Prot. %	Prot. % at DM	Prot % loss on milling	Water Abs. %	W.abs @ 14% moist	Starch damage %	HFN	Arr. mins	Peak mins	Stab. mins	Tol. BU	Res. BU	Ext. cm	Area cm2	R/E	Minolta colour L*	b*	L*-b*	Loaf vol. cm3	Bread quality	Crumb Structure	Crumb texture	Crumb colour	Quality Score 1-9	Loaf volume for unit level of protein	
ATC method			NIT07 $	NIT07	NIAB	GRN09	NIAB	PRP04	MIS48	MIS48	Cal.	Cal.$	RHE01	Calculated	MIS48 $	CHO01	RHE02				RHE03					MIS44$			MIS37$		MIS07$				Wheat Prot.	Flour Prot.
LA21.09335	KWS Zyatt	1	12.5	12.2	11.7	76.9	75.6	81.4	14.5	9.8	11.5	0.7	55.4	56.3	29	261	1.0	2.0	4.0	60	310	16.7	75	1.9	79.63	13.21	66.42	3400	Good to moderate	Slightly Weak	Fine	White	6	279	297
LA21.09101	KWS Zyatt	2	13.9	12.3	11.9	76.4	75.0	80.1	14.7	9.7	11.4	0.9	53.4	54.7	29	265	1.0	1.5	2.5	80	290	17.5	74	1.7	81.53	11.57	69.96	3700	Good	Resilient	Fine	White	7	301	325
LA21.09336	KWS Zyatt	3	12.4	12.3	12.0	75.9	74.9	80.8	14.5	9.9	11.6	0.7	55.5	56.4	29	269	1.0	1.5	4.0	70	340	15.5	76	2.2	80.27	12.55	67.72	3560	Good	Resilient	Fine	Creamy	7	289	307
LA21.09337	KWS Zyatt	4	12.3	12.3	11.9	76.3	74.9	81.2	14.8	9.9	11.6	0.7	54.7	56.1	30	277	1.0	2.0	4.0	60	290	17.1	72	1.7	80.06	12.71	67.35	3560	Good	Resilient	Fine	Creamy	7	289	306
LA21.09338	KWS Zyatt	5	12.4	13.0	12.5	76.9	75.7	78.8	14.9	10.3	12.1	0.9	54.5	56.1	28	262	1.0	1.5	2.5	60	380	16.2	89	2.3	80.57	11.98	68.59	3520	Good	Resilient	Fine	Creamy	7	271	291
LA21.09102	KWS Zyatt	6	13.3	12.9	12.1	76.5	75.5	80.8	14.7	10.3	12.1	0.8	54.4	55.7	29	270	1.5	2.0	3.5	60	360	17.0	86	2.1	81.06	11.81	69.25	3800	Good	Resilient	Fine	White	7	295	315
LA21.09339	KWS Zyatt	7	12.2	13.0	12.7	76.2	75.1	80.8	14.5	10.5	12.3	0.7	56.3	57.2	33	262	1.0	2.0	4.5	60	290	17.6	75	1.6	79.34	12.94	66.40	3540	Good	Resilient	Slightly coarse	Creamy	7	272	288
LA21.09340	KWS Zyatt	8	12.4	13.0	12.6	76.2	75.1	79.3	14.7	10.4	12.2	0.8	54.5	55.8	30	259	1.5	2.0	3.5	80	370	17.4	89	2.1	80.95	12.47	68.48	3640	Very good	Resilient	Fine	White	8	280	299
LA21.09341	KWS Zyatt	9	12.3	12.3	12.0	76.1	74.1	81.0	14.6	9.9	11.6	0.7	54.9	56.0	31	255	1.5	2.0	4.0	70	280	15.5	65	1.8	79.42	12.86	66.56	3490	Good	Resilient	Slightly coarse	White	7	284	301
LA21.09342	KWS Zyatt	10	12.3	12.5	12.2	75.8	75.0	79.0	14.6	9.7	11.4	1.1	53.8	54.9	28	263	1.0	1.5	2.5	60	310	17.8	78	1.7	81.34	12.18	69.16	3660	Very good	Resilient	Fine	White	8	293	322
LA21.09343	KWS Zyatt	11	12.3	13.0	12.6	76.5	75.4	80.6	14.8	10.5	12.3	0.7	54.6	56.0	31	248	1.5	2.5	4.5	50	350	17.0	81	2.1	80.19	12.70	67.49	3620	Good	Resilient	Slightly coarse	Creamy	7	278	294
LA21.09344	KWS Zyatt	12	12.1	12.9	12.7	76.4	74.8	78.9	15.0	10.4	12.2	0.7	53.0	54.8	27	240	1.0	2.0	3.5	60	370	16.4	87	2.3	80.49	12.29	68.20	3560	Good	Resilient	Fine	White	7	276	291
LA21.09345	RGT Skyfall	1	12.1	12.6	12.2	78.0	76.8	80.5	14.8	9.7	11.4	1.2	57.2	58.6	30	211	1.5	2.0	2.5	80	330	17.5	85	1.9	77.52	12.96	64.56	3480	Moderate	Weak	Slightly coarse	White	4	276	306
LA21.09346	RGT Skyfall	2	12.3	12.5	12.0	77.4	76.1	78.3	14.8	9.6	11.3	1.2	55.7	57.1	27	211	1.0	1.5	2.5	70	350	17.8	88	2.0	78.89	12.73	66.16	3580	Good to moderate	Resilient	Slightly coarse	White	6	286	317
LA21.09347	RGT Skyfall	3	12.2	12.4	12.1	78	76.0	80.2	14.6	9.9	11.6	0.8	56.7	57.8	29	216	1.0	1.5	3.5	60	310	17.5	78	1.8	79.21	12.56	66.65	3520	Good to moderate	Slightly Weak	Slightly coarse	White	6	284	304
LA21.09348	RGT Skyfall	4	12.2	12.7	12.3	77.7	76.2	78.3	14.7	9.8	11.5	1.2	55.8	57.1	28	220	1.0	2.0	2.5	80	360	18.4	94	2.0	79.77	12.47	67.30	3550	Good to moderate	Slightly Weak	Slightly coarse	White	6	280	309
LA21.09349	RGT Skyfall	5	11.9	13.0	12.4	77.4	76.6	79.7	14.9	10.2	12.0	1.0	56.9	58.5	30	214	1.0	2.0	2.5	90	370	18.6	95	2.0	77.99	12.65	65.34	3470	Moderate to good	Slightly Weak	Slightly coarse	Creamy	5	267	290
LA21.09350	RGT Skyfall	6	11.9	12.8	12.6	77.3	76.4	80.0	14.7	10.2	12.0	0.8	57.4	58.7	31	222	1.0	2.0	3.5	60	340	18.6	92	1.8	77.40	12.53	64.87	3540	Moderate to good	Slightly Weak	Slightly coarse	Creamy	5	277	296
LA21.09351	RGT Skyfall	7	12.1	12.9	12.4	77.3	75.8	78.6	14.7	10.1	11.8	1.1	57.2	58.5	28	228	1.0	2.0	2.5	80	380	21.2	114	1.8	78.53	12.64	65.89	3410	Moderate to good	Slightly Weak	Slightly coarse	White	5	264	288
