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Modern triticale crops for increased yields, reduced inputs, increased profitability and reduced greenhouse gas emissions from UK cereal production

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This is the final report of a 40 month project (RD-2009-3699) which started in March 2012. The work was conducted in parallel with an Innovate UK Technology Strategy Board project with ADAS, Agrovista, Ensus, CF Fertilisers, RAGT, Saaten Union & Senova which paid for the experiments and many of the measurements reported here. An additional contract of £70,000 from AHDB Cereals & Oilseeds funded additional measurements to understand the physiological basis of the difference between wheat and triticale.

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1. Abstract

Recent experiments (2007 – 2011) suggested that triticale could offer opportunities for growers to improve yields whilst also saving on inputs. An Innovate UK project (101093) was set up to further investigate the relative yields, N requirements, nutritional values, and biofuel performances of wheat and triticale. It included a series of field trials (2012 – 2014), comparing yields and N requirements of two wheat (JB Diego, Beluga) and two triticale (Grenado, Benetto) varieties in two sets of paired rotational (first and second cereal) experiments per year, and comparing a wider set of varieties in a further four experiments per year. The AHDB Cereals & Oilseeds-funded project aimed to add value to the Innovate UK project though improving the underlying understanding of the questions relevant to growers. This project reports results from both projects combined.

Results from a total of 20 experiments (2011 – 2014) were used in a cross-site analysis. Triticale out-yielded wheat at 15 out of 20 sites, out-yielding wheat by an average of 0.6 t/ha. When analysed by rotational position, triticale out-yielded wheat by an average of 3% for first cereals and 8% for second cereals. A meta-analysis of N response trials showed no significant difference between economically optimum N rates for wheat and triticale. Lodging was rarely a problem and only severe enough that it may have affected yield in 3 of the 21 experiments. Measurements carried out to understand the basis for the higher triticale yields showed that it was due to achieving a higher biomass (1.5 t/ha higher at harvest, on average) rather than through greater portioning to the grain. This greater total growth may be in part due to earlier development in triticale, starting stem extension earlier (Benetto was 19 days and Grenado 8 days earlier) thus intercepting more light more quickly. Flowering was also reached more quickly in triticale, but maturity date was only slightly earlier, giving a longer duration for grain-filling. Light interception of triticale was greater than wheat, though its GAI was not always greater. This implies a higher extinction co-efficient for triticale, each unit of GAI intercepting more light than wheat. Triticale varieties generally showed a lower incidence of take-all, but there was little evidence that triticale has a bigger or deeper root system, although Benetto did have more roots at the surface.

Triticale generally had lower (0.6%) grain protein concentrations than wheat, meaning that the amino acid contents, which were generally comparable to wheat on a % protein basis, were actually lower than wheat on a dry matter basis. However, lysine contents were slightly higher in triticale. An AHDB Pork study found that pig DE and NE were very similar for the two species; DE was 14.57 MJ/kg for triticale and 14.59 MJ/kg for wheat. Triticale appeared to have a lower alcohol yield per tonne than wheat, but on a per hectare basis, triticale gave higher yields because of its greater yields. These higher yields also led to greenhouse gas savings for triticale compared to wheat on a per tonne and per hectare basis, especially when grown as a second cereal. A gross margin analysis also showed a £27/ha advantage of triticale when grown as a second cereal.

Taking account of all the results, triticale appears to be a useful option for growers, especially as a second cereal. Its performance was confirmed by growers who tested it against wheat in a series of tramline trials.

2. Introduction

Much of the current industry opinion about triticale was formed over 20 years ago, and is based on experiences then. Traditionally triticale is seen as a low input crop for poor land in low yielding situations (Gutteridge *et al*., 1993; Overthrow & Carver, 2003), but ADAS results from experiments run between 2007 and 2011 suggested that triticale could offer opportunities for growers to improve yields much more widely, whilst also saving on costly fertiliser and agrochemical inputs (Kindred *et al*., 2010; Sylvester-Bradley *et al*., 2010; Weightman *et al*., 2011).

Following 11 trials in which triticale significantly out-yielded wheat, an Innovate UK project (101093) was set up which aimed to further investigate the relative yields, N requirements, nutritional values, and biofuel performances of wheat and triticale. The focus of this Innovate UK project was the development of supply chains of triticale for bioethanol production, and the potential for enhanced quality and sustainability of the DDGS co-product for animal feed, especially if the triticale yields more and requires less N fertiliser. The Innovate UK project included a series of field trials in each of the harvest seasons 2012–2014, comparing yields and N requirements of two wheat and two triticale varieties in two sets of paired rotational (first and second cereal) experiments per year, and comparing a wider set of wheat and triticale varieties in a further four experiments per year. The aim of the AHDB Cereals & Oilseeds-funded project was to add value to the Innovate UK project though improving the underlying science and understanding of the questions relevant to arable growers, and through providing additional communication with growers and other stakeholders through the normal AHDB Cereals & Oilseeds Knowledge Transfer mechanisms. Therefore, this project reports results and conclusions from both projects combined.

Specific objectives were:

1. To understand the underlying causes for the differences in yield, N requirement and nitrogen use efficiency (NUE) between wheat and triticale.
2. To report the findings of the full Innovate UK project to the arable industry, including evaluation of gross margins, greenhouse gas (GHG) savings, nutritional value, value for bioethanol, and straw for energy.

3. Materials and methods

3.1. Project funding

This report includes experimental work done for AHDB Cereals & Oilseeds project RD-2009-3699 and work done for a parallel project funded by Innovate UK (101093), formerly the Technology Strategy Board, and ADAS, Agrovista, Ensus, CF Fertilisers, RAGT, Saaten Union and Senova.

The Innovate UK project included

- Establishment and treatment of all field experiments
- Assessments of lodging and yield in all plot experiments
- Pre-harvest growth analysis on selected treatments in experiments HM11, IK12a, CB12a, IK12b, CB12b, CB13, TH13, CO14-1a, CO14-2a, CO14-1b and CO14-2b
- Assessment of protein and specific weight on all grain samples
- Nutritional analyses

The AHDB Cereals & Oilseeds project included the following additional assessments on selected treatments in experiments HM12, HM13 and HM14.

- Growth analysis and light interception at GS61
- Pre-harvest growth analysis
- Timing of key developmental stages (HM12 and HM13 only)
- Take-all severity (HM12 and HM14 only)
- Root length density
- Thousand grain weight (HM14 only)

3.2. Plot experiments

A total of 21 plot experiments were carried out in the UK from harvest years 2011 to 2014. Each experiment included at least two winter wheat and two winter triticale varieties, and some experiments also included N rate treatments; all treatments were replicated at least three times. The location, soil type and rotational position (first or second cereal) varied between experiments (Table 1).

Experiments were laid out in a split-split-plot design with N rate as the main plot, species as the sub-plot and variety as the sub-sub-plot. Varieties from different species were randomised separately, to avoid shading of wheat by triticale, which is taller. At three sites (HM12, HM13 and HM14), first and second cereal positions were included in a single experiment, as the first level of main plot within each block. This was achieved by setting up the blocks the previous year with the second cereal areas preceded by wheat and the first cereal areas preceded by oats.

Table 1. Site and treatment details for each experiment. Sites CR09, CR10 and HM10 are included only in cross-site analyses, being fully reported elsewhere.

Site code	Location	Soil type	Harvest year	Rotational position	Wheat varieties	Triticale varieties	Nitrogen rates (kg N/ha)
HM11	N. Yorks	Shallow	2011	2nd cereal	Beluga, JB Diego	Benetto, Grenado	0, 90, 180, 270, 360
CO11-1	Suffolk	Loam	2011	1st cereal	Beluga, Delphi, Hystar, JB Diego, Monterey	Agostino, Bellac, Benetto, Grenado, Tulus	0, 130, 170, 230, 290
CO11-2	Suffolk	Loam	2011	2nd cereal	Beluga, Delphi, Hystar, JB Diego, Monterey	Agostino, Bellac, Benetto, Grenado, Tulus	0, 130, 170, 230, 290
HM12-1	N. Yorks	Sandy clay loam	2012	1st cereal	Beluga, JB Diego	Benetto, Grenado	0, 90, 180, 270, 360
HM12-2	N. Yorks	Sandy clay loam	2012	2nd cereal	Beluga, JB Diego	Benetto, Grenado	0, 90, 180, 270, 360
IK12a	Essex	Sandy clay loam	2012	1st cereal	Beluga, JB Diego	Benetto, Grenado	0, 90, 180, 270, 360
CB12a	Cambs	Silty clay loam	2012	2nd cereal	Beluga, JB Diego	Benetto, Grenado	0, 90, 180, 270, 360
IK12b	Essex	Sandy clay loam	2012	1st cereal	BAW15, Hystar, KWS Santiago, Torch	Agostino, Agrilac, Ragtac, Tulus	0, 90, 180
CB12b	Cambs	Silty clay loam	2012	2nd cereal	BAW15, Hystar, KWS Santiago, Torch	Agostino, Agrilac, Ragtac, Tulus	0, 90, 180
CO12	Suffolk	Loam	2012	2nd cereal	BA W16, Beluga, Cougar, Hystar, JB Diego, NOS13009.36, SJ08-50, SJ7420510, Torch, Tuxedo	Agostino, Agrilac, Benetto, Grenado, KWS Fido, Ragtac, Tulus, Twingo (and rye varieties Agronom, SU Skaltio)	Single standard rate
HM13-1	N. Yorks	Sandy clay loam	2013	1st cereal	Beluga, JB Diego	Benetto, Grenado	0, 90, 180, 270, 360
HM13-2	N. Yorks	Sandy clay loam	2013	2nd cereal	Beluga, JB Diego	Benetto, Grenado	0, 90, 180, 270, 360
CB13	Cambs	Silty clay loam	2013	2nd cereal	BA W16, Beluga, Cougar, Delphi, Hystar, Hyteck, Icon, JB Diego, SJ7420510, Tuxedo	Agostino, Benetto, Grenado, KWS Fido, Ragtac, SW 1431, Tulus	Single standard rate
CO13	Suffolk	Loam	2013	2nd cereal	BA W16, Beluga, Cougar, Delphi, Hystar, Hyteck, Icon, JB Diego, SJ7420510, Tuxedo	Agostino, Benetto, Grenado, KWS Fido, Ragtac, SW 1431, Tulus (and rye varieties Dukato, SU Mephisto, SU Phoenix)	Single standard rate
TH13	Essex		2013	2nd cereal	Cougar, Delphi, Hystar, KWS Santiago	Agostino, KWS Fido, Ragtac, Tulus	0, 90, 180
HM14-1	N. Yorks	Sandy clay loam	2014	1st cereal	Beluga, JB Diego	Benetto, Grenado	0, 90, 180, 270, 360
HM14-2	N. Yorks	Sandy clay loam	2014	2nd cereal	Beluga, JB Diego	Benetto, Grenado	0, 90, 180, 270, 360
CO14-1a	Suffolk	Loam	2014	1st cereal	Beluga, JB Diego	Benetto, Grenado	0, 80, 160, 240, 320
CO14-2a	Suffolk	Loam	2014	2nd cereal	Beluga, JB Diego	Benetto, Grenado	0, 80, 160, 240, 320
CO14-1b	Suffolk	Loam	2014	1st cereal	Cougar, Delphi, Hystar, KWS Santiago	Agostino, KWS Fido, Ragtac, Tulus	0, 80, 160
CO14-2b	Suffolk	Loam	2014	2nd cereal	Cougar, Delphi, Hystar, KWS Santiago	Agostino, KWS Fido, Ragtac, Tulus	0, 80, 160
CR09	Suffolk	Clay loam	2009	2nd cereal	Istabraq, JB Diego, Ketchum, Marksman, Scout, Solstice	Benetto, Borwo, Grenado	0, 70, 140, 200, 260
CR10	Suffolk	Clay loam	2010	2nd cereal	Batallion, Beluga, Duxford, Oakley, Panorama	Bellac, Benetto, Grenado, Tulus	0, 70, 170, 220, 290, 360
HM10	Suffolk	Clay loam	2010	2nd cereal	JB Diego, Viscount	Benetto, Grenado	0, 90, 180, 270, 360

Experiments were sown using plot drills with a width of at least 1.5 m and plot lengths of at least 12 m. Within each experiment, wheat and triticale received the same maintenance applications and were drilled and harvested on the same day.

N treatments were applied as ammonium nitrate prills, broadcast by hand. Each N rate was applied in two or three split applications, timed according to RB209 guidelines.

Three earlier experiments, which are more fully reported elsewhere (Weightman *et al*., 2011), were included in cross-site analyses. These were CR09 (funded by RAGT, Senova and Syngenta), CR10 (funded by BASF, Monsanto, RAGT, Saaten Union, Senova and Syngenta) and HM10 (funded by HGCA) (Table 1).

3.3. Tramline trials

In harvest year 2014, four on-farm tramline trials were carried out, comparing wheat and triticale yields grown in different tramlines within the same field (Table 2). Each site consisted of at least two tramlines of triticale, totalling at least 2 ha. Tramline splits between triticale and wheat were agreed between ADAS and the host farmers following consideration of underlying variability in the field. The triticale was managed for high yield and as per the wheat in that field. At some sites, additional PGRs were applied. The triticale and wheat were harvested separately and yields were determined using yield mapping software or a weighbridge.

Table 2. Tramline trials comparing wheat and triticale in harvest year 2014.

Site no.	County	Soil type	Rotational position	Wheat variety	Triticale variety
1	N. Yorks	Light sand	1st cereal	JB Diego	Tulus
2	Staffs	Light	1st cereal	Solstice	Benetto
3	Staffs	Heavy	2nd cereal	Crusoe	Grenado
4	Northants	Clay loam	2nd cereal	Relay	Ragtac

3.4. Weather conditions

In 2011 there was an exceptionally dry spring – the driest on record in England and Wales. By contrast, in 2012 England had the wettest April to June period and the wettest year on record. Harvest year 2013 was notable for a cold and prolonged winter, resulting in most crops being about three weeks late in hitting key growth stages throughout spring and early summer; rainfall was within the normal range. 2014 was an unusually warm year, with a wetter than usual winter, but spring rainfall within the normal range.

3.5. Assessments of plot experiments

3.5.1. Developmental stages

At HM12 and HM13, assessments were made to establish the length of key developmental stages in each variety. Assessments were made on all varieties at N rate 180 kg N/ha in the first cereal position. Experiments were visited every two to three days as the crop neared the key growth stages GS31 (beginning of stem extension), GS39 (flag leaf emergence), GS59 (ear emergence) and GS61 (beginning of anthesis); a plot was recorded as having reached a growth stage when more than half the plants assessed were at that growth stage.

On at least five dates between mid-June and early August, senescence was assessed at N rates 0 and 180 kg N/ha at both first and second cereal position. Assessments were made of % leaf area remaining green for the top three leaf layers, stems and ears on a whole plot basis.

Ear maturity was assessed at N rates 0 and 180 kg N/ha at both first and second cereal position. Ears were sampled at around GS85 (soft dough), weighed, dried and re-weighed to give % ear moisture which has been shown to correspond to differences in grain moisture content and time to maturity; higher moisture content indicating later maturity (Sylvester-Bradley *et al*., 2010).

3.5.2. GS61 growth analyses

At HM12, HM13 and HM14, assessments at GS61 (beginning of anthesis) were made on all varieties at N rates 0, 180 and 360 kg N/ha at both rotational positions.

Light interception was measured with a 'Sunscan' ceptometer. Measurements were taken at six positions per plot of light at ground level beneath the crop, simultaneously with ambient light level.

Samples were taken of about 50 shoots per plot, cut at ground level. Records were made of numbers of fertile and infertile tillers, then the fertile tillers split into green leaves, stems and ears. The fresh weight of each subsample was recorded, and the area of each measured using a leaf area machine. Samples were dried before measurement of dry weight and %N content (Dumas method).

3.5.3. Take-all

At HM12, HM13 and HM14, 25 plants per plot were sampled for all varieties at 180 kg N/ha in first and second cereal positions. Roots were washed then take-all severity was assessed on the following scale:

- Nil (N): no lesions on any root
- Slight (S): lesions present on <25% roots
- Moderate 1 (M1): lesions present on 25% to <50% roots
- Moderate 2 (M2): lesions present on 50% to <75% roots
- Severe (Sv): lesions present on at least 75% roots.

Take-all incidence was calculated as % plants with at least slight take-all. Take all index (0–100 scale) was calculated from the number of plants in each category as follows:

Take-all index = S + 2*M1 + 3*M2 + 4*Sv

3.5.4. Pre-harvest growth analyses

Whole crop samples were collected prior to harvest in 18 of the 21 plot experiments, by sampling 50 tillers per plot from selected varieties and N rates. Samples were separated into straw and ears and the ears threshed using a hand threshing machine to separate grain and chaff. Each component plant part was dried for at least 24 hours at 100°C, then weighed to determine the proportion of biomass in each of grain, straw and chaff. Results were converted to biomass in t/ha using yield data from plot combines. Straw and chaff samples were re-combined before analysis for % N content by Dumas method. Grain samples collected from the combine harvester were similarly analysed for % N content.

3.5.5. Lodging

Lodging (% plot area at greater than 45° from vertical) and leaning (% plot area at 10° to 45° from vertical) were assessed immediately prior to harvest at all sites. These data were used to calculate a lodging index on a 0–100 scale: lodging index = % area lodged + (% area leaning/2).

3.5.6. Rooting

Root cores were taken from all varieties grown at 180 kg N/ha at HM12-1, HM13-1 and HM14-1. Four cores per plot were sampled to 1 m depth at HM12-1 and HM13-1, and to 40 cm depth at HM14-1 due to shallow soil, using a 2.6 cm diameter Hydrocare soil core extractor. Soil cores were split into 20 cm depth horizons before washing using a Delta-T root washer with 550 micron filters. Roots were then scanned to measure root length density (cm root per cm^3 soil).

3.5.7. Yield

Grain yield was assessed at all sites using a plot combine on an individual plot area of at least 15 m^2. Grain moisture was measured by Dickey John and the yield results were corrected to t/ha at 85% dry matter.