LA21.09352	RGT Skyfall	8	12.0	13.0	12.5	77.3	75.7	80.3	14.6	10.2	11.9	1.1	58.2	59.3	31	212	1.0	2.0	3.0	80	340	18.9	91	1.8	77.09	12.92	64.17	3290	Moderate	Resilient	Coarse	Creamy	4	253	275
LA21.09353	RGT Skyfall	9	11.9	12.7	12.3	76.7	76.2	78.4	14.6	9.7	11.4	1.3	56.2	57.3	26	197	1.0	2.0	3.0	80	350	17.8	91	2.0	79.14	12.41	66.73	3510	Good	Resilient	Slightly coarse	Creamy	7	276	309
LA21.09354	RGT Skyfall	10	11.8	12.6	12.2	77.8	76.1	80.6	14.6	9.9	11.6	1.0	57.6	58.7	29	208	1.0	2.0	3.0	60	290	18.1	75	1.6	77.44	13.04	64.40	3450	Moderate to good	Slightly Weak	Slightly coarse	Creamy	5	274	298
LA21.09355	RGT Skyfall	11	12.0	13.1	12.6	77.4	76.2	80.1	14.9	10.4	12.2	0.9	57.0	58.6	26	224	1.0	2.0	3.5	50	350	19.2	98	1.8	77.26	12.90	64.36	3470	Moderate to good	Slightly Weak	Slightly coarse	Creamy	5	265	284
LA21.09356	RGT Skyfall	12	12.1	12.8	12.4	77.9	76.5	80.1	14.6	10.2	11.9	0.9	57.1	58.2	29	211	1.5	2.0	3.0	70	340	18.6	85	1.8	77.55	12.99	64.56	3430	Good to moderate	Slightly Weak	Slightly coarse	Creamy	6	268	287
2021 Series 2 NIAB (SS) - All Sample Mean			12.3	12.7	12.3	76.9	76.2	79.9	14.7	10.1	11.8	0.9	55.8	57.0	29	238	1.1	1.9	3.3	68	335	17.7	85	1.9	79.28	12.59	66.69	3531					6.2	278	300
2021 Series 2 NIAB (SS) - All Sample Max			13.9	13.1	12.7	78.0	76.8	81.4	15.0	10.5	12.3	1.3	58.2	59.3	33	277	1.5	2.5	4.5	90	380	21.2	114	2.3	81.53	13.21	69.96	3800					8.0	301	325
2021 Series 2 NIAB (SS) - All Sample Min			11.8	12.2	11.7	75.8	75.7	78.3	14.5	9.6	11.3	0.7	53.0	54.7	26	197	1.0	1.5	2.5	50	280	15.5	65	1.6	77.09	11.57	64.17	3290					4.0	253	275
2021 Series 2 NIAB (SS) - T1 mean			12.3	12.4	12.0	77.5	76.2	81.0	14.7	9.8	11.4	1.0	56.3	57.5	30	236	1.3	2.0	3.3	70	320	17.1	80	1.9	78.58	13.09	65.49	3440					5.0	277	301
2021 Series 2 NIAB (SS) - T2 mean			13.1	12.4	12.0	76.9	75.6	79.2	14.8	9.7	11.3	1.1	54.6	55.9	28	238	1.0	1.5	2.5	75	320	17.7	81	1.9	80.21	12.15	68.06	3640					6.5	294	321
2021 Series 2 NIAB (SS) - T3 mean			12.3	12.4	12.1	77.0	75.5	80.5	14.6	9.9	11.6	0.8	56.1	57.1	29	243	1.0	1.5	3.8	65	325	16.5	77	2.0	79.74	12.56	67.19	3540					6.5	287	306
2021 Series 2 NIAB (SS) - T4 mean			12.3	12.5	12.1	77.0	75.6	79.8	14.8	9.9	11.6	0.9	55.3	56.6	29	249	1.0	2.0	3.3	70	325	17.8	83	1.9	79.92	12.59	67.33	3555					6.5	284	308
2021 Series 2 NIAB (SS) - T5 mean			12.2	13.0	12.5	77.2	76.2	79.3	14.9	10.3	12.0	1.0	55.7	57.3	29	238	1.0	1.8	2.5	75	375	17.4	92	2.2	79.28	12.32	66.97	3495					6.0	269	290
2021 Series 2 NIAB (SS) - T6 mean			12.6	12.9	12.4	76.9	76.0	80.4	14.7	10.3	12.0	0.8	55.9	57.2	30	246	1.3	2.0	3.5	60	350	17.8	89	2.0	79.23	12.17	67.06	3670					6.0	286	305
2021 Series 2 NIAB (SS) - T7 mean			12.2	13.0	12.6	76.8	75.5	79.7	14.6	10.3	12.1	0.9	56.8	57.8	31	245	1.0	2.0	3.5	70	335	19.4	95	1.7	78.94	12.79	66.15	3475					6.0	268	288
2021 Series 2 NIAB (SS) - T8 mean			12.2	13.0	12.6	76.8	75.4	79.8	14.7	10.3	12.1	0.9	56.4	57.5	31	236	1.3	2.0	3.3	80	355	18.2	90	2.0	79.02	12.70	66.33	3465					6.0	267	287
2021 Series 2 NIAB (SS) - T9 mean			12.1	12.5	12.2	76.4	75.2	79.7	14.6	9.8	11.5	1.0	55.6	56.6	29	226	1.3	2.0	3.5	75	315	16.7	78	1.9	79.28	12.64	66.65	3500					7.0	280	305
2021 Series 2 NIAB (SS) - T10 mean			12.1	12.6	12.2	76.8	75.6	79.8	14.6	9.8	11.5	1.1	55.7	56.8	29	236	1.0	1.8	2.8	60	300	18.0	77	1.7	79.39	12.61	66.78	3555					6.5	283	310
2021 Series 2 NIAB (SS) - T11 mean			12.2	13.1	12.6	77.0	75.8	80.4	14.9	10.5	12.3	0.8	55.8	57.3	29	236	1.3	2.3	4.0	50	350	18.1	90	2.0	78.73	12.80	65.93	3545					6.0	272	289
2021 Series 2 NIAB (SS) - T12 mean			12.1	12.9	12.6	77.2	75.7	79.5	14.8	10.3	12.1	0.8	55.1	56.5	28	226	1.3	2.0	3.3	65	355	17.5	86	2.1	79.02	12.64	66.38	3495					6.5	272	289
2021 Series 2 NIAB (SS) - KWS Zyatt mean			12.5	12.6	12.2	76.3	75.1	80.2	14.7	10.1	11.8	0.8	54.6	55.8	30	261	1.2	1.9	3.6	64	328	16.8	####	2.0	80.40	12.44	67.97	3588					7.1	284	303
2021 Series 2 NIAB (SS) - RGT Skyfall mean			12.0	12.8	12.3	77.5	76.2	79.6	14.7	10.0	11.7	1.1	56.9	58.2	29	215	1.1	1.9	2.9	72	343	18.5	####	1.9	78.15	12.73	65.42	3475					5.3	272	297

Table A3.13: Rheology and baking results from the ATC Commercial Wheat Crop Surveys for crop harvests 2019-2021.

	Grain Protein % DM	Flour W.abs @14% moisture	Flour Stability Mins	Flour Resistance BU	Extensibility cm	R/E	Bread Score Score 1-9	Flour Protein % DM
KWS Zyatt 19	12.8	54.8	4.1	297	16.8	1.8	3.9	12.0
KWS Zyatt 20	12.5	55.0	4.3	332	17.3	1.9	7.0	12.0
KWS Zyatt 21	12.9	56.0	3.6	317	15.4	2.2	5.5	12.0
Skyfall 19	12.7	56.2	4.1	340	17.1	2.0	4.9	11.8
Skyfall 20	13.3	57.2	3.7	328	17.9	1.9	5.7	12.6
Skyfall 21	12.8	56.0	5.4	400	16.2	2.5	6.4	12.0
KWS Siskin 19	12.6	55.1	2.4	293	17.4	1.7	5.2	11.9
KWS Siskin 20 **	11.3	54.6	3.8	240	16.0	1.6	5.0	11.2
KWS Siskin 21 **	12.3	55.4	3.5	245	16.4	1.5	4.0	11.5

Table A3.14: Rheology and baking for cross site / year N and S rate and timing study.