3.5.8. Grain quality

Specific weight was measured by Dickey John on all grain samples at all sites. Grain protein content was measured by FOSS Infratec 1241 NIR on all samples at all sites except HM10. In the first year the use of the FOSS grain network triticale calibration was compared to that for wheat for the triticale samples and for grain N% by Dumas method. This showed the wheat calibration to be appropriate for triticale so the wheat calibration was used in subsequent years.

In two experiments (HM14-1 and HM14-2), thousand grain weight (g) was measured on the same treatments used for the biomass assessments described above. The number of ears/m^2 was calculated using the yield data from the plot combines and the grain weight per tiller measured above. The number of grains per ear was calculated using thousand grain weight, grain yield and ears/m^2.

Grain amino acid content in selected samples of both first and second cereals were analysed by mixture of NIR and wet chemistry conducted by Evonik Industries, Germany.

3.6. Statistical analyses

A linear plus exponential model (George, 1984) was used to fit grain yield responses to N (Equation 1), where y is grain yield (t/ha at 85% dry matter), N is the amount of N applied (kg N/ha), and *a*, *b*, *c*, and *r* are empirically derived parameters which (crudely) describe respectively the asymptote, the potential yield change if no N was applied, the rate of yield loss due to over-application of N, and the shape of the response.

$$y = a + brN + cN \qquad \text{Equation 1}$$

Each linear plus exponential function was fitted using a stepwise process involving the following steps: (i) fitting a common curve to all varieties, (ii) fitting parallel curves for each variety by allowing parameter *a* to vary, (iii) fitting non-parallel curves for each variety by allowing parameters *a*, *b* and *c* to vary, and (iv) fitting separate curves for each variety by allowing all parameters to vary. The sums of squares explained at each stage was calculated, and a test was made of the improvement in fit over the previous model. If there was no significant improvement between two stages, then the previous model was taken as the best description of the data.

The economically optimum N rate (N_{opt}) was determined from the fitted parameters as in Equation 2, where k is the breakeven price ratio, i.e. the crop yield (kg) needed to pay for 1 kg N. *k* was calculated using a grain price of £200/t for both wheat and triticale and a N cost of £300/t ammonium nitrate (34.5% N), giving a value of 4.412. The yield at N_{opt} was calculated from the fitted parameters using Equation 1.

$$N_{opt} = (\ln(k/1000 - c) - \ln(b \ln r)) / \ln r \qquad \text{Equation 2}$$

To examine the effects of species on N_{opt}, the fitted parameters from step (iii) above were used for each site to calculate a separate N_{opt} for each variety, using a k value of 10 to maximize the number of site x variety combinations for which N_{opt} could be calculated. A paired t-test was done to compare the mean N_{opt} for wheat with the mean N_{opt} for triticale at each site. For the 13 N response experiments which included the varieties Beluga, Benetto, Grenado and JB Diego (Table 1), an ANOVA was done to examine the effect of variety on Nopt, using site as the block factor.

To examine the effects of species on yield at N_{opt}, the fitted parameters from step (ii) above were used for each site to calculate a common N_{opt} for all varieties, using a k value of 4.412 as above, which was then used to calculate yield at N_{opt} as in Equation 2. A paired t-test was done to compare the mean yield at N_{opt} for wheat with the mean yield at N_{opt} for triticale at each site. For the 13 N response experiments which included the varieties Beluga, Benetto, Grenado and JB Diego (Table 1), an ANOVA was done to examine the effect of variety on yield at N_{opt}, using site as the block factor.

Split-plot analysis of variance (ANOVA) was used to analyse variates including yield, lodging index, harvest index, biomass, crop N content, light interception, green area index, take-all index and root length density.

Paired t-tests were done to compare the mean crop biomass, crop N content and ears/m^2 for wheat and for triticale at each site. For the 11 sites which included the varieties Beluga, Benetto, Grenado and JB Diego and for which preharvest growth analysis had been done, ANOVAs were done to examine the effect of variety on mean crop biomass, crop N content and ears/m^2, using site as the block factor.

Genstat 14th edition (www.genstat.com) was used for all statistical analyses.

4. Results and discussion

4.1. Lodging

There was no lodging or leaning in any treatment at HM11, CO11, HM13, CB13, CO13, TH13, HM14-2 or CO14. At HM12 there was a small amount of leaning in Benetto, Grenado and Beluga at the higher N rates in both the first and second cereals, to a maximum lodging index of 8.3. At IK12b there was some leaning in Agrilac and Tulus, to a maximum lodging index of 18.5. At CB12b there was some leaning in Agrilac, to a maximum lodging index of 8.5. At HM14-1 there was some leaning in all varieties, to a maximum lodging index of 6.7.

Lodging was only severe enough that it may have affected yield at IK12a, CB12a and CO12. There were significant effects of N rate and variety at IK12a and CB12a (Table 3), and of variety at CO12 (Table 4): lodging severity increased with N rate and was generally more severe for triticale varieties than for wheat varieties.

Table 3. The effects of N rate and variety on lodging index (0–100 scale) for the two N response experiments in which lodging occurred.

	Lodging index (0–100 scale)									
Site	IK12					CB12				
N rate (kg N/ha)	0	90	180	270	360	0	90	180	270	360
Triticale varieties										
Benetto	0.0	0.0	6.7	48.3	76.7	0.0	0.0	21.7	43.3	63.3
Grenado	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	15.0
Wheat varieties										
Beluga	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.3	15.0	17.5
JB Diego	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	21.7
N rate P value	<0.001					0.007				
N rate S.E.D.	1.30					6.16				
Variety P value	<0.001					<0.001				
Variety S.E.D.	1.29					4.37				
N rate x Variety P value	<0.001					0.018				
N rate x Variety S.E.D.	2.82					10.47				

Table 4. The effects of variety on lodging index (0–100 scale) at CO12.

	Lodging (0–100 scale)
Rye varieties	
Agronom	43.8
Skaltio	71.3
Triticale varieties	
Agostino	0.0
Agrilac	0.0
Benetto	40.0
Grenado	0.0
Ragtac	0.0
KWS Fido	33.8
Tulus	0.0
Twingo	0.0
Wheat varieties	
BA W16	0.0
Beluga	0.0
Cougar	0.0
Hystar	0.0
JB Diego	0.0
NOS13009.36	0.0
SJ08-50	0.0
SJ7420510	0.0
Torch	0.0
Tuxedo	0.0
Variety P value	<0.001
Variety S.E.D.	7.17

4.2. Yield

There were significant effects of variety and (where included) N rate in every experiment (Table 6 to Table 10).

In a meta-analysis of triticale/wheat comparison trials, the best triticale variety out-yielded the best wheat variety at 14 out of 20 sites, and the mean triticale yield was higher than the mean wheat yield at 15 out of 20 sites. T-tests comparing mean triticale and mean wheat yield, or best triticale and best wheat yield, each showed triticale to significantly out-yield wheat, by an average of 0.6 t/ha (Table 5).

Table 5. Comparison of triticale and wheat yields across 20 sites.

Site	Rotational position	Mean triticale yield (t/ha) across all N rate	Mean wheat yield (t/ha) across all N rate	Best triticale variety (t/ha) at best N rate	Best wheat variety (t/ha) at best N rate
CR09	2	9.27	7.52	12.22	10.72
CR10	2	7.98	8.09	10.07	9.85
HM10	2	7.14	6.73	9.61	9.34
HM11	2	5.97	4.66	7.60	6.25
CO11-1	1	9.87	9.14	11.35	10.88
CO11-2	2	8.40	7.43	10.04	8.48
HM12-1	1	8.17	7.15	9.80	8.98
HM12-2	2	7.42	5.25	9.40	6.87
IK12	1	8.80	8.04	10.96	9.78
CB12	2	8.09	6.40	9.32	7.66
CO12	2	8.47	8.32	9.67	10.34
HM13-1	1	7.47	7.14	9.36	8.80
HM13-2	2	6.89	6.48	9.04	8.27
CB13	2	6.69	6.47	7.31	7.05
CO13	2	9.32	9.53	10.20	10.23
TH13	2	6.87	7.41	8.75	9.03
HM14-1	1	7.04	7.08	9.30	9.84
HM14-2	2	5.07	3.98	6.92	5.90
CO14-1	1	11.74	11.69	13.09	12.83
CO14-2	2	9.75	9.98	11.66	11.98
T-test P value		0.002		0.003	
Triticale advantage (t/ha)		0.60		0.63	
Triticale advantage (%)		8.03		6.88	

Table 6. The effects of rotational position, N rate and variety on grain yield at HM12, HM13 and HM14.

		Yield (t/ha at 85% dry matter)					
N rate (kg/ha)	Variety	HM12-1	HM12-2	HM13-1	HM13-2	HM14-1	HM14-2
0	Beluga	3.63	2.78	4.12	4.22	2.10	0.70
	JB Diego	4.32	3.55	4.21	4.36	2.09	1.02
	Benetto	6.31	5.67	4.22	4.04	3.88	3.48
	Grenado	5.26	3.64	3.90	4.14	3.10	2.37
90	Beluga	7.19	4.94	6.58	6.31	5.98	2.62
	JB Diego	7.54	5.68	6.97	6.09	6.32	3.54
	Benetto	8.75	7.97	7.29	6.17	6.67	4.85
	Grenado	7.97	6.67	7.18	6.02	6.03	3.76
180	Beluga	7.03	4.78	7.96	6.58	8.05	4.37
	JB Diego	7.86	6.17	8.28	6.69	8.65	4.73
	Benetto	9.29	9.11	8.68	7.84	7.86	6.22
	Grenado	8.52	7.68	8.35	7.41	7.49	5.34
270	Beluga	8.49	5.56	8.02	7.20	8.47	3.11
	JB Diego	8.98	6.87	8.44	7.37	9.54	5.01
	Benetto	9.80	9.40	9.36	7.94	9.32	6.68
	Grenado	8.52	7.25	8.68	7.89	8.55	5.93
360	Beluga	7.80	5.55	8.00	7.73	8.86	4.31
	JB Diego	8.65	6.61	8.80	8.27	9.42	5.90
	Benetto	9.40	9.39	8.77	9.04	9.18	6.54
	Grenado	7.91	7.41	8.23	8.38	8.30	5.28
		P value	SED	P value	SED	P value	SED
Rotation		NS	0.396	NS	0.375	0.010	0.652
N rate		<0.001	0.287	<0.001	0.334	<0.001	0.360
Variety		<0.001	0.180	<0.001	0.107	<0.001	0.176
Rotation x N rate		NS	0.537	NS	0.564	NS	0.795
Rotation x variety		<0.001	0.453	NS	0.397	<0.001	0.686
N rate x variety		NS	0.451	0.029	0.393	<0.001	0.496
Rotation x N x variety		NS	0.728	NS	0.636	NS	0.930

Table 7. The effects of N rate and variety on grain yield at HM11, IK12a, CB12a, CO14-1a and CO14-2a.

		Yield (t/ha at 85% dry matter)					
N rate (kg/ha)	Variety	HM11	IK12a	CB12a	N rate	CO14-1a	CO14-2a
0	Beluga	2.76	3.82	6.23	0	10.65	6.37
	JB Diego	3.93	3.97	6.07		10.06	5.85
	Benetto	4.59	4.68	6.72		9.27	6.21
	Grenado	3.65	4.02	6.02		10.02	6.28
90	Beluga	4.09	7.89	6.90	80	11.19	9.81
	JB Diego	5.59	7.98	7.66		11.39	9.53
	Benetto	6.43	9.13	9.32		12.31	9.08
	Grenado	4.88	8.38	8.93		11.78	9.00
180	Beluga	3.86	9.25	5.85	160	11.90	10.82
	JB Diego	5.51	9.30	6.93		12.17	11.10
	Benetto	7.02	10.45	8.69		12.86	11.10
	Grenado	5.71	9.86	8.43		11.94	10.28
270	Beluga	4.44	9.78	6.06	240	11.81	11.23
	JB Diego	6.25	9.35	6.57		12.83	11.32
	Benetto	7.60	10.62	8.52		11.93	11.65
	Grenado	6.07	9.91	8.39		12.14	11.20
360	Beluga	4.28	9.48	5.38	320	12.14	11.98
	JB Diego	5.88	9.58	6.37		12.76	11.81
	Benetto	7.22	10.96	7.87		13.09	11.66
	Grenado	6.03	9.99	7.98		12.10	11.00
N rate	P value	<0.001	<0.001	<0.001		<0.001	<0.001
Variety	P value	<0.001	<0.001	<0.001		0.012	<0.001
N rate x variety	P value	NS	NS	<0.001		<0.001	<0.001
N rate	SED	0.242	0.207	0.210		0.126	0.096
Variety	SED	0.127	0.179	0.150		0.118	0.086
N rate x variety	SED	0.345	0.404	0.359		0.261	0.192

Table 8. The effects of N rate and variety on grain yield at CO11-1 and CO11-2.

Site	Variety	Yield (t/ha at 85% dry matter) N rate (kg N/ha) 0	130	170	230	290
CO11-1	Beluga	9.02	10.08	10.88	10.81	9.88
	Delphi	7.77	9.02	8.34	8.85	9.87
	Hystar	6.41	7.87	8.66	8.75	8.83
	JB Diego	8.34	9.77	9.74	10.53	9.90
	Monterey	7.89	8.53	8.94	9.56	10.33
	Agostino	7.75	8.85	9.23	9.62	9.42
	Bellac	7.90	9.57	9.20	9.33	9.93
	Benetto	9.40	10.59	10.70	11.02	10.81
	Grenado	9.19	11.35	10.50	10.38	10.20
	Tulus	8.91	10.46	10.76	10.86	10.71
CO11-2	Beluga	4.90	7.62	7.14	7.56	7.71
	Delphi	5.09	7.82	7.85	7.97	8.16
	Hystar	4.81	8.04	8.48	8.32	7.75
	JB Diego	5.33	7.57	8.18	8.17	8.48
	Monterey	6.23	7.74	8.37	8.42	8.02
	Agostino	4.42	8.13	8.48	8.81	8.36
	Bellac	5.27	8.50	9.51	9.52	9.23
	Benetto	5.82	9.09	9.62	9.62	9.56
	Grenado	5.67	8.93	8.95	9.33	9.52
	Tulus	5.76	8.74	9.29	10.04	9.79
		CO11-1	CO11-2			
N rate	P value	<0.001	<0.001			
Variety	P value	<0.001	<0.001			
N rate x variety	P value	<0.001	<0.001			
N rate	SED	0.129	0.146			
Variety	SED	0.091	0.104			
N rate x variety	SED	0.288	0.328			

Table 9. The effects of N rate and variety on grain yield at IK12b, CB12b, TH, CO14-1b and CO14-2b.

		Yield (t/ha at 85% dry matter)				
N rate (kg N/ha)	Variety	IK12b	CB12b	TH13	CO14-1b	CO14-2b
0	BA W15	3.72	5.74			
	Cougar			6.03	8.83	6.03
	Delphi			5.61	8.76	5.65
	Hystar	3.55	6.17	5.62	8.77	5.82
	KWS Santiago	3.72	5.64	5.98	10.15	5.74
	Torch	3.55	6.02			
	Agostino	2.81	5.07	5.08	8.45	5.44
	Agrilac	3.81	5.48			
	KWS Fido			5.31	7.95	6.06
	Ragtac	4.05	6.26	5.86	8.58	6.30
	Tulus	4.01	5.21	5.44	8.77	5.89
90	BA W15	6.81	6.78			
	Cougar			8.20	9.65	10.37
	Delphi			8.22	11.01	11.35
	Hystar	7.08	7.80	7.38	10.60	10.62
	KWS Santiago	7.47	6.81	8.00	11.06	10.92
	Torch	6.91	5.89			
	Agostino	7.13	8.46	6.87	10.23	10.35
	Agrilac	7.11	8.65			
	KWS Fido			7.05	11.21	11.22
	Ragtac	8.15	8.94	7.12	10.18	10.38
	Tulus	7.90	8.68	6.97	10.77	10.76
180	BA W15	8.59	6.37			
	Cougar			8.16	10.69	8.62
	Delphi			8.74	11.22	8.97
	Hystar	9.43	7.76	8.63	11.03	9.54
	KWS Santiago	9.74	6.01	9.03	11.70	9.51
	Torch	9.53	5.08			
	Agostino	9.98	8.99	7.73	11.40	9.02
	Agrilac	10.08	8.93			
	KWS Fido			8.14	11.85	9.19
	Ragtac	10.58	8.80	8.75	11.09	9.42
	Tulus	10.41	9.12	8.12	11.34	9.81
N rate	P value	<0.001	<0.001	<0.001	<0.001	<0.001
Variety	P value	<0.001	<0.001	<0.001	<0.001	0.016
N rate x variety	P value	<0.001	<0.001	0.020	<0.001	<0.001
N rate	SED	0.492	0.203	0.141	0.165	0.082
Variety	SED	0.110	0.142	0.151	0.148	0.140
N rate x variety	SED	0.523	0.307	0.283	0.292	0.242

Table 10. The effects of variety on grain yield at CO12, CB13 and CO13.

		Yield (t/ha at 85% dry matter)		
		CO12	CB13	CO13
Wheat	BA W16	8.83	6.14	9.48
	Beluga	8.76	6.36	9.23
	Cougar	7.21	6.65	9.21
	Delphi		6.29	9.70
	Hystar	10.37	6.55	9.22
	Hyteck		7.01	10.23
	Icon		6.14	9.26
	JB Diego	8.22	6.14	9.66
	NOS13009.36	7.69		
	SJ08-50	8.28		
	SJ7420510	8.24	7.05	9.93
	Torch	8.03		
	Tuxedo		6.31	9.36
Triticale	Agostino	8.24	6.04	8.22
	Agrilac	8.28		
	Benetto	8.75	6.82	9.51
	Grenado	7.54	6.65	9.44
	KWS Fido		6.98	9.30
	Ragtac	8.58	7.31	9.96
	SW 1431	9.68	6.65	10.20
	Tulus	9.42	6.37	8.65
	Twingo	7.28		
Rye	Agronom	10.64		
	Dukato			8.26
	SU Mephisto			9.04
	SU Phoenix			8.96
	SU Skialto	10.93		
Variety	P value	<0.001	0.003	<0.001
Variety	SED	0.257	0.321	0.194

4.3. Yield response to N

At CO11-1 and CO14-2, statistics supported the fitting of linear plus exponential N response curves with all parameters separate; and at CR09, CR10, HM11, CO11-2, CB12, HM13-2, HM14-1 and CO14-1, statistics supported the fitting of curves with all linear parameters separate. In both cases, this gave different optimum N rates for each variety. At the other six sites, parallel response curves were the most suitable option (Figure 1). The fitted N response curves explained between 60.8% variation (HM14-2) and 98.3% variation (CO14-2).