Cross site / year mean values - N & S timing					Wheat					Flour			Farino		Extensograph			Baking			
Crop year	No. of samples	Variety	Treatment No.	New assigned codes for DA	Prot. % at DM	Prot	Sp.wt. (kg/hl)	Sp wht	Ext.rate %	Prot. %	Prot. % at DM	W.abs @ 14% moist	Stab. mins	Tol. BU	Res. BU	Ext. cm	R/E	Loaf vol. cm3	Quality Score 1-9	Loaf volume for unit level of protein	
					NIT07	NIAB	GRN09	NIAB	PRP04	MIS48	Cal.	Calculated	RHE02		RHE03			MIS37$		Wheat Prot.	Flour Prot.
2019 & 2021	8	Zyatt	40AN, $0SO_3$	1	12.3	11.8	78.2	77.9	81.5	9.7	11.4	54.9	3.6	75	295	16.3	1.8	3668	6.5	298	322
2019	4	Zyatt	40AN, $25SO_3$	2	12.7	12.0	79.4	79.6	82.0	9.9	11.5	55.4	3.8	85	265	17.1	1.6	3665	6.0	288	320
2019 & 2021	8	Zyatt	40AN, $50SO_3$	3	12.4	11.8	77.9	77.8	81.2	9.7	11.3	55.1	3.5	73	273	16.8	1.6	3760	6.8	303	333
2019 & 2021	8	Zyatt	40AN, $75SO_3$	4	12.3	11.8	78.0	77.8	81.0	9.7	11.4	54.7	3.6	73	298	15.8	1.9	3708	6.3	303	326
2021	4	Zyatt	40AN, $100SO_3$	13	12.1	11.6	77.4	76.0	81.0	9.7	11.3	55.1	3.5	65	295	16.5	1.8	3675	6.5	305	325
2019 & 2021	8	Zyatt	40FU, $0SO_3$	5	12.8	12.2	78.5	78.2	80.6	10.1	11.8	55.4	3.4	63	333	16.5	2.0	3678	6.3	287	311
2019	4	Zyatt	40FU, $25SO_3$	6	12.8	12.2	79.3	79.6	82.1	10.3	12.0	55.7	4.0	70	280	16.5	1.7	3725	5.0	292	310
2019 & 2021	8	Zyatt	40FU, $50SO_3$	7	12.3	11.9	77.9	77.9	81.1	9.8	11.4	54.7	3.5	73	333	16.3	2.1	3805	6.5	310	333
2019 & 2021	8	Zyatt	40FU, $75SO_3$	8	12.5	12.1	78.2	77.9	81.5	10.1	11.8	55.7	4.0	70	293	16.9	1.7	3648	5.8	292	309
2021	4	Zyatt	40FU, $100SO_3$	14	12.5	12.2	77.4	76.3	79.5	10.0	11.6	54.9	3.5	65	360	16.6	2.2	3625	7.0	290	312
2019 & 2021	8	Zyatt	40AN, 25-$25S0_3$	9	12.3	11.9	77.8	77.4	81.5	9.9	11.5	55.4	4.1	68	265	16.3	1.7	3608	5.5	292	313
2019 & 2021	8	Zyatt	40AN, 25-25-$25S0_3$	10	12.3	11.8	77.9	77.8	80.6	9.6	11.3	54.4	3.4	70	283	16.8	1.7	3663	5.5	298	325
2019 & 2021	8	Zyatt	40FU, 25-$25S0_3$	11	12.8	12.2	78.2	78.0	80.8	10.2	11.9	55.2	4.1	63	323	17.0	1.9	3745	6.5	292	314
2019 & 2021	8	Zyatt	40FU, 25-25-$25S0_3$	12	12.8	12.2	78.3	77.9	81.1	10.2	12.0	55.3	4.1	65	308	16.7	1.9	3685	5.8	288	309
2019 & 2021	8	Skyfall	40AN, $0SO_3$	1	12.7	12.1	78.9	78.5	80.9	9.9	11.6	57.0	3.9	65	290	16.8	1.7	3610	4.5	283	311
2019	4	Skyfall	40AN, $25SO_3$	2	13.0	12.2	79.0	79.4	81.3	10.1	11.7	56.4	4.0	70	215	17.2	1.3	3645	4.0	280	310
2019 & 2021	8	Skyfall	40AN, $50SO_3$	3	12.8	12.1	78.3	78.3	80.5	9.9	11.6	56.6	3.3	70	260	17.7	1.5	3657	5.3	285	315
2019 & 2021	8	Skyfall	40AN, $75SO_3$	4	12.8	12.2	79.0	78.4	80.3	9.9	11.6	56.7	3.6	65	283	17.4	1.7	3560	5.5	278	307
2021	4	Skyfall	40AN, $100SO_3$	13	12.7	12.3	77.7	76.2	78.3	9.8	11.5	57.1	2.5	80	360	18.4	2.0	3550	6.0	280	309
2019 & 2021	8	Skyfall	40FU, $0SO_3$	5	12.8	12.2	78.9	78.7	80.1	9.9	11.6	56.9	3.5	80	330	17.5	1.9	3618	6.0	283	311
2019	4	Skyfall	40FU, $25SO_3$	6	13.0	12.2	79.1	79.5	81.3	10.0	11.6	56.3	4.5	70	260	17.0	1.6	3785	6.0	292	326
2019 & 2021	8	Skyfall	40FU, $50SO_3$	7	12.9	12.1	78.8	78.4	80.8	10.1	11.8	57.2	4.4	53	298	18.0	1.7	3700	5.8	286	315
2019 & 2021	8	Skyfall	40FU, $75SO_3$	8	12.7	12.2	78.8	78.2	80.7	10.0	11.6	57.4	4.0	68	310	18.4	1.7	3628	5.5	286	312
2021	4	Skyfall	40FU, $100SO_3$	14	12.8	12.0	78.4	77.1	79.5	9.9	11.6	57.9	3.5	65	360	17.8	2.1	3465	4.5	272	300
2019 & 2021	8	Skyfall	40AN, 25-$25S0_3$	9	12.9	12.2	78.7	78.3	80.4	10.0	11.7	57.2	3.8	73	278	17.3	1.6	3590	5.3	279	308
2019 & 2021	8	Skyfall	40AN, 25-25-$25S0_3$	10	12.7	12.2	78.9	78.3	80.5	9.9	11.6	56.9	3.8	63	278	17.7	1.6	3580	4.3	283	310
2019 & 2021	8	Skyfall	40FU, 25-$25S0_3$	11	13.0	12.5	78.8	78.6	80.8	10.2	12.0	57.7	4.0	58	293	18.1	1.6	3623	5.0	279	303
2019 & 2021	8	Skyfall	40FU, 25-25-$25S0_3$	12	12.9	12.2	78.9	78.5	80.6	10.1	11.8	57.3	3.5	68	305	17.8	1.7	3623	5.3	280	306

APPENDIX 4. Additional baking rheology for Variety x Nitrogen Trial - Essex, 2021

Introduction

An additional dataset from Agrii in 2021 was provided to look at the impact of variety, N rate and timing interactions. This dataset compliments the work reported in this project and provides a further insight into the affects of nitrogen applications on grain quality and on rheology and baking.

Materials and Methods

The trial was a full replicated randomised design with three replicates on a silty clay loam soil. Within the trial, three Group 1 varieties (Crusoe, RGT Skyfall and KWS Zyatt) were grown under five nitrogen rates of 150, 200, 250 and 300 kg N/ha all with late N or 250 kg N/ha with no late N, all applied as ammonium nitrate. Due to the dry weather, application timings were delayed, with target GS 33-37 applied at GS 51 and target GS 45-51 applied at GS 65, as detailed in Table A4.1.

Table A4.1: Variety and nitrogen treatment the additional Agrii site.

Variety	kg N/ha (Target: Mid March) (Actual: GS21)	kg N/ha (Target: GS31-32) (Actual: GS30)	kg N/ha (Target: GS33-37) (Actual: GS51)	kg N/ha (Target: GS45-51) (Actual: GS65)	Total nitrogen (kg N/ha)
Crusoe	60	50	0	40	150
RGT Skyfall	60	50	0	40	150
KWS Zyatt	60	50	0	40	150
Crusoe	60	50	50	40	200
RGT Skyfall	60	50	50	40	200
KWS Zyatt	60	50	50	40	200
Crusoe	60	80	70	40	250
RGT Skyfall	60	80	70	40	250
KWS Zyatt	60	80	70	40	250
Crusoe	100	80	70	0	250
RGT Skyfall	100	80	70	0	250
KWS Zyatt	100	80	70	0	250
Crusoe	60	110	90	40	300
RGT Skyfall	60	110	90	40	300
KWS Zyatt	60	110	90	40	300

Yield

Grain yield averaged 7.42 t/ha across the trial with Cruse yielding the highest with a mean yield of 7.54 t/ha regardless of N rate, RGT Skyfall was intermediary with a yield of 7.48 t/ha and KWS Zyatt had the lowest yield, averaging 7.22 t/ha (Figure A4.1). There were significant differences between some treatments (P=0.001), particularly with RGT Skyfall which resulted in the lowest yield with 200 kg N/ha (6.98 t/ha) but the highest yield with 250 kg N/ha (7.88 t/ha).

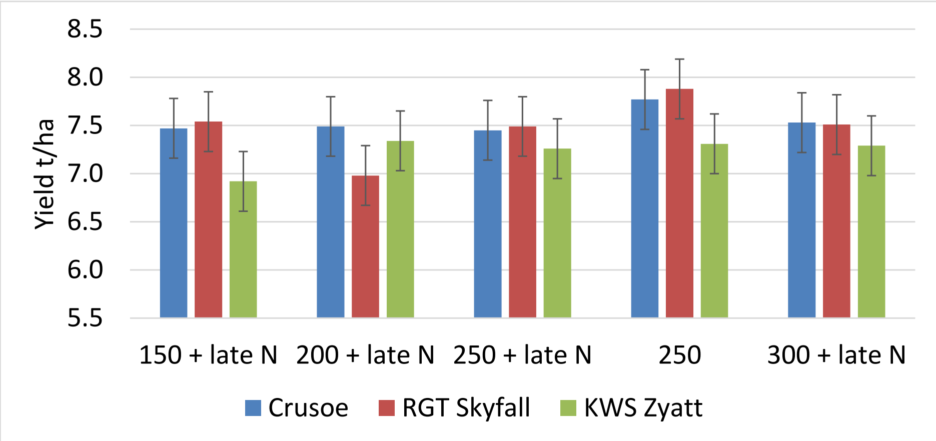

Figure A4.1: Mean yield (t/ha) in response to Variety and N rate and timing. Error bars are the LSD (0.10%).

Grain protein

Grain protein showed a steady increase with the addition of nitrogen, at most N rates above 200 kg N/ha attained a grain protein of at least 13.0 % (Figure A4.2). Crusoe had the highest grain protein, averaging 13.4 % (range 12.7 % to 13.9 %); Both KWS Zyatt and RGT Skyfall averaged 13.2 % grain protein. The protein increased from 12.4 % with 150 kg N/ha to 13.7 % for the 300 kg N/ha rate.