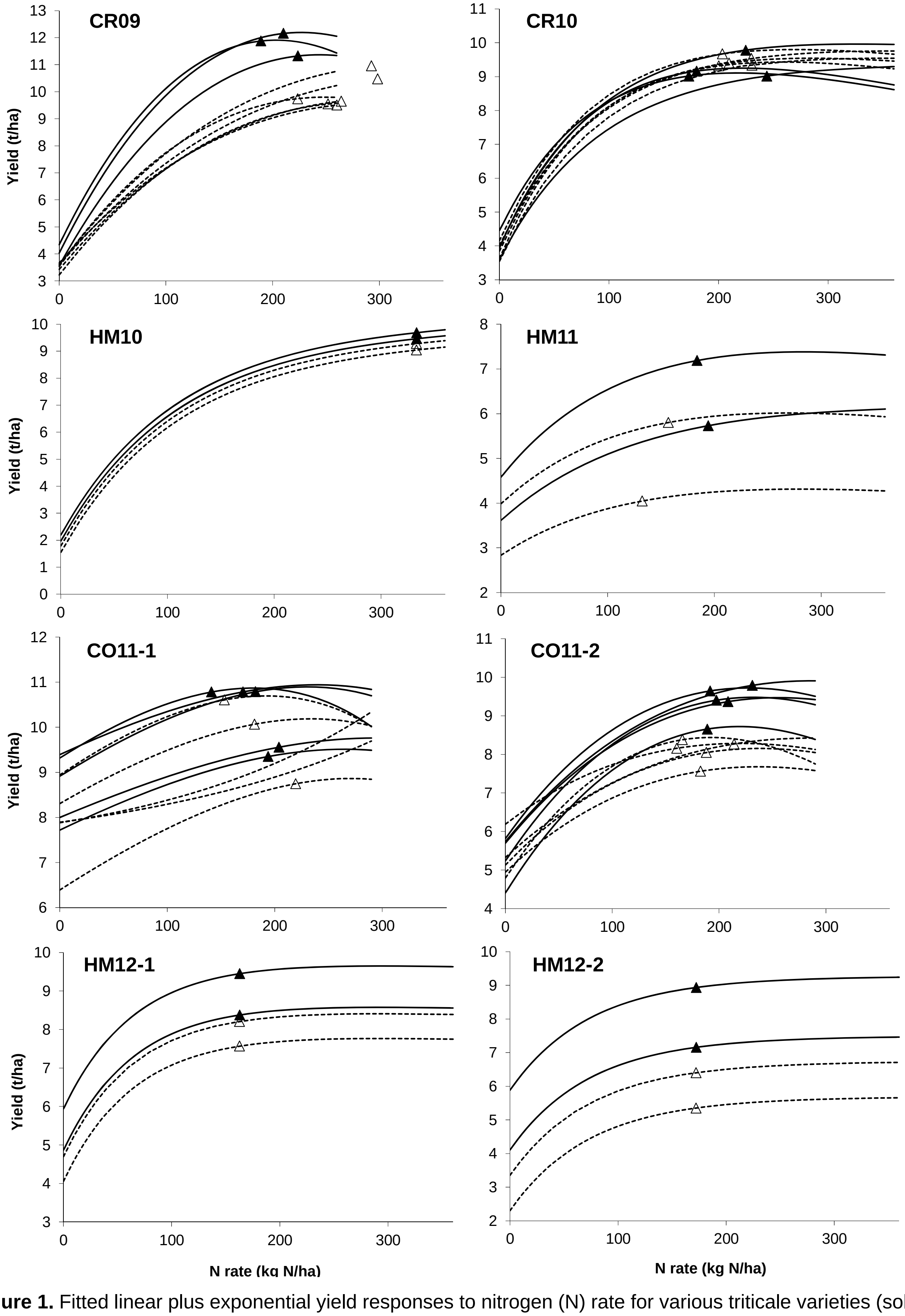

Figure 1. Fitted linear plus exponential yield responses to nitrogen (N) rate for various triticale varieties (solid lines) and wheat varieties (dotted lines) at 16 sites. Calculated economically optimal N rates are shown for each variety (filled triangles for triticale and open triangles for wheat). Variance explained by fitted curves as follows: CR09 96.2%, CR10 95.4%, HM10 96.1%, HM11 89.4%, CO11-1 90.8%, CO11-2 92.6%, HM12-1 81.7%, HM12-2 77.4%, IK12 95.7%, CB12 87.6%, HM13-1 89.7%, HM13-2 76%, HM14-1 94.4%, HM14-2 60.8%, CO14-1 85.8%, CO14-2 98.3%.

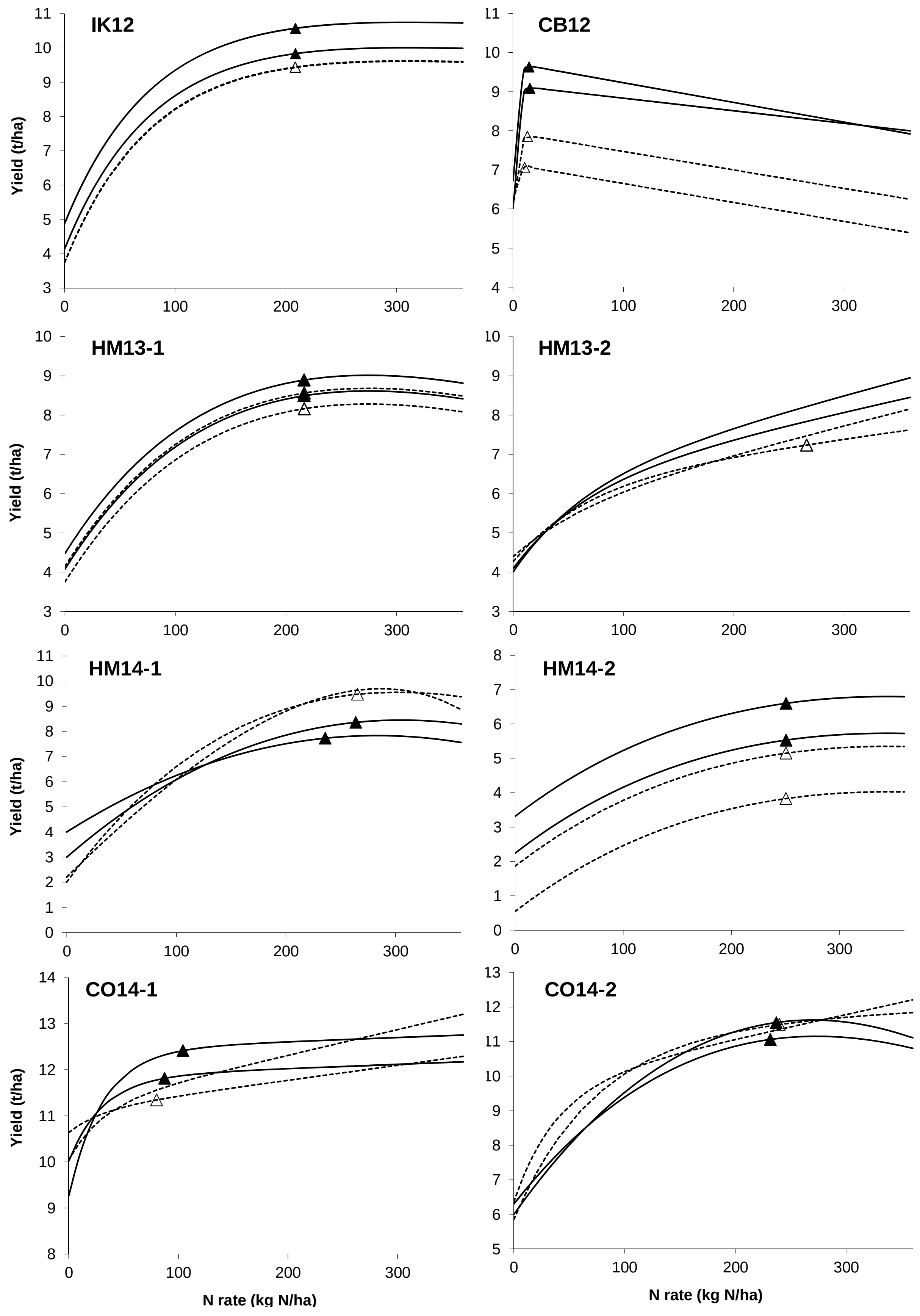

Figure 1 (continued). Fitted linear plus exponential yield responses to nitrogen (N) rate for various triticale varieties (solid lines) and wheat varieties (dotted lines) at 16 sites. Calculated economically optimal N rates are shown for each variety (filled triangles for triticale and open triangles for wheat). Variance explained by fitted curves as follows: CR09 96.2%, CR10 95.4%, HM10 96.1%, HM11 89.4%, CO11-1 90.8%, CO11-2 92.6%, HM12-1 81.7%, HM12-2 77.4%, IK12 95.7%, CB12 87.6%, HM13-1 89.7%, HM13-2 76%, HM14-1 94.4%, HM14-2 60.8%, CO14-1 85.8%, CO14-2 98.3%.

In a meta-analysis of triticale/wheat N response trials, t-tests showed no significant difference between economically optimum N rates (N_{opt}) for wheat and triticale (Table 11). An analysis of the sites which included Beluga, JB Diego, Benetto and Grenado found a significant effect of variety on N_{opt}, with Beluga having a significantly lower N_{opt} than the other three varieties (Table 12).

Table 11. Comparison of mean optimum N rates (N_{opt}) for wheat and triticale. N_{opt} values were calculated using a break even ratio (k) of 10, to maximise the number of site x variety combinations for which N_{opt} could be calculated.

Site	Rotational position	Triticale mean N_{opt} (kg N/ha) with fixed R	Wheat mean N_{opt} (kg N/ha) with fixed R	Triticale mean N_{opt} (kg N/ha) with R varying	Wheat mean N_{opt} (kg N/ha) with R varying
CR09	2	187	220		
CR10	2	156	163	152	169
HM10	2	223	222	226	222
HM11	2	106	68		
CO11-2	2	159	127		
HM12-1	1	106	130		
HM12-2	2	119	99		
IK12	1	159	154	154	159
CB12	2	13	10	21	16
HM13-1	1	160	157	174	155
HM13-2	2	185	139	185	24
HM14-1	1	209	221	27	215
HM14-2	2	151	168		
CO14-1	1	66	46	58	7
CO14-2	2	170	171	191	145
T-test P value	All sites	NS (0.416)		NS (0.786)	
T-test P value	1st cereals only	NS (0.850)		NS (0.609)	
T-test P value	2nd cereals only	NS (0.335)		NS (0.279)	

Table 12. Comparison of mean optimum N rates (N_{opt}) for wheat varieties Beluga and JB Diego and triticale varieties Benetto and Grenado. N_{opt} values were calculated using a break even ratio (k) of 10, to maximise the number of site x variety combinations for which N_{opt} could be calculated.

		N_{opt} (kg N/ha)			
Site	Rotational position	Beluga	JB Diego	Benetto	Grenado
HM11	2	51	85	116	96
CO11-2	2	125	142	152	157
HM12-1	1	128	132	109	104
HM12-2	2	93	106	122	117
IK12	1	156	153	162	156
CB12	2	9	12	13	14
HM13-1	1	150	164	165	156
HM13-2	2	128	151	199	171
HM14-1	1	218	224	215	202
HM14-2	2	142	194	151	151
CO14-1	1	26	66	75	58
CO14-2	2	171	171	177	163
Mean		116	133	138	129
	Variety P value	0.007			
	Variety SED	5.98			

4.4. Developmental stages

In 2012, variety had a significant effect on the length of the foundation stage (drilling to GS31) but not the construction phase (GS31 to GS61). The foundation stage was shorter for the triticale varieties than the wheat varieties, with stem extension starting 19 days earlier for Benetto and eight days earlier for Grenado than for the wheat varieties Beluga and JB Diego. Because the construction phase was similar for all varieties, this means that the triticale varieties also reached anthesis and so began grain filling sooner than the wheat (Figure 2).

In 2013 variety had a significant effect on the length of both the foundation and construction stages. The foundation stage was again shorter for triticale than wheat, although the difference was much smaller than in 2012 (Figure 3). The construction phase was also shorter, so as in 2012, the triticale varieties began grain filling earlier than the wheat.

In 2012, across all assessment dates and plant parts assessed, there were significant effects of rotational position, N rate and variety on senescence. N rate had the greatest effect, accelerating senescence by around three weeks. Senescence was slightly earlier in the first cereal position than the second. The varietal effect was small but consistent across plant parts: at each assessment, the triticale varieties typically had 1% more green area remaining than the wheat varieties, equivalent to senescence occurring about a day later.

In 2013, across all assessment dates and plant parts assessed, there were significant effects of N rate on senescence but not rotational position or variety. N rate had the greatest effect, accelerating senescence by around three weeks. Senescence was slightly earlier in the first cereal position than the second. The varietal effect was small but consistent across plant parts: at each assessment, the triticale varieties typically had 1% more green area remaining than the wheat varieties, equivalent to senescence occurring about a day later.

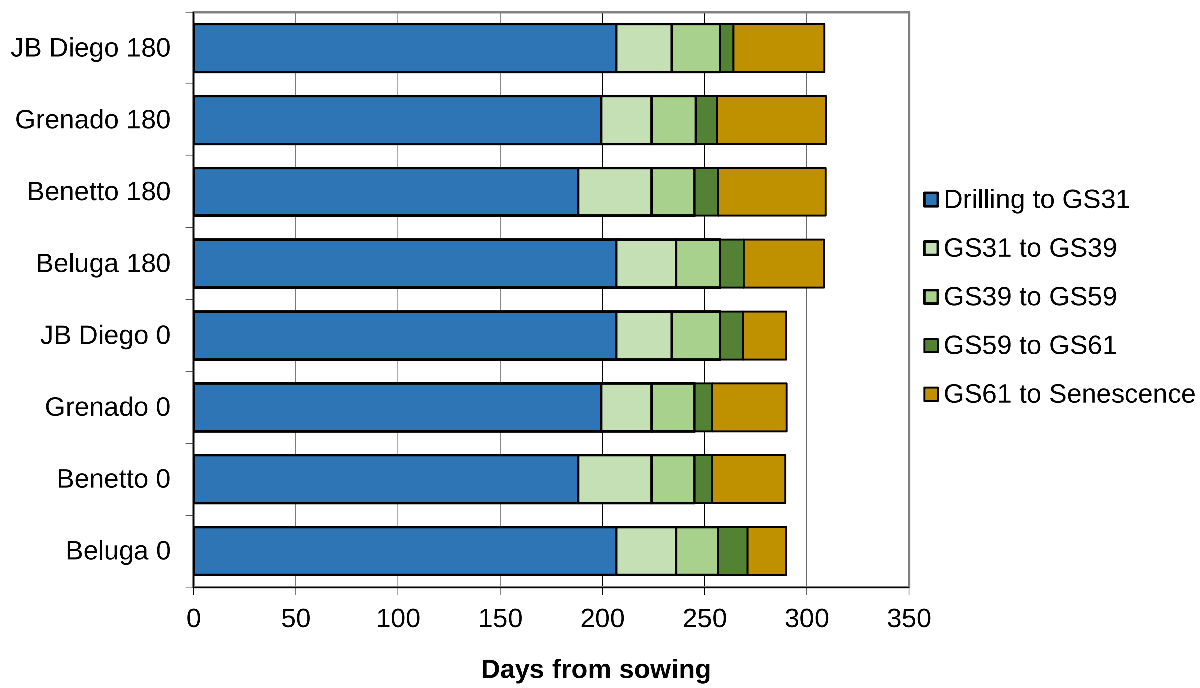

Figure 2. The effects of N rate (0 or 180 kg N/ha) and variety on crop development at HM2012. Senescence is taken as the date when mean green area across leaves 1–3, stem and ear is 25%.

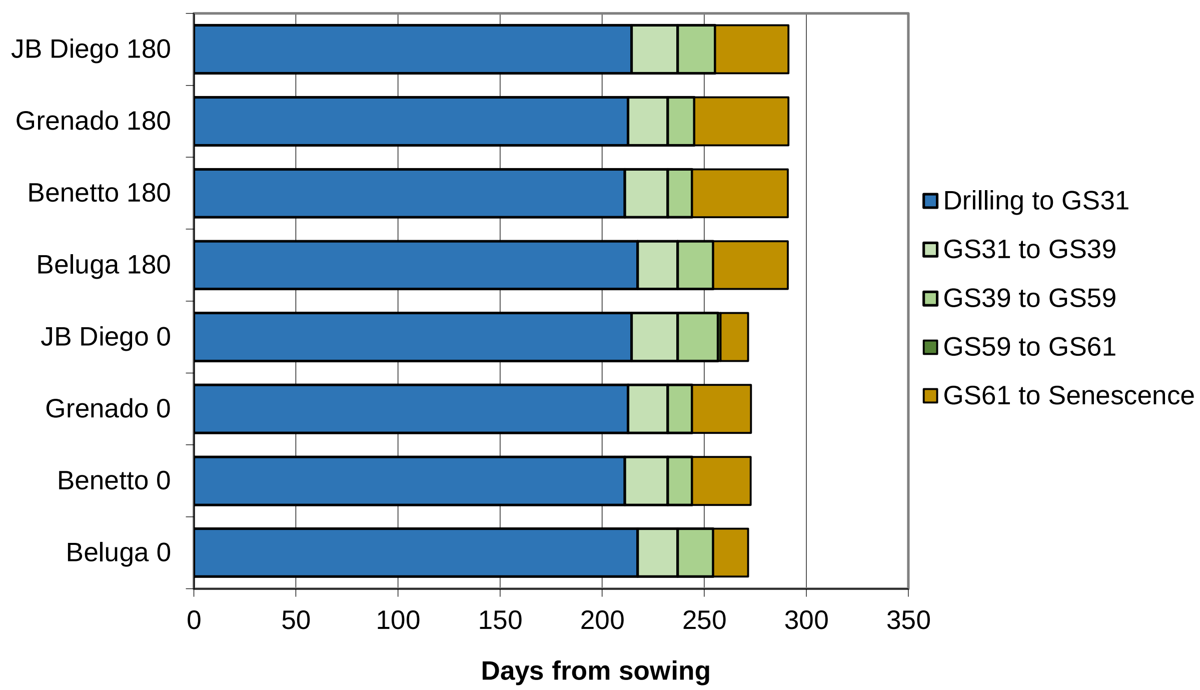

Figure 3. The effects of N rate (0 or 180 kg N/ha) and variety on crop development at HM2013. Senescence is taken as the date when mean green area across leaves 1–3, stem and ear is 25%.