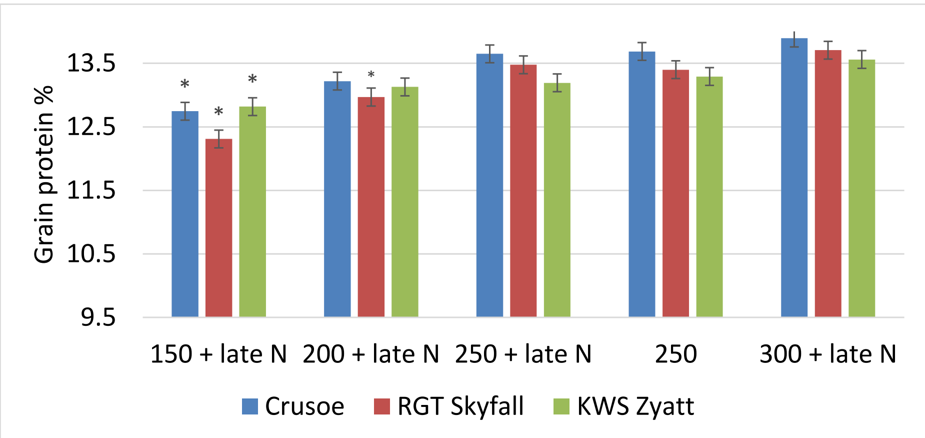

Figure A4.2: Mean grain protein (%) in response to Variety and N rate and timing. Where the mean values are significantly lower for that variety and the respective crop year, then a * has been placed above the corresponding bar in the graph. Error bars are the LSD (0.10%).

Specific weight

Specific weight for all three varieties was generally low, averaging 75.3 with little differences between varieties with few treatments being above the 76 kg/hl specification for UKFM (Figure A4.3).

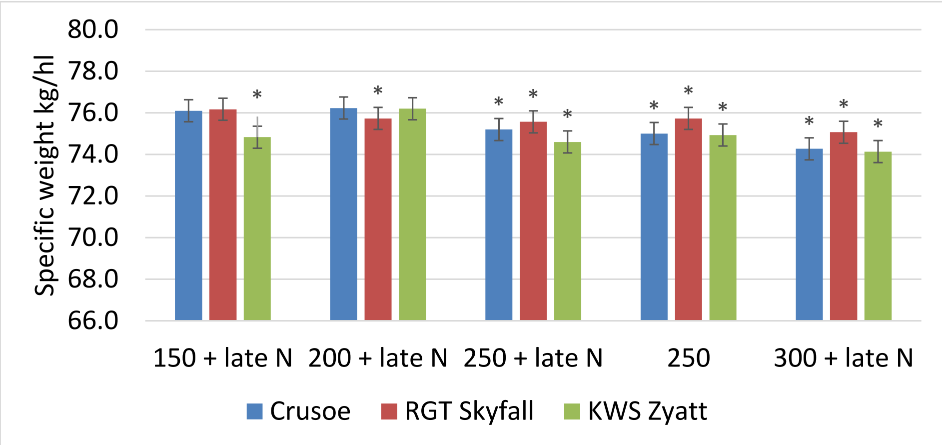

Figure A4.3: Mean specific weight (kg/hl) in response to Variety and N rate and timing. Where the mean values are significantly lower for that variety and the respective crop year, then a * has been placed above the corresponding bar in the graph. Error bars are the LSD (0.10%).

Hagberg Falling Number

Hagberg falling number were generally above the 250 specification for UKFM (Figure A4.4). However, KWS Zyatt was the lowest of the three varieties, averaging 268 as opposed to 341 and 348 for Crusoe and RGT Skyfall, respectively.

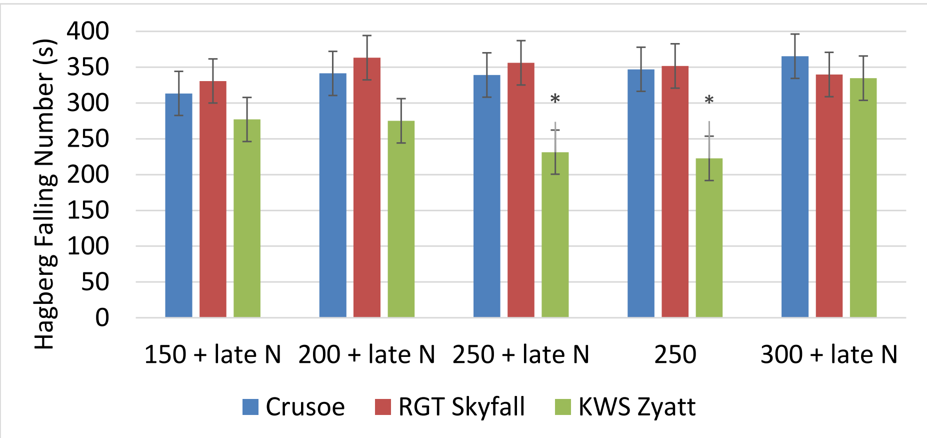

Figure A4.4: Mean Hagberg falling number (s) in response to Variety and N rate and timing. Where the mean values are significantly lower for that variety and the respective crop year, then a * has been placed above the corresponding bar in the graph. Error bars are the LSD (0.10%).