4.5. Biomass, light interception and N partitioning at GS61

At all three sites, there were significant effects of N rate and variety on crop biomass at GS61, but rotational position had a significant effect only at HM14 (Table 13). The biomass of all plant parts increased with N rate. Benetto had a particularly high stem biomass in all years (Figure 4), and both the triticale varieties had higher ear biomass than the wheat varieties, particularly in 2012 and 2014. The effects of variety on leaf biomass were less consistent between years.

Table 13. Effects of rotation, N rate and variety on total biomass at GS61, at HM12, HM13 and HM14.

		Total biomass (t/ha) at GS61					
N rate (kg/ha)	Variety	HM12-1	HM12-2	HM13-1	HM13-2	HM14-1	HM14-2
0	Beluga	5.86	5.15	2.61	2.51	3.00	1.08
	JB Diego	7.28	7.46	2.69	2.83	2.04	1.29
	Benetto	10.47	10.92	4.24	3.26	6.00	6.99
	Grenado	8.11	7.41	3.12	2.61	4.62	5.80
180	Beluga	9.82	9.12	3.60	3.59	9.60	6.32
	JB Diego	8.89	9.25	3.90	3.74	9.23	5.42
	Benetto	14.63	16.17	4.64	5.70	11.31	9.93
	Grenado	10.95	10.36	4.17	4.32	7.99	7.44
360	Beluga	9.81	9.05	3.68	4.30	8.34	4.54
	JB Diego	10.20	11.09	4.40	4.37	8.82	6.68
	Benetto	14.36	12.68	4.51	4.74	12.74	10.49
	Grenado	10.31	15.30	4.24	4.03	9.14	5.90
		P value	SED	P value	SED	P value	SED
Rotation		NS	0.337	NS	0.097	0.050	1.282
N rate		<0.001	0.646	<0.001	0.159	<0.001	0.753
Variety		<0.001	0.695	<0.001	0.162	<0.001	0.247
Rotation x N rate		NS	0.819	NS	0.223	NS	1.549
Rotation x variety		NS	0.915	NS	0.221	<0.001	1.317
N rate x variety		NS	1.226	NS	0.351	<0.001	0.839
Rotation x N x variety		NS	1.686	NS	0.496	<0.001	1.635

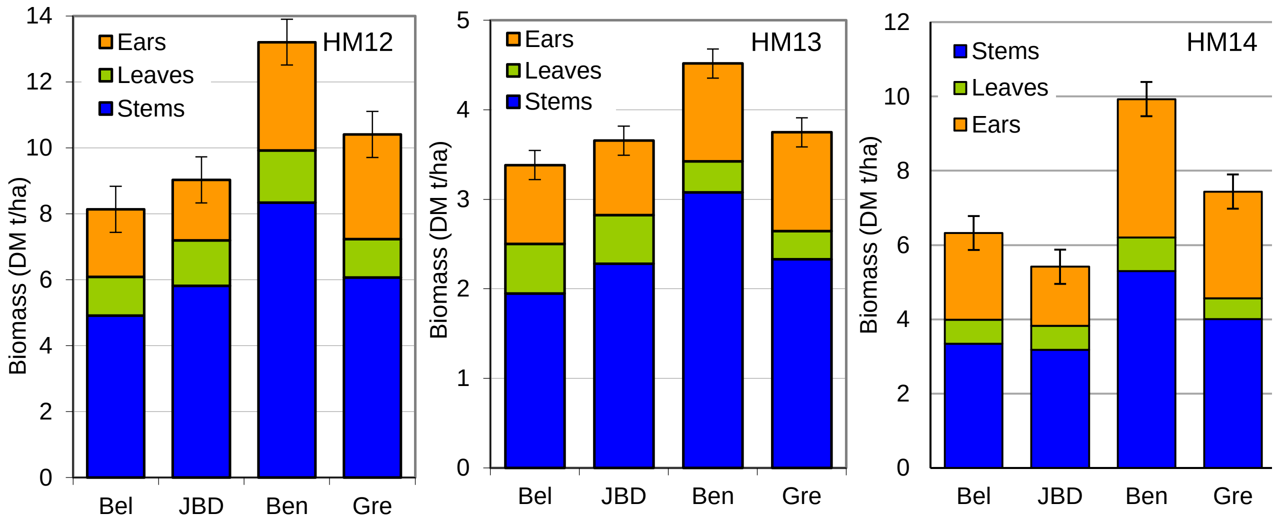

Figure 4. Effects of variety on ear, leaf and stem biomass at GS61 at HM12, HM13 and HM14. Data are averaged across N rates and rotational positions. Error bars show standard error of difference for total biomass.

In all three years there was a significant effects of N rate on crop N content at GS61; variety had a significant effect at HM12 and HM14; rotational position had a significant effect only at HM14 (The effect of variety on N content at GS61 was not consistent between years. At HM12 Benetto had the highest total N content at all N rates, due to its high ear and stem N content; Grenado also had a high ear N content, relative to the wheat varieties. At HM13 the wheat varieties had higher leaf N content than the triticale varieties but lower ear N content, resulting in no difference in total crop N. At HM14 Benetto had higher total N content than the other three varieties, due mainly to high ear N content (Figure 5).

At all three sites, there was a significant effect of N rate on green area index (GAI) (Table 15) and light interception (Table 16) at GS61. Variety had a significant effect on GAI at HM13 and HM14, and light interception at all sites. The first cereal plots had significantly higher light interception than second cereal plots in 2014 (**Error! Reference source not found.**), but there were no other effects of rotational position on GAI or light interception. Light interception and the GAI of all plant parts increased with N rate, with a large increase from 0 to 180 kg N/ha and a much smaller increase to 360 kg N/ha. The triticale varieties had higher ear GAI than the wheat varieties in all years but lower leaf GAI in 2012 and 2013 (Figure 6). The effects of variety on stem GAI were less consistent between years. Benetto generally had higher light interception than the other varieties (Figure 6), particularly at the lower N rates.

Table 14). Crop N content increased with N rate for all plant parts in all years.

The effect of variety on N content at GS61 was not consistent between years. At HM12 Benetto had the highest total N content at all N rates, due to its high ear and stem N content; Grenado also had a high ear N content, relative to the wheat varieties. At HM13 the wheat varieties had higher leaf N content than the triticale varieties but lower ear N content, resulting in no difference in total crop N. At HM14 Benetto had higher total N content than the other three varieties, due mainly to high ear N content (Figure 5).

At all three sites, there was a significant effect of N rate on green area index (GAI) (Table 15) and light interception (Table 16) at GS61. Variety had a significant effect on GAI at HM13 and HM14, and light interception at all sites. The first cereal plots had significantly higher light interception than second cereal plots in 2014 (**Error! Reference source not found.**), but there were no other effects of rotational position on GAI or light interception. Light interception and the GAI of all plant parts increased with N rate, with a large increase from 0 to 180 kg N/ha and a much smaller increase to 360 kg N/ha. The triticale varieties had higher ear GAI than the wheat varieties in all years but lower leaf GAI in 2012 and 2013 (Figure 6). The effects of variety on stem GAI were less

consistent between years. Benetto generally had higher light interception than the other varieties (Figure 6), particularly at the lower N rates.

Table 14. Effects of rotation, N rate and variety on crop N content (kg N/ha) at GS61, at HM12, HM13 and HM14.

		N content (kg N/ha) at GS61					
N rate (kg/ha)	Variety	HM12-1	HM12-2	HM13-1	HM13-2	HM14-1	HM14-2
0	Beluga	48.9	44.5	29.8	31.4	33.0	11.3
	JB Diego	52.4	64.8	27.7	33.4	19.7	15.1
	Benetto	76.6	83.7	39.7	31.6	50.4	31.6
	Grenado	60.6	52.9	31.2	25.2	39.6	48.1
180	Beluga	154.5	135.8	70.6	69.6	152.9	98.3
	JB Diego	147.6	148.3	74.8	79.4	167.8	81.9
	Benetto	189.9	238.3	71.0	87.3	171.8	147.8
	Grenado	152.3	150.1	70.8	74.9	101.1	100.8
360	Beluga	171.2	166.0	82.6	105.9	157.2	79.6
	JB Diego	173.4	197.0	99.6	88.3	157.1	120.9
	Benetto	254.5	229.3	82.4	88.9	200.8	170.3
	Grenado	187.0	272.6	89.3	80.8	155.0	96.5
		P value	SED	P value	SED	P value	SED
Rotation		NS	4.00	NS	3.20	0.041	14.53
N rate		<0.001	13.45	<0.001	4.90	<0.001	7.81
Variety		<0.001	10.21	NS	3.51	<0.001	3.20
Rotation x N rate		NS	16.03	NS	6.98	NS	17.10
Rotation x variety		NS	13.13	NS	5.36	<0.001	15.05
N rate x variety		NS	20.38	NS	8.39	<0.001	9.16
Rotation x N x variety		NS	26.95	NS	11.88	0.034	18.39

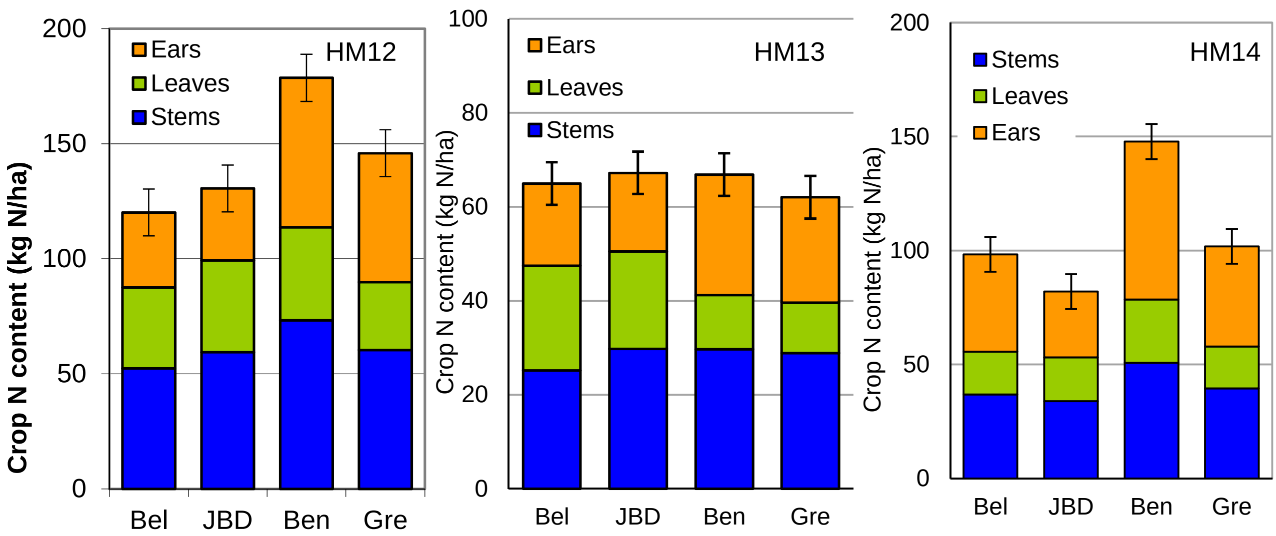

Figure 5. Effects of variety on ear, leaf and stem N content at GS61 at HM12, HM13 and HM14. Data are averaged across N rates and rotational positions. Error bars show standard error of difference for total crop N content.

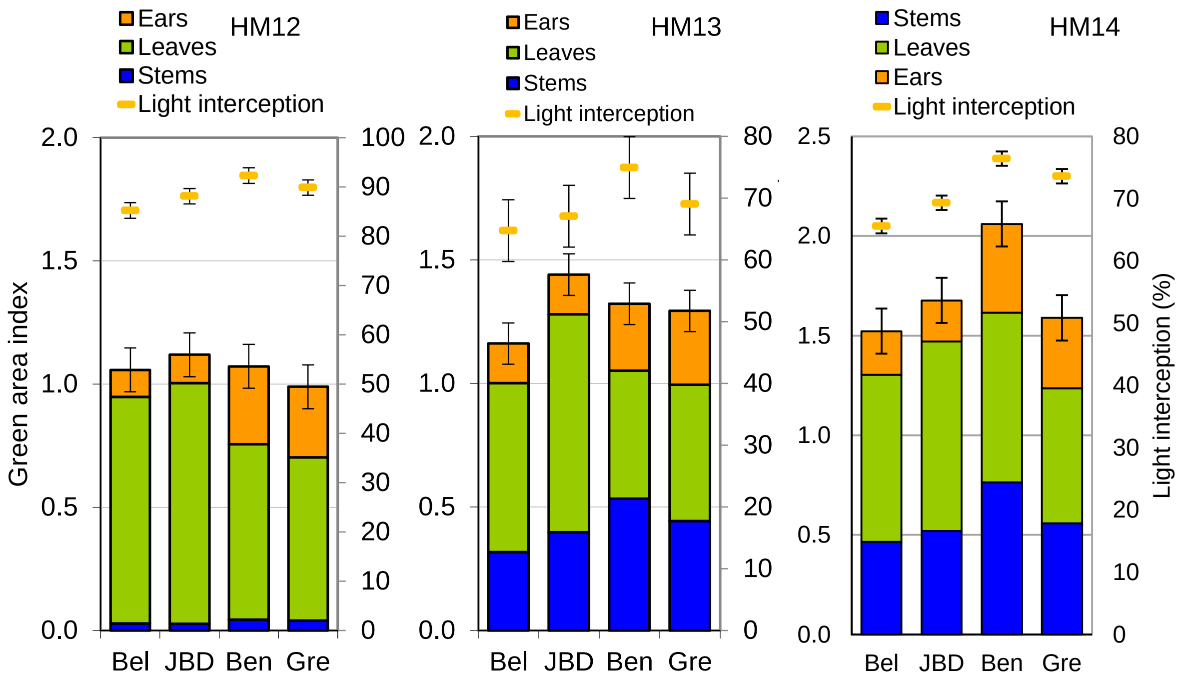

Figure 6. Effects of variety on ear, leaf and stem green area index, and whole crop light interception, at GS61 at HM12, HM13 and HM14. Data are averaged across N rates and rotational positions. Error bars show standard error of difference for total green area index and light interception.

Table 15. Effects of rotation, N rate and variety on total green area index at GS61 at HM12, HM13 and HM14.

N rate (kg/ha)	Variety	Green area index at GS61 HM12-1	HM12-2	HM13-1	HM13-2	HM14-1	HM14-2
0	Beluga	0.45	0.38	0.80	0.87	0.63	0.18
	JB Diego	0.31	0.48	0.90	0.95	0.64	0.25
	Benetto	0.42	0.40	1.07	0.81	1.01	0.85
	Grenado	0.40	0.42	0.85	0.79	0.84	0.81
180	Beluga	1.42	1.11	1.29	1.26	2.30	1.30
	JB Diego	1.38	1.35	1.67	1.52	2.55	1.22
	Benetto	1.17	1.44	1.31	1.74	2.78	2.20
	Grenado	1.13	0.95	1.53	1.52	2.08	1.61
360	Beluga	1.56	1.44	1.40	1.35	2.58	1.11
	JB Diego	1.67	1.59	1.90	1.70	2.64	1.88
	Benetto	1.50	1.43	1.50	1.51	3.22	2.43
	Grenado	1.18	1.37	1.52	1.55	2.67	1.50
		P value	SED	P value	SED	P value	SED
Rotation		NS	0.793	NS	0.047	NS	0.374
N rate		<0.001	0.888	<0.001	0.055	<0.001	0.167
Variety		NS	0.887	<0.001	0.044	<0.001	0.113
Rotation x N rate		NS	1.296	NS	0.084	NS	0.421
Rotation x variety		NS	1.345	NS	0.071	0.005	0.399
N rate x variety		NS	1.599	NS	0.101	0.034	0.238
Rotation x N x variety		NS	2.284	NS	0.147	NS	0.485

Table 16. Effects of rotation, N rate and variety on whole crop light interception measured using a Sunscan ceptometer, at HM12, HM13 and HM14.

N rate (kg/ha)	Variety	Light interception (%) HM12-1	HM12-2	HM13-1	HM13-2	HM14-1	HM14-2
0	Beluga	72.5	69.5	56.3	55.1	52.8	33.2
	JB Diego	69.7	75.8	52.4	50.1	52.4	30.9
	Benetto	83.7	81.6	63.1	65.1	63.7	48.4
	Grenado	83.1	68.8	59.8	55.7	60.6	47.3
180	Beluga	93.5	89.5	67.2	69.3	82.1	69.1
	JB Diego	95.2	95.3	78.3	70.4	86.4	76.5
	Benetto	96.4	96.4	78.2	82.9	89.3	81.7
	Grenado	96.9	95.6	73.0	71.8	86.1	78.8
360	Beluga	92.0	94.4	70.2	70.2	85.5	71.2
	JB Diego	96.8	95.8	71.6	79.5	89.9	79.5
	Benetto	97.6	98.0	82.5	77.9	90.6	83.4
	Grenado	97.7	97.2	75.2	78.6	86.6	81.4
		P value	SED	P value	SED	P value	SED
Rotation		NS	1.74	NS	3.43	0.019	3.01
N rate		<0.001	1.83	<0.001	2.87	<0.001	1.89
Variety		<0.001	1.57	<0.001	1.73	<0.001	1.18
Rotation x N rate		NS	2.74	NS	4.99	NS	3.72
Rotation x variety		NS	2.59	NS	4.03	0.017	3.33
N rate x variety		NS	2.98	NS	4.42	0.001	2.59
Rotation x N x variety		NS	4.31	NS	6.89	NS	4.48

4.6. Biomass and N partitioning pre-harvest

Crop biomass at harvest was generally higher for triticale varieties than for wheat varieties, with Benetto having particularly high biomass, principally due to its high straw biomass (Figure 7). N rate and variety had significant effects on biomass at most sites (Table 17, Table 18, Table 19). A comparison of mean triticale biomass with mean wheat biomass for each site (across all N rates) showed triticale to have a biomass of 13.2 t/ha compared with 11.7 t/ha for wheat (P<0.001). An analysis of the sites which had the main four varieties in common (using data at the standard N rate for each site) gave mean total biomass of 15.0 t/ha for Benetto, 13.0 t/ha for Grenado, 12.4 t/ha for JB Diego and 11.5 t.ha for Beluga (P<0.001).

Harvest index (the proportion of crop biomass in the grain at harvest) was higher for all the wheat varieties tested than all the triticale varieties (Figure 8): mean harvest indices for wheat varieties ranged from 54.3% to 55.1%, and for triticale varieties from 50.6% to 53.2%.

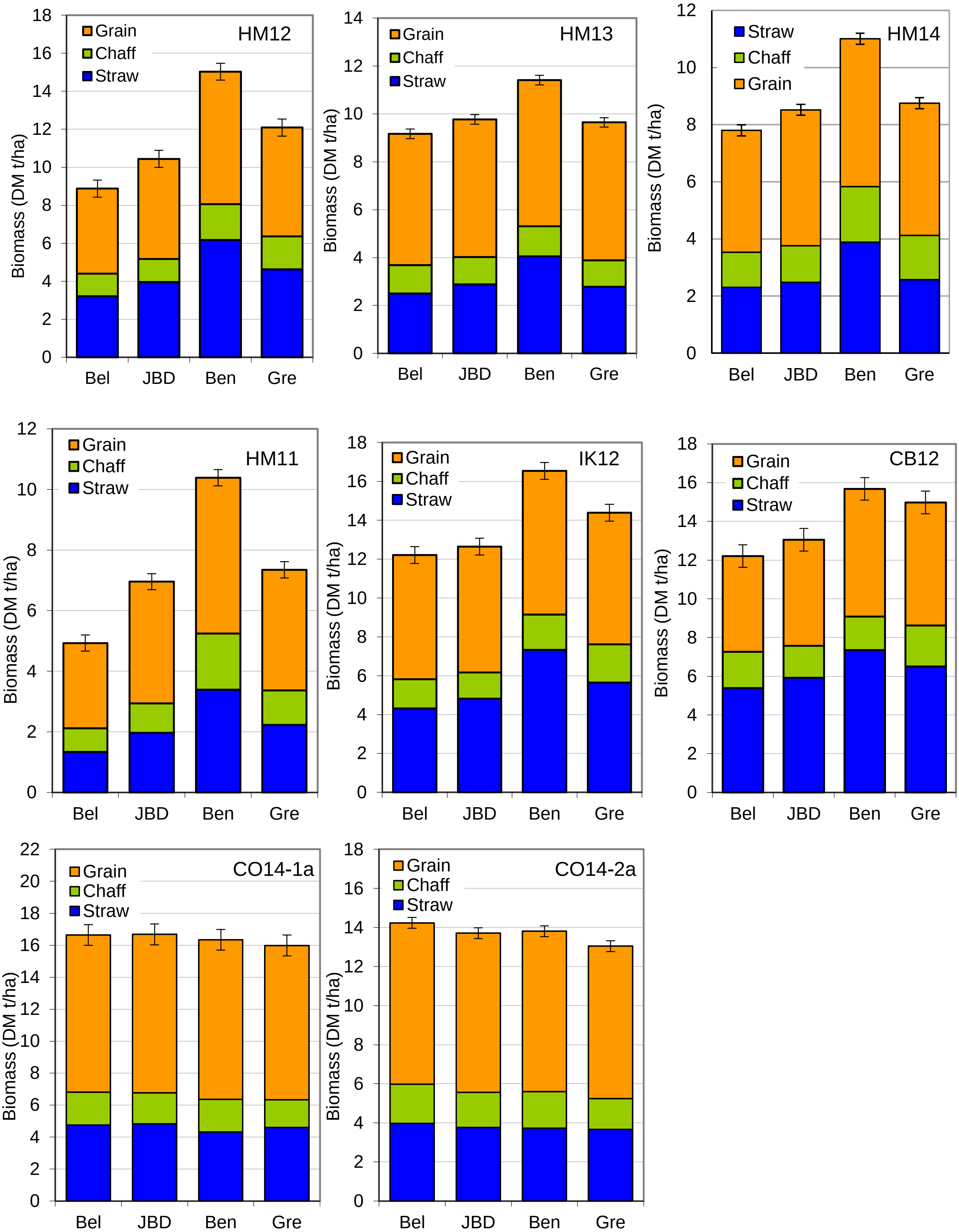

Figure 7. Effects of variety on straw, chaff and grain biomass at harvest at eight sites. Data are averaged across N rates and rotational positions. Error bars show standard error of difference for total biomass.

Table 17. Effects of rotation, N rate and variety on total biomass at harvest at HM12, HM13 and HM14.

N rate (kg/ha)	Variety	Biomass (t/ha) at harvest HM12-1	HM12-2	HM13-1	HM13-2	HM14-1	HM14-2
0	Beluga	5.86	5.15	5.91	6.35	3.49	1.14
	JB Diego	7.28	7.46	6.27	6.60	3.22	1.72
	Benetto	10.47	10.92	6.99	6.94	6.95	7.21
	Grenado	8.11	7.41	5.92	6.14	5.11	6.35
180	Beluga	9.82	9.12	11.11	9.34	11.72	6.87
	JB Diego	8.89	9.25	11.91	9.56	12.30	7.71
	Benetto	14.63	16.17	13.60	12.58	12.79	12.49
	Grenado	10.95	10.36	11.88	10.47	10.99	8.77
360	Beluga	9.81	9.05	11.41	10.84	13.23	6.88
	JB Diego	10.20	11.09	12.16	11.95	13.78	8.94
	Benetto	14.36	12.68	13.05	14.14	15.27	11.87
	Grenado	10.31	15.30	10.85	11.48	12.27	8.95
		P value	SED	P value	SED	P value	SED
Rotation		NS	0.337	NS	0.727	0.050	1.282
N rate		<0.001	0.646	<0.001	0.576	<0.001	0.753
Variety		<0.001	0.695	<0.001	0.154	<0.001	0.247
Rotation x N rate		NS	0.819	NS	1.029	NS	1.549
Rotation x variety		NS	0.915	NS	0.751	<0.001	1.317
N rate x variety		NS	1.226	<0.001	0.648	<0.001	0.839
Rotation x N x variety		NS	1.686	NS	1.112	<0.001	1.635

Table 18. Effects of N rate and variety on total biomass at harvest, at HM11, IK12a, CB12a, CO14-1a and CO14-2a.

N rate (kg N/ha)	Variety	Biomass (t/ha) at harvest HM11	IK12a	CB12a	N rate (kg N/ha)	CO14-1a	CO14-2a
0	Beluga	4.07	6.65	10.60	0	15.11	8.70
	JB Diego	5.98	6.69	10.81		13.51	8.24
	Benetto	8.44	9.29	12.32		13.41	9.02
	Grenado	5.97	7.59	11.25		14.42	9.20
180	Beluga	5.79	14.28	13.67	160	18.25	16.21
	JB Diego	7.94	14.81	14.00		18.52	16.26
	Benetto	11.82	19.04	17.82		17.41	15.25
	Grenado	8.73	16.83	16.81		16.35	13.85
360	Beluga		15.70	12.34	320	17.30	17.17
	JB Diego		16.43	14.36		17.98	16.63
	Benetto		21.29	16.90		18.21	17.17
	Grenado		18.74	16.87		17.18	16.09
N rate	P value	0.036	<0.001	0.002		<0.001	<0.001
Variety	P value	<0.001	<0.001	<0.001		NS	0.015
N x variety	P value	0.037	NS	NS		NS	0.003
N rate	SED	0.475	0.324	0.532		0.306	0.221
Variety	SED	0.268	0.430	0.584		0.651	0.277
N x variety	SED	0.577	0.722	1.025		1.022	0.470

Table 19. Effect of variety on total biomass at harvest, at IK12b, CB12b, CB13, CO14-1b and CO14-2b.

	Biomass (t/ha) at harvest				
Variety	IK12b	CB12b	CB13	CO14-1b	CO14-2b
BAW15	14.70	13.66			
Cougar			8.16	14.89	14.82
Delphi				16.19	16.43
Hystar	16.10	14.07	8.83	15.73	15.28
JB Diego			9.50		
KWS Santiago	16.35	13.47		16.54	15.80
Torch	19.26	13.56			
Agostino	18.79	16.12		16.02	15.93
Agrilac	17.59	15.62			
Benetto			9.50		
KWS Fido			8.92	15.89	15.69
Ragtac	20.90	16.55	9.24	15.42	14.73
Tulus	21.19	16.48	8.59	14.48	14.30
P value	NS	0.019	NS	0.016	0.031
SED	2.799	1.024	0.899	0.496	0.567

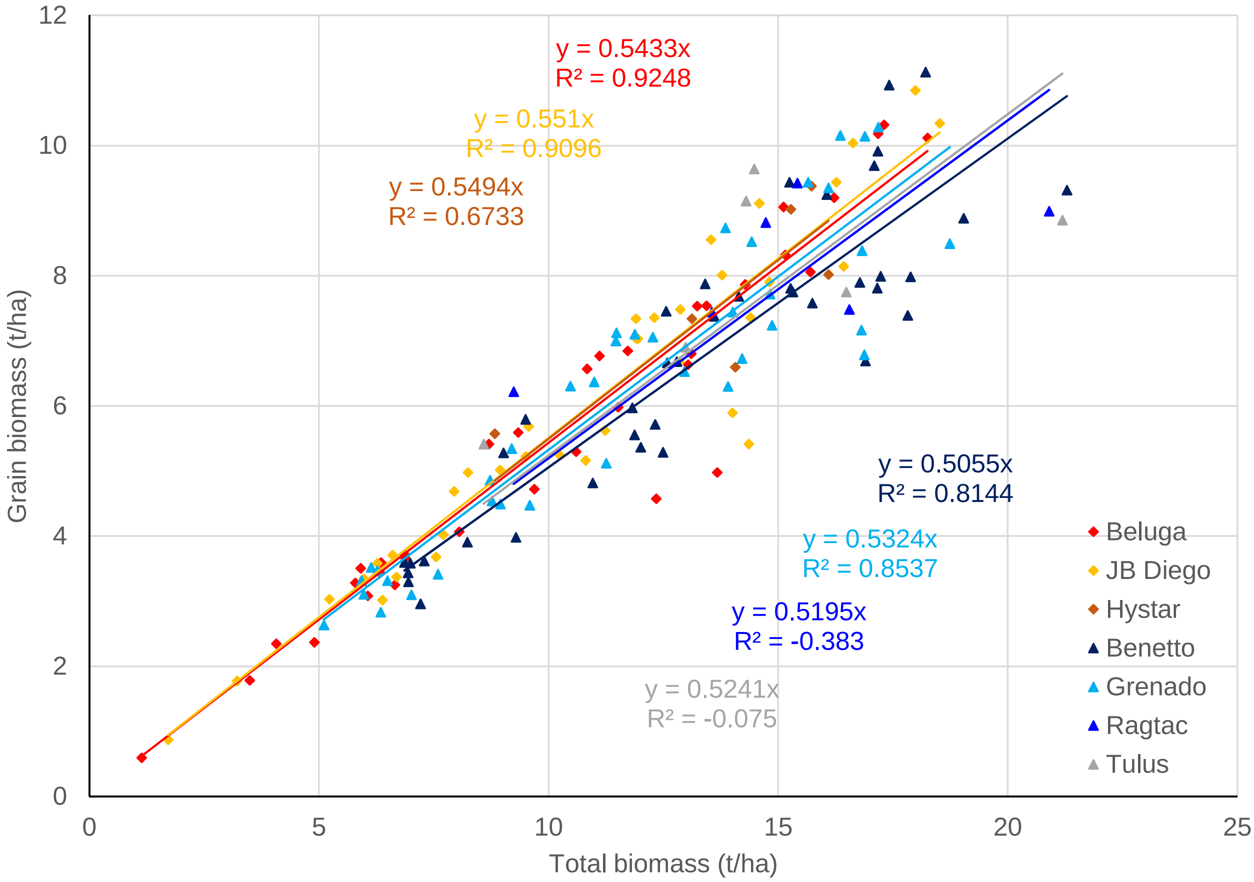

Figure 8. Relationship between total biomass and grain biomass at harvest for three wheat varieties (Beluga, JB Diego and Hystar) and four triticale varieties (Benetto, Grenado, Ragtac and Tulus). Each point shows the mean data for one site x rotation x N rate x variety combination. All varieties are included which have at least six data points. Linear trendlines have intercepts set at 0 and equations displayed above: slopes show harvest indices.

Crop N uptake at harvest was generally higher for triticale varieties than for wheat varieties, with Benetto having particularly high N uptake (Figure 9). The high N uptake of triticale crops was due to high biomass rather than to high N concentration, which was typically lower for triticale than for wheat (Figure 10). N rate and variety had significant effects on N uptake at most sites (

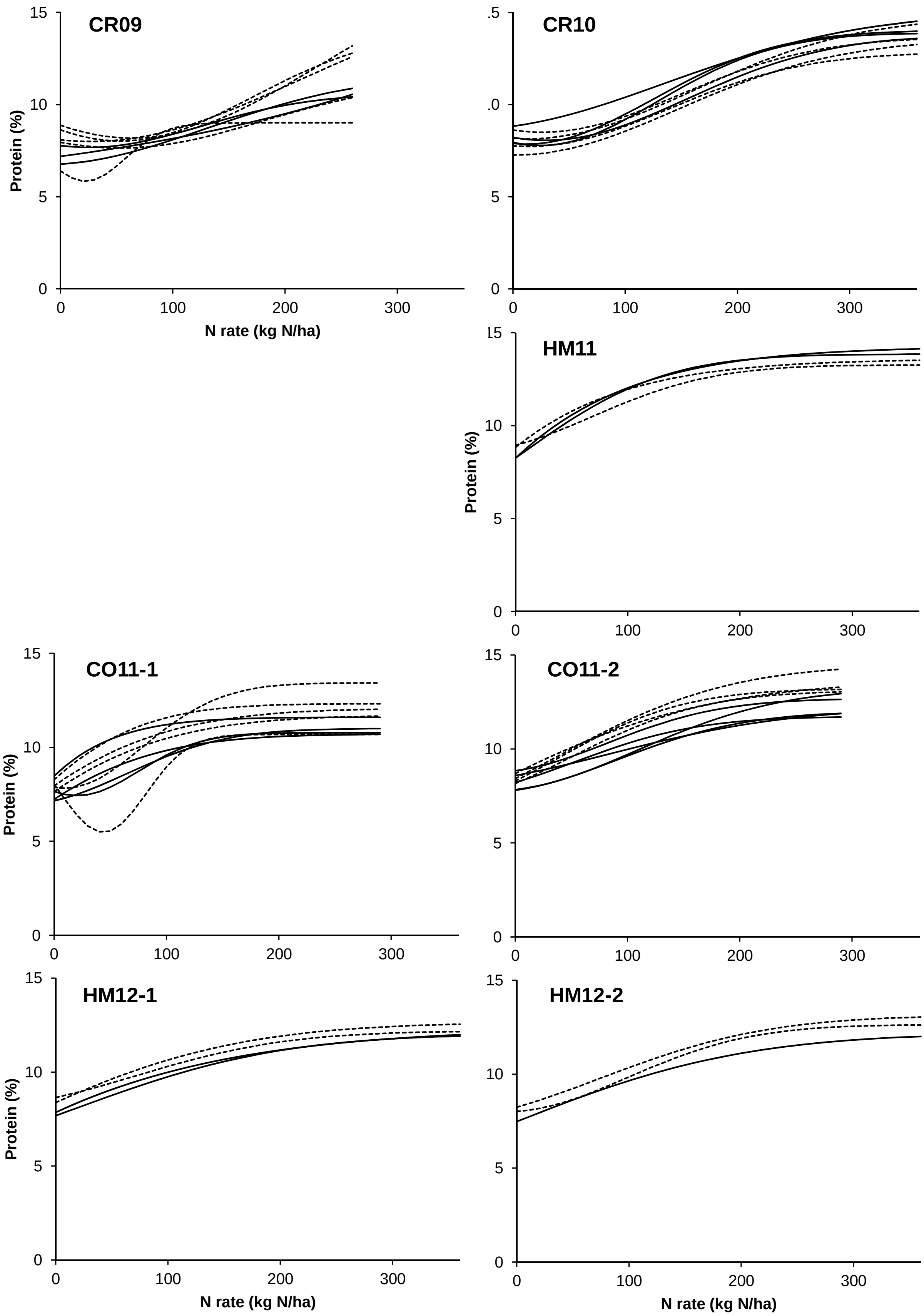

Figure 10. Fitted normal type curves with depletion showing grain protein responses to nitrogen (N) rate for various triticale varieties (solid lines) and wheat varieties (dotted lines) at 15 sites. Grain protein was not measured at HM10.