Baking and rheology

The full dataset of baking and rheology is shown in Table A4.3. However, a summery of key rheology and baking parameters is shown in Table A4.2. Skyfall was the harder milling and had a stronger gluten quality than the other two varieties. These differences are known features of these Group 1 varieties. The samples with the lower nitrogen application level of 150 kg N/ha had the better baking score compared to the other nitrogen treatments. The samples which received no late N were the harder milling samples, but with the weakest gluten quality and the lowest mean bread quality score.

Table A4.2: Summary of rheology and test baking parameters for ammonium nitrate and foliar urea treatments. Combined mean values are the mean of variety and site for ammonium nitrate and foliar urea treatments.

	Farinograph	Extensograph			Baking	
	Stability time (min)	Resistance (BU)	Extensibility (cm)	R/E	Loaf volume (cm^3)	Bread Score
150 kg N/ha Late N	4.5	273	18.1	1.5	3593	7
200 kg N/ha Late N	4.2	273	19.2	1.5	3567	6
250 kg N/ha Late N	4.5	290	19.9	1.5	3497	6
250 kg N/ha	4.0	227	19.5	1.2	3530	5
150 kg N/ha Late N	4.8	290	20.0	1.4	3613	6
Crusoe Mean	4.0	274	20.9	1.3	3548	5
RGT Skyfall Mean	4.7	284	17.7	1.6	3550	6
KWS Zyatt mean	4.5	254	19.4	1.3	3582	6

Baking and rheology

Table A4.3: Rheology and baking for the additional Variety x Nitrogen trial.