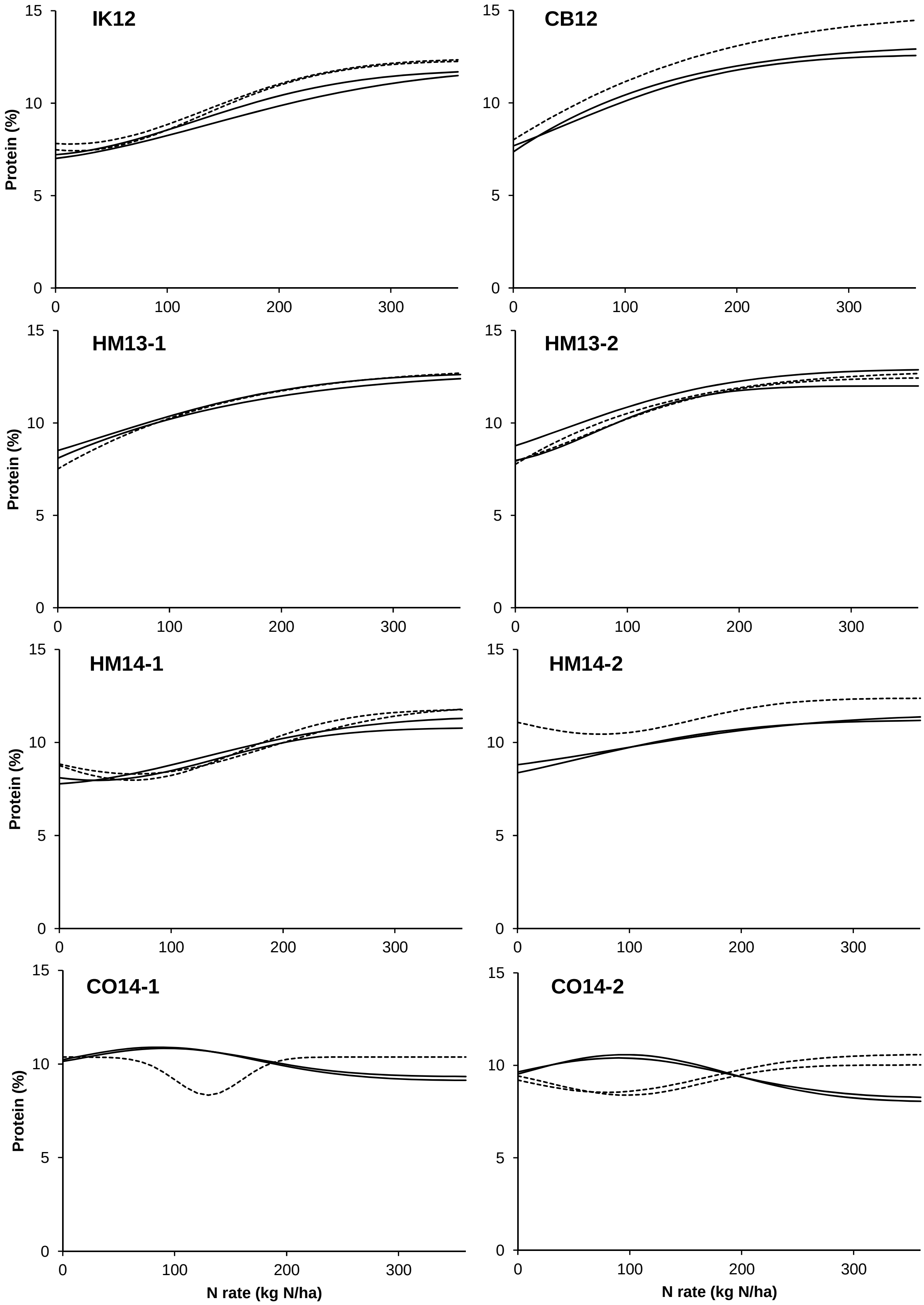

Figure 10 (continued). Fitted normal type curves with depletion showing grain protein responses to nitrogen (N) rate for various triticale varieties (solid lines) and wheat varieties (dotted lines) at 15 sites. Grain protein was not measured at HM10.

Table 20, Table 21, Table 22).

A comparison of mean triticale N uptake with mean wheat N uptake for each site (across all N rates) showed triticale to have a N uptake of 160.9 kg/ha compared with 147.7 kg/ha for wheat ($P<0.001$). An analysis of the sites which had the main four varieties in common (using data at the standard N rate for each site) gave mean total N uptake of 187.3 kg/ha for Benetto, 166.5 kg/ha for Grenado, 159.3 kg/ha for JB Diego and 148.5 kg/ha for Beluga ($P<0.001$).

There was no difference in N harvest index (NHI, the proportion of crop N found in the grain at harvest) between Beluga, JB Diego, Benetto and Grenado (Figure 11), showing that the higher yield of triticale than wheat is related to higher N uptake, rather than more efficient N utilisation.

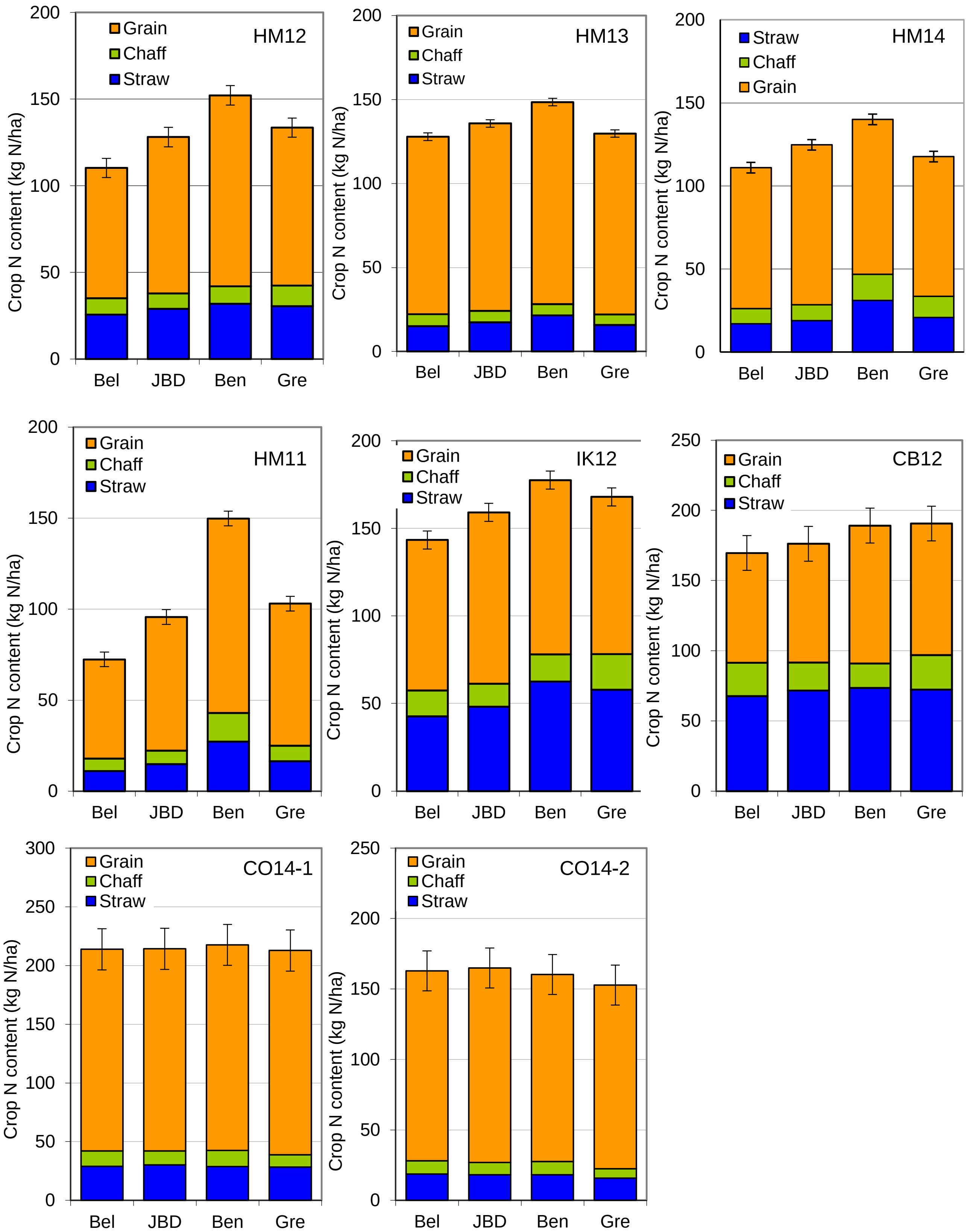

Figure 9. Effects of variety on straw, chaff and grain N content at harvest at eight sites. Data are averaged across N rates and rotational positions. Error bars show standard error of difference for total crop N content.

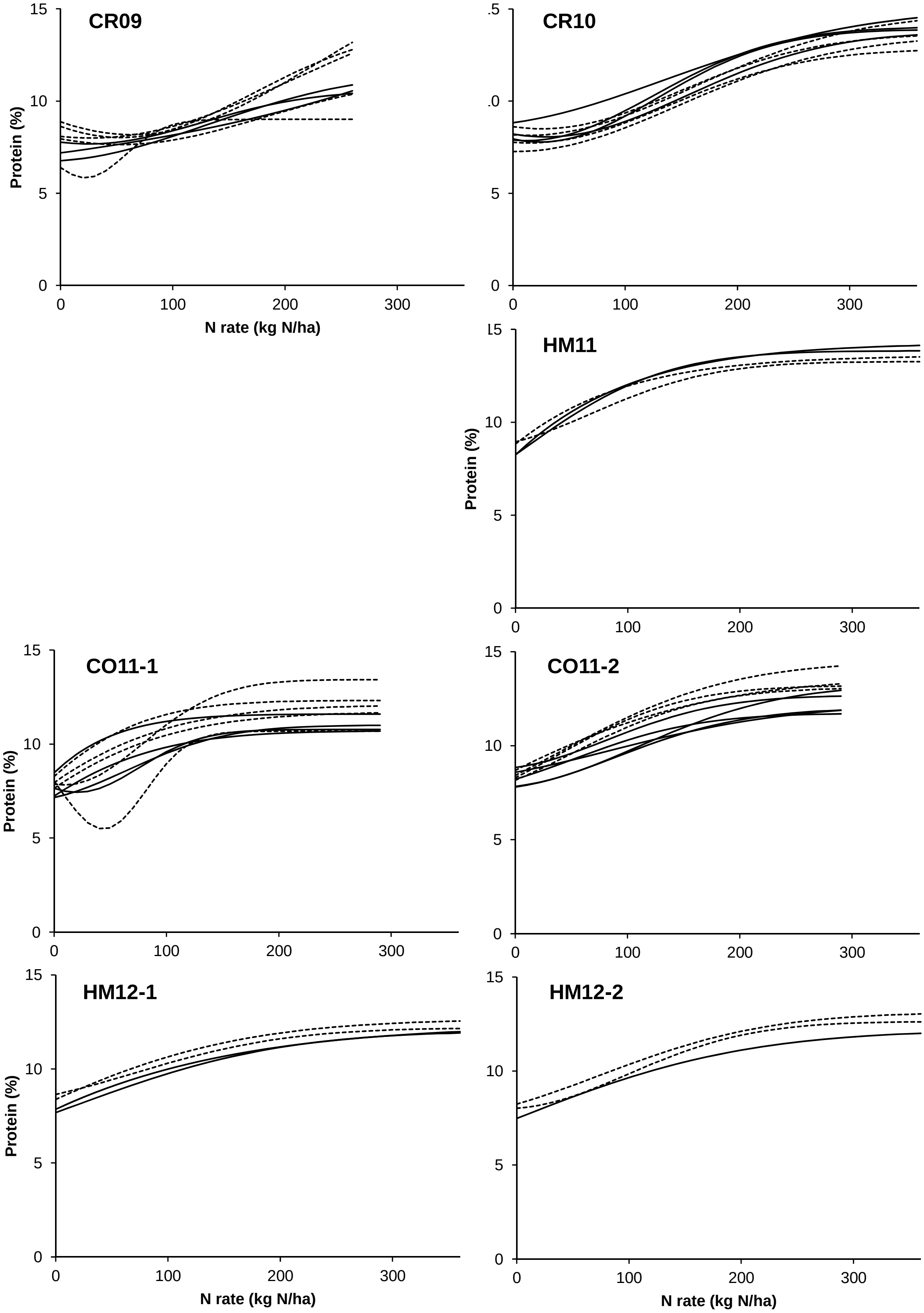

Figure 10. Fitted normal type curves with depletion showing grain protein responses to nitrogen (N) rate for various triticale varieties (solid lines) and wheat varieties (dotted lines) at 15 sites. Grain protein was not measured at HM10.

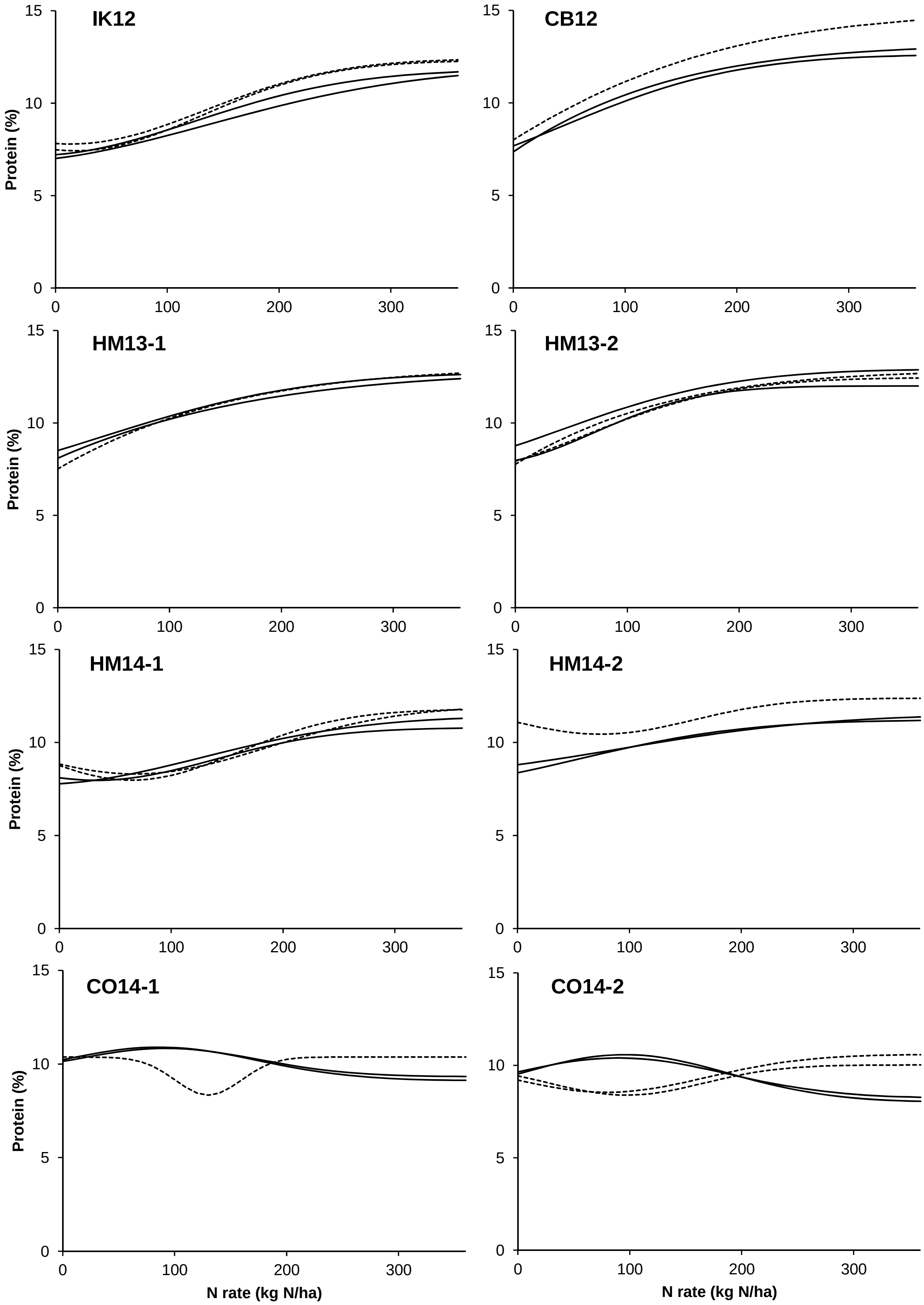

Figure 10 (continued). Fitted normal type curves with depletion showing grain protein responses to nitrogen (N) rate for various triticale varieties (solid lines) and wheat varieties (dotted lines) at 15 sites. Grain protein was not measured at HM10.

Table 20. Effects of rotation, N rate and variety on crop N uptake at harvest, at HM12, HM13 and HM14.

		N uptake (kg N/ha) at harvest					
N rate (kg/ha)	Variety	HM12-1	HM12-2	HM13-1	HM13-2	HM14-1	HM14-2
0	Beluga	47.4	35.7	57.1	64.5	37.3	13.2
	JB Diego	55.8	46.8	69.0	67.6	34.6	22.7
	Benetto	77.2	64.2	59.7	60.8	59.6	65.2
	Grenado	65.0	42.9	62.6	64.2	47.5	60.0
180	Beluga	147.3	103.6	164.5	137.0	149.1	98.5
	JB Diego	161.7	127.3	183.2	177.1	158.8	103.5
	Benetto	176.1	166.4	167.3	154.2	151.4	153.5
	Grenado	166.1	141.4	174.5	142.3	135.9	120.7
360	Beluga	188.7	139.1	186.3	177.1	197.7	105.0
	JB Diego	211.6	165.7	194.8	214.5	219.5	141.3
	Benetto	213.4	215.6	173.0	178.0	235.2	175.4
	Grenado	197.7	188.4	200.8	192.2	184.9	137.7
		P value	SED	P value	SED	P value	SED
Rotation		NS	8.26	NS	8.86	0.041	14.53
N rate		<0.001	6.29	<0.001	7.82	<0.001	7.81
Variety		<0.001	5.58	<0.001	2.25	<0.001	3.20
Rotation x N rate		NS	11.00	NS	12.65	NS	17.10
Rotation x variety		NS	10.72	0.003	2.41	<0.001	15.05
N rate x variety		NS	10.47	<0.001	9.78	<0.001	9.16
Rotation x N x variety		NS	16.15	0.024	8.27	0.034	18.39

Table 21. Effects of N rate and variety on crop N uptake at harvest, at HM11, IK12a, CB12a, CO14-1a and CO14-2a.

		N uptake (kg N/ha) at harvest					
N rate (kg N/ha)	Variety	HM11	IK12a	CB12a	N rate (kg N/ha)	CO14-1a	CO14-2a
0	Beluga	44.3	54.9	82.3	0	193.1	90.0
	JB Diego	66.3	52.2	92.9		182.5	98.1
	Benetto	73.9	65.7	88.2		177.0	106.9
	Grenado	59.8	56.3	86.7		191.9	114.6
			57.3	87.0			
180	Beluga	100.5	158.2	216.1	160	211.0	169.2
	JB Diego	125.1	180.6	202.5		220.1	174.7
	Benetto	201.8	193.7	231.7		248.7	199.9
	Grenado	146.3	186.0	223.2		236.9	177.5
			179.6	218.4			
360	Beluga		217.2	210.6	320	245.1	214.9
	JB Diego		244.6	234.9		240.0	221.7
	Benetto		273.2	247.6		226.8	173.8
	Grenado		261.6	262.0		253.0	166.2
N rate	P value	0.007	<0.001	<0.001		0.046	0.002
Variety	P value	<0.001	<0.001	NS		NS	NS
N x variety	P value	<0.001	0.037	NS		NS	NS
N rate	SED	6.80	4.85	7.70		15.16	11.05
Variety	SED	4.06	5.13	12.40		19.71	14.16
N x variety	SED	8.42	9.09	20.13		33.22	23.94

Table 22. Effects of N rate and variety on crop N uptake at harvest, at IK12b, CB12b and CB13, CO14-1b and CO14-2b.

	N uptake (t/ha) at harvest				
Variety	IK12b	CB12b	CB13	CO14-1b	CO14-2b
BAW15	185.8	210.9			
Cougar			94.7	178.3	169.9
Delphi				203.2	175.9
Hystar	182.9	204.1	99.8	186.7	164.1
JB Diego			99.5		
KWS Santiago	199.1	204.1		194.6	160.7
Torch	197.6	195.3			
Agostino	204.2	210.1		194.7	187.7
Agrilac	188.5	210.8			
Benetto			102.2		
KWS Fido			100.1	204.9	169.6
Ragtac	225.0	219.4	161.9	192.9	161.7
Tulus	219.8	225.3			
P value	NS	NS	NS	NS	NS
SED	28.13	14.5	27.8	20.10	23.32

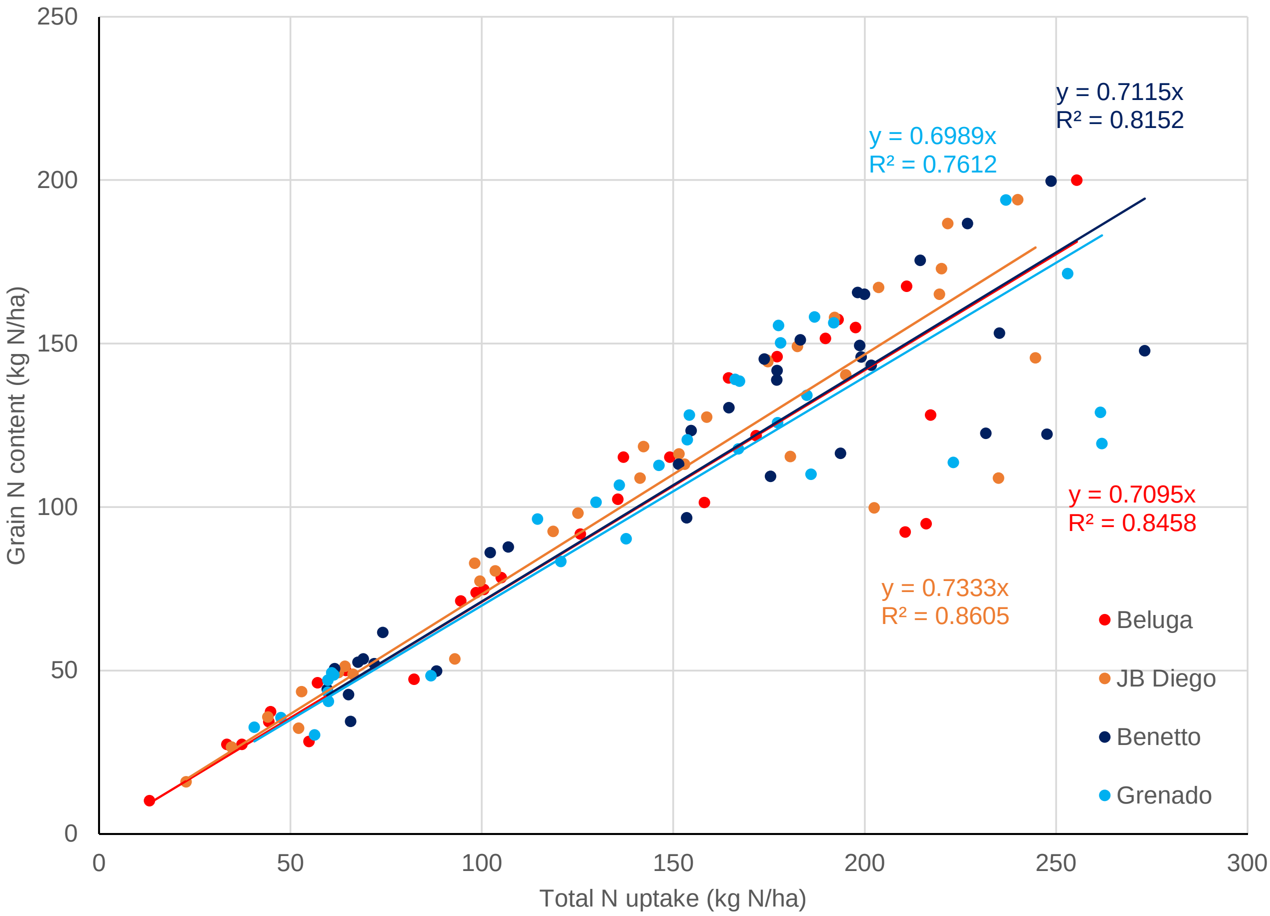

Figure 11. Relationship between total N uptake and grain N content at harvest for two wheat varieties (Beluga and JB Diego) and two triticale varieties (Benetto and Grenado). Each point shows the mean data for one site x rotation x N rate x variety combination. Linear trendlines have intercepts set at 0 and equations displayed above: slopes show nitrogen harvest indices. There is no significant difference between the fitted regression lines.

4.7. Yield components

At the sites where triticale had a large yield advantage over wheat (e.g. HM11, HM12, CB12, HM14-2), this advantage was due mainly to triticale having more ears/m^2 than wheat; there was relatively little difference in grain yield per ear (Figure 12). An exception was CB12b, where all the triticale varieties had higher grain yield, higher grain yield/ear and lower ears/m^2 than all the wheat varieties.

At HM14, the only site where individual grain weight was measured, there were significant effects of variety on all the yield components ears/m^2, grains/ear and grain weight. In the first cereal position, Grenado stood out as having a higher grain weight per ear (Figure 12), which was entirely due to high grain number per ear (Table 24), and despite having lower thousand grain weight than the other varieties (Table 23). In the second cereal position, Benetto had a large yield advantage over the other varieties, which was due to a combination of more ears/m^2 and higher grain weight; Benetto did not have more grains/ear than the other varieties.

A comparison of the mean ears/m^2 for triticale and wheat at each site gave 377 ears/m^2 for triticale and 359 for wheat, but this difference was not significant ($P=0.167$). Using the sites which had the main four varieties in common, an analysis of variety mean ears/m^2 at standard N rate for site gave overall means of 413 for Benetto, 370 for Grenado, 351 for JB Diego and 342 for Beluga ($P<0.001$).

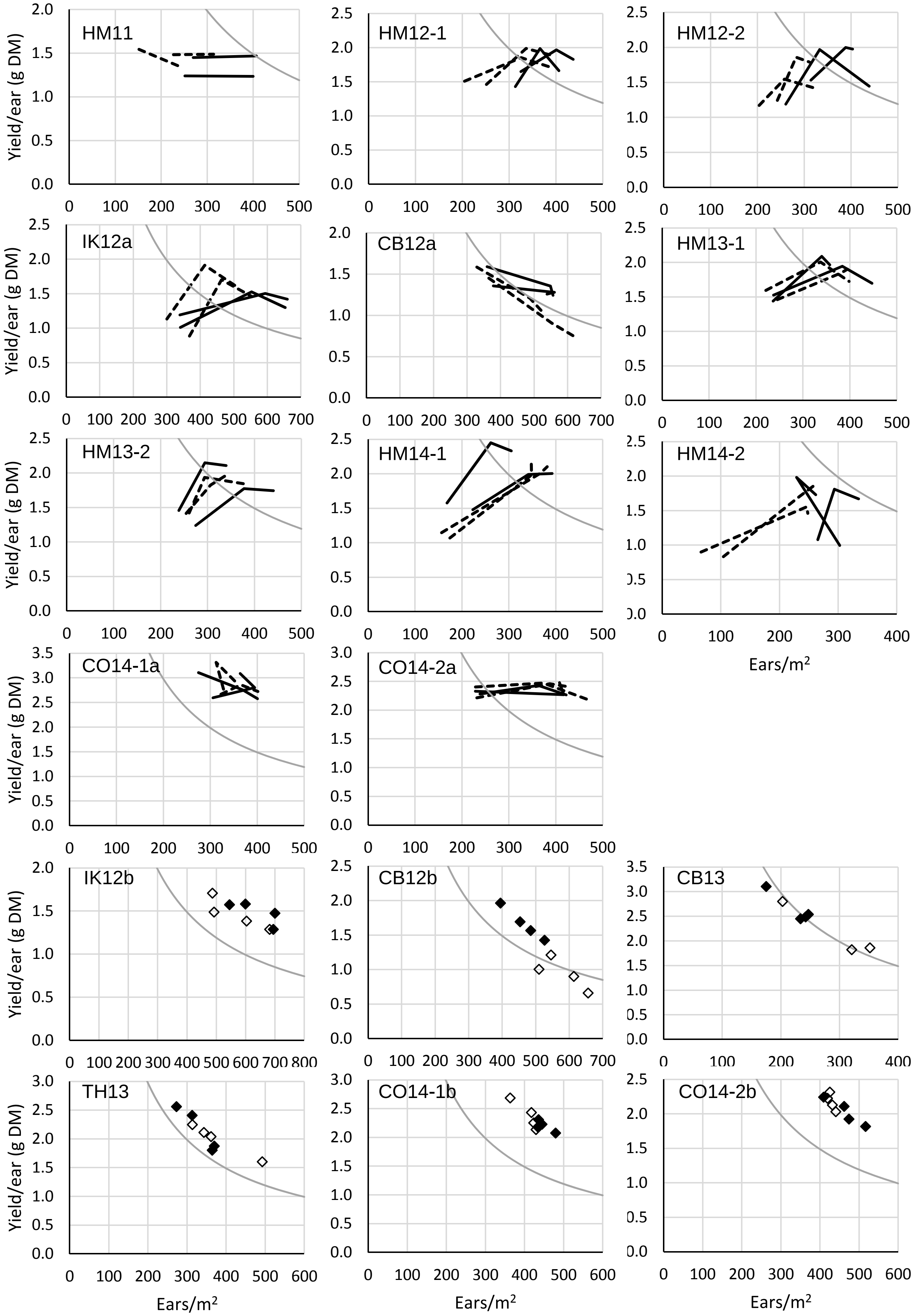

Figure 12. Relationship between the yield components ears/m2 and yield/ear (g dry matter) for triticale (solid lines, filled diamonds) and wheat (dashed lines, open diamonds) at 17 sites. Lines denote a single variety at different N rates; diamonds denote measurements taken at a single, medium N rate. Grey curves show combinations of ears/m^2 and yield/ear required to give 7 t/ha grain yield at 85% dry matter.

Table 23. The effects of rotational position, N rate and variety on thousand grain weight (TGW) at HM14.

		TGW (g at 85% DM)	
N rate	Variety	HM14-1	HM14-2
0	Beluga	42.9	25.8
	JB Diego	37.2	25.5
	Benetto	39.3	30.6
	Grenado	35.6	27.2
90	Beluga	44.7	31.0
	JB Diego	39.3	30.6
	Benetto	41.4	37.6
	Grenado	38.8	33.3
180	Beluga	47.7	36.2
	JB Diego	40.1	34.6
	Benetto	41.7	39.6
	Grenado	38.7	37.3
270	Beluga	48.6	34.7
	JB Diego	42.6	36.7
	Benetto	41.6	41.9
	Grenado	37.4	34.6
360	Beluga	46.1	40.0
	JB Diego	40.1	36.7
	Benetto	42.4	42.1
	Grenado	39.3	35.3
		P value	SED
Rotation		0.004	1.16
N rate		<0.001	0.46
Variety		<0.001	0.51
Rotation x N rate		<0.001	1.29
Rotation x variety		<0.001	1.31
N rate x variety		NS	1.08
Rotation x N x variety		NS	1.89

Table 24. The effects of rotational position, N rate and variety on ears/m^2 and grains/ear at HM14.

		Ears/m^2		Grains/ear	
N rate	Variety	HM14-1	HM14-2	HM14-1	HM14-2
0	Beluga	174	66	29.3	37.4
	JB Diego	156	105	36.2	35.0
	Benetto	223	266	44.2	41.3
	Grenado	168	303	52.1	41.6
180	Beluga	348	246	48.9	50.7
	JB Diego	367	234	59.2	57.8
	Benetto	342	294	55.9	53.7
	Grenado	261	229	74.7	62.8
360	Beluga	348	248	55.4	42.8
	JB Diego	382	264	61.7	60.7
	Benetto	392	335	55.5	46.7
	Grenado	305	262	69.9	58.0
		P value	SED	P value	SED
Rotation		NS	41.7	0.046	1.52
N rate		<0.001	31.4	<0.001	1.30
Variety		<0.001	11.9	<0.001	2.38
Rotation x N rate		NS	55.3	NS	2.14
Rotation x variety		<0.001	44.2	NS	3.29
N rate x variety		<0.001	36.1	NS	3.80
Rotation x N x variety		<0.001	60.7	NS	5.49

4.8. Take-all

In 2012 there was very little take-all in the first cereal, but moderate severity in the second cereal (Figure 13a). Take-all index was significantly affected by rotational position, variety and the interaction between them: there was little difference between varieties in the first cereal position, but as in the second cereal position take-all was lower for the triticale varieties, and particularly for Benetto.

In 2013, take-all levels were relatively low, with an average of 21% incidence in first cereal plots and 38% incidence in second cereal plots (Figure 13b). Take-all index was not significantly affected by rotational position or variety.

In 2014, all plants assessed were affected by take-all, and severity was higher than in 2012 (Figure 13c). Take-all index was not significantly affected by rotational position or variety.

4.9. Rooting

In 2012 there was no significant effect of variety on root length density (RLD) (Figure 14a).

In 2013 there was a significant effect of variety on RLD, with Beluga having significantly higher average RLD than Grenado and JB Diego (Figure 14b); Benetto had the next highest RLD, but this did not differ significantly from the other varieties.

In 2014 there was a significant effect of variety on RLD, with Benetto and JB Diego having higher RLD than Beluga and Grenado (Figure 14c).

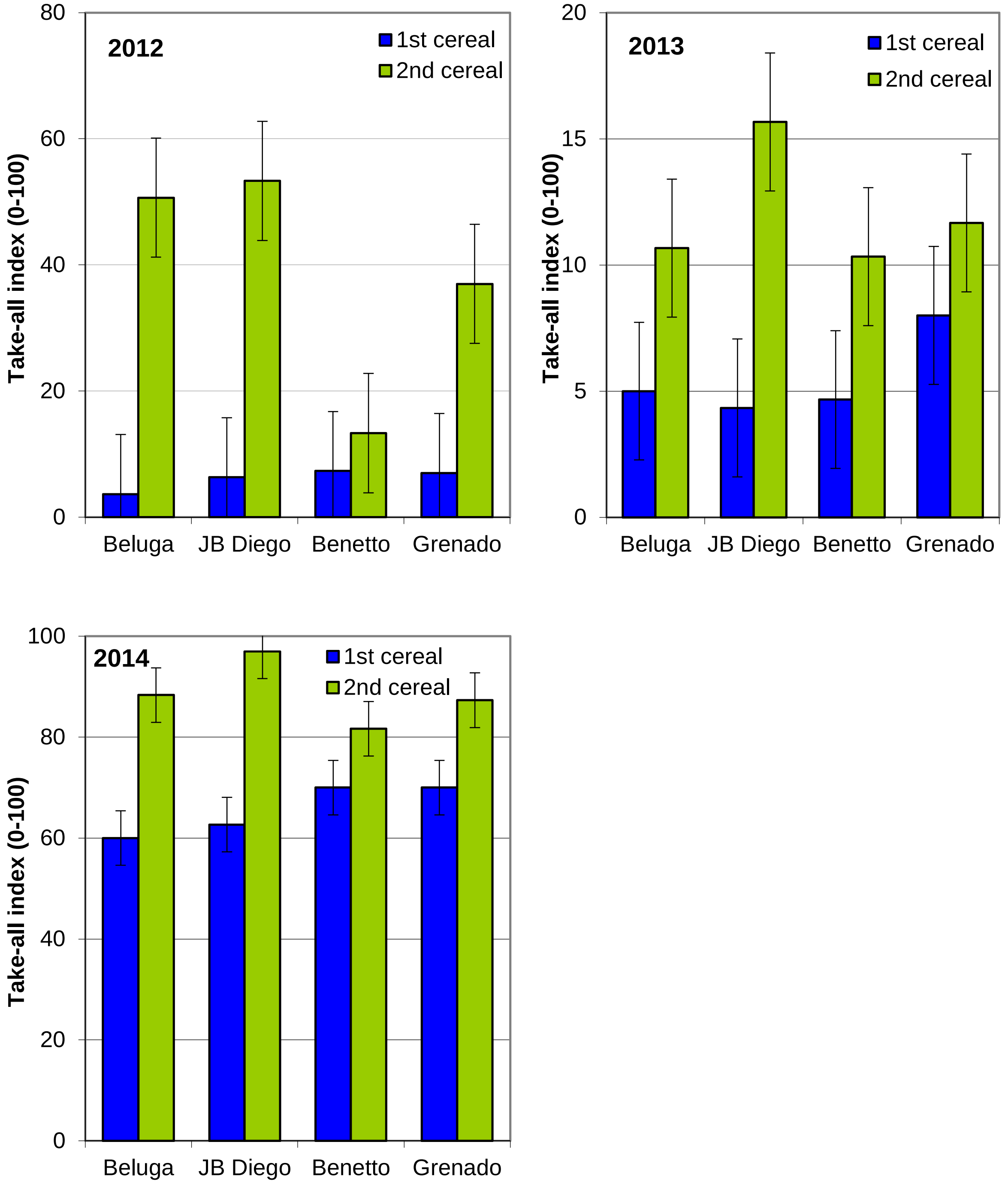

Figure 13. Effects of rotational position and variety on take-all index (0–100 scale) at HM2012, HM2013 and HM2014. Error bars show SED for rotational position x variety interaction.