Essex Additional 2021 N rate			Wheat analysis				Flour								Farinograph				Extensograph					CBP test baking $									
ATC sample no.	Variety	Treatment No.	Moist. %	Prot. % at DM	Sp.wt. (kg/hl)	Ext.rate %	Moist. %	Prot. %	Prot. % at DM	Prot % loss on milling	Water Abs. %	W.abs @ 14% moist	Starch damage %	HFN	Arr. mins	Peak. mins	Stab. mins	Tol. BU	Res. BU	Ext. cm	Area cm2	R/E	Minolta colour L*	b*	L*-b*	Loaf vol. cm3	Bread quality	Crumb Structure	Crumb texture	Crumb colour	Quality Score 1-9	Loaf volume for unit level of protein	
ATC method			NIT07 $	NIT07	GRN09	PRP04	MIS48	MIS48	Cal.	Cal.$	RHE01	Calculated	MIS48 $	CHO01	RHE02				RHE03					MIS44$			MIS37$		MIS07$				Wheat Prot.	Flour Prot.
LA22.00169	Crusoe	1	12.8	12.6	76.4	79.0	14.7	9.9	11.6	1.0	54.3	55.6	20	304	1.0	2.0	4.5	60	290	20.1	84	1.4	81.61	12.07	69.54	3530	Good to moderate	Slightly Weak	Fine	White	6	280	304
LA22.00170	RGT Skyfall	2	13.0	11.9	76.8	81.0	14.7	9.4	11.0	0.9	55.5	56.8	27	307	1.0	2.0	4.5	60	280	16.0	67	1.8	79.33	12.39	66.94	3550	Good to moderate	Resilient	Slightly coarse	Creamy	6	298	322
LA22.00171	KWS Zyatt	3	12.5	12.7	76.1	79.6	14.6	9.9	11.6	1.1	53.7	54.8	24	264	1.5	2.0	4.5	60	250	18.1	65	1.4	80.26	12.50	67.76	3700	Very good	Resilient	Fine	White	8	291	319
LA22.00172	Crusoe	9	13.0	13.1	76.1	80.5	14.4	10.5	12.3	0.8	56.8	57.5	26	300	2.0	3.5	3.5	90	270	22.2	79	1.2	79.10	12.41	66.69	3470	Moderate to good	Slightly Weak	Fine	White	5	265	283
LA22.00173	RGT Skyfall	10	13.0	12.8	76.9	80.5	14.9	10.3	12.1	0.7	56.0	57.6	27	339	1.5	2.0	4.5	50	280	16.8	69	1.7	79.36	12.32	67.04	3680	Very good	Resilient	Fine	White	8	288	304
LA22.00174	KWS Zyatt	11	12.6	12.7	76.4	79.8	14.9	10.2	12.0	0.7	52.6	54.2	25	271	1.0	3.5	4.5	90	270	18.5	73	1.5	80.77	12.58	68.19	3550	Good to moderate	Slightly Weak	Fine	White	6	280	296
LA22.00175	Crusoe	17	12.8	13.7	75.7	78.7	14.8	10.8	12.7	1.0	54.8	56.2	21	314	2.0	3.5	3.5	80	280	20.5	83	1.4	79.51	12.56	66.95	3450	Moderate to good	Slightly Weak	Fine	White	5	252	272
LA22.00176	RGT Skyfall	18	12.8	13.3	76.6	80.8	14.7	10.5	12.3	1.0	57.0	58.3	28	303	1.5	4.0	4.5	90	270	18.8	73	1.4	78.16	12.75	65.41	3380	Moderate to good	Resilient	Slightly coarse	Creamy	5	254	275
LA22.00177	KWS Zyatt	19	12.5	13.0	74.4	78.7	14.5	10.5	12.3	0.7	54.2	55.1	29	319	1.0	4.0	5.5	80	320	20.5	96	1.6	80.22	13.02	67.20	3660	Good	Resilient	Fine	White	7	282	298
LA22.00178	Crusoe	25	12.9	13.7	75.8	80.5	14.6	10.9	12.8	0.9	56.5	57.6	25	303	2.0	3.5	3.5	90	230	20.7	70	1.1	78.83	12.77	66.06	3580	Good to moderate	Slightly Weak	Fine	Creamy	6	261	280
LA22.00179	RGT Skyfall	26	12.6	13.2	76.3	80.9	14.6	10.5	12.3	0.9	57.0	58.1	28	325	1.0	4.0	4.5	80	240	17.7	63	1.4	78.74	13.03	65.71	3500	Moderate to good	Resilient	Slightly coarse	White	5	265	285
LA22.00180	KWS Zyatt	27	12.5	13.4	75.9	81.2	14.8	10.7	12.6	0.8	54.5	55.9	30	266	1.5	3.5	4.0	100	210	20.0	61	1.1	79.29	13.69	65.60	3510	Moderate to good	Slightly Weak	Fine	Creamy	5	262	279
LA22.00181	Crusoe	33	12.9	13.8	75.4	78.5	15.0	11.2	13.2	0.6	54.0	55.8	22	310	1.0	2.0	5.0	40	300	21.2	92	1.4	79.30	12.56	66.74	3710	Moderate to good	Slightly Weak	Slightly coarse	Creamy	5	269	282
LA22.00182	RGT Skyfall	34	13.0	13.9	75.8	78.8	14.7	10.8	11.3	2.6	55.5	56.8	27	323	1.5	2.0	5.5	30	350	19.1	95	1.8	79.65	12.68	66.97	3640	Good	Resilient	Fine	White	7	262	323
LA22.00183	KWS Zyatt	35	12.4	13.4	74.6	81.1	14.6	10.7	12.5	0.9	55.2	56.3	30	289	1.5	3.5	4.0	90	220	19.7	61	1.1	77.60	13.12	64.48	3490	Moderate to good	Slightly Weak	Fine	Creamy	5	260	279
2021 Extra Agrii N trials - All Sample Mean			12.8	13.1	75.9	80.0	14.7	10.5	12.2	1.0	55.2	56.4	25.9	302	1.4	3.0	4.4	73	271	19.3	75	1.4	79.45	12.70	66.75	3560					6	271	293
2021 Extra Agrii N trials - All Sample Max			13.0	13.9	76.9	81.2	15.0	11.2	13.2	2.6	57.0	58.3	30.0	339	2.0	4.0	5.5	100	350	22.2	96	1.8	81.61	13.69	69.54	3710					8	298	323
2021 Extra Agrii N trials - All Sample Min			12.4	11.9	74.4	78.5	14.4	9.4	11.0	0.6	52.6	54.2	20.0	264	1.0	2.0	3.5	30	210	16.0	61	1.1	77.60	12.07	64.48	3380					5	252	272
2021 Extra Agrii N trials - 150kgN/ha mean			12.8	12.4	76.4	79.9	14.7	9.7	11.4	1.0	54.5	55.7	24	292	1.2	2.0	4.5	60	273	18.1	72	1.5	80.40	12.32	68.08	3593					7	290	315
2021 Extra Agrii N trials - 200kgN/ha mean			12.9	12.9	76.5	80.3	14.7	10.3	12.1	0.8	55.1	56.5	26	303	1.5	3.0	4.2	77	273	19.2	74	1.5	79.74	12.44	67.31	3567					6	277	294
2021 Extra Agrii N trials - 250kgN/ha mean			12.7	13.3	75.6	79.4	14.7	10.6	12.4	0.9	55.3	56.5	26	312	1.5	3.8	4.5	83	290	19.9	84	1.5	79.30	12.78	66.52	3497					6	262	282
2021 Extra Agrii N trials - 250kgN/ha mean			12.7	13.4	76.0	80.9	14.7	10.7	12.5	0.9	56.0	57.2	28	298	1.5	3.7	4.0	90	227	19.5	65	1.2	78.95	13.16	65.79	3530					5	263	282
2021 Extra Agrii N trials - 300kgN/ha mean			12.8	13.7	75.3	79.5	14.8	10.9	12.3	1.4	54.9	56.3	26	307	1.3	2.5	4.8	53	290	20.0	83	1.4	78.85	12.79	66.06	3613					6	264	294
2021 Extra Agrii N trials - Crusoe mean			12.9	13.4	75.9	79.4	14.7	10.7	12.5	0.9	55.3	56.5	23	306	1.6	2.9	4.0	72	274	20.9	82	1.3	79.67	12.47	67.20	3548					5	265	284
2021 Extra Agrii N trials - RGT Skyfall mea			12.9	13.0	76.5	80.4	14.7	10.3	11.8	1.2	56.2	57.5	27	319	1.3	2.8	4.7	62	284	17.7	73	1.6	79.05	12.63	66.41	3550					6	273	302
2021 Extra Agrii N trials - KWS Zyatt mean			12.5	13.0	75.5	80.1	14.7	10.4	12.2	0.8	54.0	55.3	28	282	1.3	3.3	4.5	84	254	19.4	71	1.3	79.63	12.98	66.65	3582					6	275	294