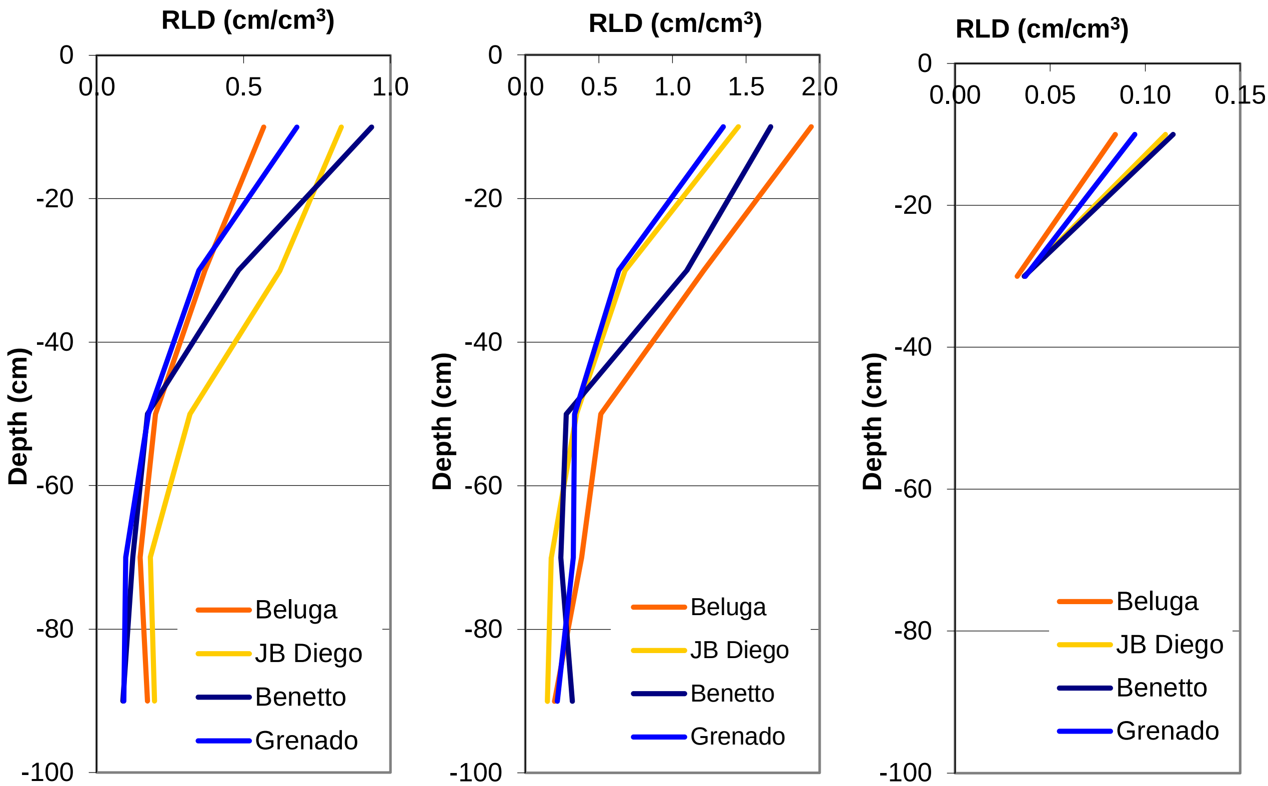

Figure 14. Effects of variety on root length density at 0–100 cm depth at HM12 and HM13, and 0–40 cm depth at HM14 (first cereal position).

4.10. Grain quality

Each field season, protein concentration was tested on all grain samples and a subset of grain samples were tested for fibre and starch. There was wide variation in grain quality by site, year and rotational position. Across all sites and years no significant differences in grain fibre or starch percentage were observed between triticale and wheat, however wheat was shown to possess a significantly greater crude protein fraction ; at a standard N rate (180 kg N/ha) wheat grain contained 0.69% more protein, on average (11 experiments; Table 25). There were also often differences between the varieties within species. In wheat, JB Diego always had higher protein concentrations than Beluga, and in the vast majority of cases both wheat varieties gave higher levels than both triticale varieties (Table 25). The relative differences between the triticale varieties in their protein concentrations were more variable. On average, Grenado had slightly (0.06%) higher protein concentrations than Benetto but the range was between 0.64% lower and 0.23% higher (Table 25) depending on season, rotational position and N rate.

Amino acid content also showed significant variation (Table 26), however levels of individual amino acids as a proportion of the crude protein fragment in triticale were mostly 90% of their respective levels in wheat or higher. The similarity in amino acid levels by protein was somewhat confounded by the reduced protein content in triticale, meaning that amino acid levels by proportion of dry matter were slightly lower in triticale compared to wheat. However, these again were comparable and (with the exception of tryptophan) were again present in triticale at 90% of their respective level in wheat or higher.

Table 25. Effect of season, rotation and Nitrogen rate on Grain Protein (%), Crude Fibre (%) and Starch (%) content of triticale and wheat, and the standard varieties tested. N.B. Averages for triticale and wheat may include varieties other than the four specified and so may not equal the mean of the two varieties specified.

	Protein (%)				**Crude Fibre (%)**				**Starch (%)**			
	Triticale		**Wheat**		**Triticale**		**Wheat**		**Triticale**		**Wheat**	
	Benetto	Grenado	Beluga	JB Diego	Benetto	Grenado	Beluga	JB Diego	Benetto	Grenado	Beluga	JB Diego
Average at standard N rate (~180kg N/ha)												
	10.92		11.61		2.20		2.25		57.85		60.16	
	11.06	11.12	11.90	11.89	2.30	2.10	1.90	2.60	57.20	58.20	61.60	58.60
Seasonal variation (standard N rate)												
2011	11.52		12.34		2.20		2.50		58.90		58.60	
	11.08	11.22	11.54	11.62	2.37	1.98		2.54	57.20	60.20	-	58.62
2012	10.88		11.92		2.30		2.40		58.10		60.50	
	10.48	10.26	11.08	11.25	2.54	2.30	2.02	3.08	57.76	59.52	61.96	58.32
2013	11.43		11.39		2.20		2.20		56.70		60.70	
	10.94	10.42	10.59	10.77	2.50	2.25	2.00	2.60	55.47	57.25	60.60	60.10
2014	9.53		9.91		2.03		2.10		57.98		60.03	
	-	-	-	-	2.17	1.87	1.78	2.21	58.08	58.81	60.67	58.89
Rotational variation												
1st cereal	10.25		10.79		2.15		2.21		59.56		61.47	
	10.18	10.12	10.60	10.84	2.22	1.86	1.79	2.38	59.05	60.75	60.80	59.51
2nd cereal	11.51		12.40		2.27		2.42		56.54		58.22	
	10.79	11.02	11.56	11.64	2.43	2.13	1.93	2.58	56.53	58.25	61.18	58.39
Variation with N rate												
0 kg N/ha	8.14		8.25		2.12		2.15		60.77		60.81	
	8.32	7.69	8.00	8.13	2.30	1.97	1.88	2.36	59.61	61.88	60.74	61.88
~180 kg N/ha	10.92		11.61		2.20		2.25		57.85		60.16	
	11.06	11.12	11.90	11.89	2.30	2.10	1.90	2.60	57.20	58.20	61.60	58.60
~350 kg N/ha	12.18		12.84		2.20		2.26		55.65		56.74	
	12.27	12.37	13.06	13.04	2.33	2.07	1.70	2.63	54.87	56.43	57.35	56.33

Table 26. Effect of season, rotation and Nitrogen rate on Amino acid fractions of crude protein of triticale and wheat, and the standard varieties tested. N.B. Averages for triticale and wheat may include varieties other than the four specified and so may not equal the mean of the two varieties specified.

	MET (% CP)				ILE (% CP)				THR (% CP)				M+C (% CP)			
	Triticale		Wheat		Triticale		Wheat		Triticale		Wheat		Triticle		Wheat	
	Benetto	Grenado	Beluga	JB Diego	Benetto	Grenado	Beluga	JB Diego	Benetto	Grenado	Beluga	JB Diego	Benetto	Grenado	Beluga	JB Diego
Average at standard N rate (~180kg N/ha)																
	1.60		1.50		3.24		3.29		3.05		2.82		3.86		3.70	
	1.59	1.57	1.51	1.49	3.24	3.24	3.29	3.30	3.04	2.99	2.84	2.82	3.86	3.80	3.70	3.69
Seasonal variation (standard N rate)																
2011	1.55		1.48		3.24		3.33		2.97		2.79		3.82		3.68	
	1.56	1.55	1.50	1.47	3.21	3.20	3.31	3.30	2.97	2.93	2.82	2.79	3.85	3.80	3.75	3.65
2012	1.62		1.47		3.24		3.28		3.09		2.80		3.88		3.59	
	1.66	1.65	1.59	1.57	3.26	3.25	3.31	3.33	3.20	3.16	2.96	2.95	3.96	3.92	3.84	3.82
2013	1.59		1.55		3.23		3.29		3.01		2.87		3.85		3.82	
	1.62	1.55	1.56	1.64	3.23	3.23	3.32	3.22	3.05	2.93	2.86	3.05	3.93	3.80	3.82	3.98
2014	1.61		1.52		3.23		3.25		3.03		2.81		3.90		3.73	
	1.67	1.64	1.57	1.57	3.29	3.18	3.28	3.28	3.20	3.11	2.91	2.89	3.94	3.98	3.85	3.83
Rotational variation																
1st cereal	1.61		1.48		3.23		3.30		3.06		2.81		3.89		3.71	
	1.63	1.61	1.57	1.55	3.23	3.20	3.29	3.33	3.11	3.05	2.92	2.93	3.93	3.91	3.84	3.81
2nd cereal	1.57		1.49		3.25		3.30		3.00		2.80		3.80		3.65	
	1.60	1.59	1.53	1.49	3.24	3.23	3.32	3.30	3.07	3.03	2.87	2.83	3.89	3.83	3.77	3.69
Variation with N rate																
0 kg N/ha	1.68		1.63		3.19		3.31		3.21		3.03		4.05		3.97	
	1.69	1.67	1.66	1.61	3.20	3.18	3.36	3.28	3.24	3.20	3.06	3.04	4.04	4.02	4.04	3.93
~180 kg N/ha	1.59		1.50		3.24		3.30		3.04		2.81		3.86		3.70	
	1.59	1.57	1.51	1.49	3.24	3.24	3.29	3.30	3.04	2.99	2.84	2.82	3.86	3.80	3.70	3.69
~350 kg N/ha	1.56		1.48		3.27		3.29		2.98		2.79		3.74		3.64	
	1.56	1.55	1.52	1.50	3.28	3.26	3.25	3.33	3.00	2.97	2.86	2.82	3.75	3.71	3.70	3.65

Table 26 (continued). Effect of season, rotation and Nitrogen rate on Amino acid fractions of crude protein of triticale and wheat, and the standard varieties tested (continued). N.B. Averages for triticale and wheat may include varieties other than the four specified and so may not equal the mean of the two varieties specified.

	LEU (% CP)				**HIS (% CP)**				**PHE (% CP)**				**VAL (% CP)**			
	Triticale		**Wheat**		**Triticale**		**Wheat**		**Triticale**		**Wheat**		**Triticle**		**Wheat**	
	Benetto	Grenado	Beluga	JB Diego	Benetto	Grenado	Beluga	JB Diego	Benetto	Grenado	Beluga	JB Diego	Benetto	Grenado	Beluga	JB Diego
Average at standard N rate (~180kg N/ha)																
	6.45		6.60		2.30		2.30		4.59		4.56		4.26		4.17	
	6.42	6.41	6.58	6.64	2.30	2.29	2.29	2.30	4.54	4.56	4.62	4.62	4.33	4.28	4.19	4.19
Seasonal variation (standard N rate)																
2011	6.46		6.70		2.31		2.30		4.55		4.67		4.27		4.20	
	6.39	6.38	6.68	6.67	2.29	2.28	2.29	2.28	4.43	4.50	4.60	4.62	4.27	4.23	4.24	4.18
2012	6.44		6.58		2.29		2.29		4.56		4.64		4.36		4.13	
	6.47	6.45	6.63	6.73	2.31	2.31	2.30	2.32	4.47	4.54	4.55	4.53	4.48	4.41	4.29	4.31
2013	6.47		6.61		2.32		2.33		4.71		4.45		3.96		4.22	
	6.43	6.45	6.59	6.44	2.33	2.29	2.32	2.29	4.70	4.63	4.53	4.48	4.33	4.19	4.22	4.32
2014	6.38		6.57		2.29		2.30		4.61		4.51		4.30		4.16	
	6.42	6.35	6.58	6.61	2.25	2.30	2.35	2.33	4.54	4.59	4.47	4.48	4.49	4.36	4.28	4.25
Rotational variation																
1st cereal	6.46		6.69		2.30		2.31		4.54		4.63		4.34		4.20	
	6.42	6.37	6.63	6.72	2.29	2.29	2.28	2.31	4.43	4.50	4.54	4.56	4.39	4.33	4.28	4.30
2nd cereal	6.44		6.61		2.30		2.29		4.60		4.63		4.28		4.16	
	6.43	6.44	6.66	6.67	2.30	2.30	2.31	2.29	4.50	4.55	4.58	4.58	4.36	4.31	4.26	4.20
Variation with N rate																
0 kg N/ha	6.43		6.75		2.30		2.32		4.40		4.33		4.45		4.40	
	6.41	6.41	6.76	6.75	2.28	2.32	2.34	2.31	4.34	4.41	4.41	4.33	4.50	4.44	4.46	4.38
~180 kg N/ha	6.45		6.63		2.30		2.30		4.58		4.59		4.27		4.18	
	6.42	6.41	6.58	6.64	2.30	2.29	2.29	2.30	4.54	4.56	4.62	4.62	4.33	4.28	4.19	4.19
~350 kg N/ha	6.47		6.57		2.28		2.27		4.62		4.66		4.26		4.14	
	6.46	6.44	6.51	6.65	2.29	2.28	2.25	2.29	4.57	4.63	4.64	4.71	4.30	4.24	4.15	4.19

Table 26 (continued). Effect of season, rotation and Nitrogen rate on Amino acid fractions of crude protein of triticale and wheat, and the standard varieties tested (continued). N.B. Averages for triticale and wheat may include varieties other than the four specified and so may not equal the mean of the two varieties specified.

	ARG (% CP)				**LYS (% CP)**				**CYS (% CP)**				**TRP (% CP)**			
	Triticale		**Wheat**		**Triticale**		**Wheat**		**Triticale**		**Wheat**		**Triticle**		**Wheat**	
	Benetto	Grenado	Beluga	JB Diego	Benetto	Grenado	Beluga	JB Diego	Benetto	Grenado	Beluga	JB Diego	Benetto	Grenado	Beluga	JB Diego
Average at standard N rate (~180kg N/ha)																
	4.89		4.85		3.25		2.82		2.26		2.19		1.12		1.25	
	4.89	4.82	4.88	4.78	3.22	3.12	2.88	2.80	2.26	2.23	2.18	2.18	1.11	1.13	1.23	1.22
Seasonal variation (standard N rate)																
2011	4.88		4.80		3.05		2.75		2.26		2.20		1.11		1.23	
	4.88	4.81	4.85	4.76	3.10	3.05	2.83	2.73	2.29	2.25	2.22	2.17	1.13	1.10	1.24	1.22
2012	4.94		4.84		3.35		2.77		2.26		2.11		1.12		1.26	
	5.07	4.96	5.00	4.96	3.56	3.46	3.10	3.03	2.30	2.27	2.25	2.25	1.13	1.10	1.18	1.20
2013	4.82		4.94		3.12		2.94		2.26		2.27		1.09		1.28	
	4.88	4.77	4.91	4.96	3.22	3.01	2.95	3.33	2.31	2.25	2.26	2.34	1.08	1.14	1.25	1.23
2014	4.75		4.69		3.13		2.76		2.28		2.18		1.11		1.23	
	5.05	4.78	4.96	4.87	3.56	3.28	2.97	2.90	2.27	2.34	2.26	2.23	1.10	1.13	1.27	1.28
Rotational variation																
1st cereal	4.96		4.83		3.29		2.79		2.28		2.22		1.12		1.27	
	5.00	4.87	4.91	4.93	3.40	3.30	3.03	2.97	2.31	2.30	2.26	2.25	1.12	1.11	1.20	1.21
2nd cereal	4.84		4.81		3.11		2.77		2.23		2.16		1.12		1.23	
	4.94	4.86	4.93	4.80	3.27	3.19	2.91	2.80	2.28	2.25	2.23	2.18	1.12	1.11	1.24	1.23
Variation with N rate																
0 kg N/ha	5.06		5.12		3.65		3.21		2.38		2.33		1.19		1.38	
	5.10	5.00	5.19	5.09	3.70	3.61	3.25	3.17	2.35	2.35	2.37	2.30	1.20	1.16	1.34	1.35
~180 kg N/ha	4.89		4.84		3.21		2.81		2.26		2.19		1.11		1.25	
	4.89	4.82	4.88	4.78	3.22	3.12	2.88	2.80	2.26	2.23	2.18	2.18	1.11	1.13	1.23	1.22
~350 kg N/ha	4.82		4.68		3.07		2.75		2.18		2.15		1.08		1.16	
	4.86	4.75	4.70	4.77	3.09	3.02	2.91	2.77	2.18	2.16	2.17	2.14	1.11	1.08	1.11	1.14

Grain quality for bioethanol production

The Innovate UK Project was funded with the aim of understanding the value of triticale DDGS (Distillers' Dried Grains with Soluble) from bioethanol production as an animal feed. However, it was not possible to process any triticale through the bioethanol plant and so there was no DDGS to test. It was investigated if a model (Olukosi & Adebiyi, 2013) that predicts the amino acid content of DDGS of wheat could be used to predict the same for triticale. However, the data required for that model is the protein content of DDGS rather than the grain, and a robust approach to estimate DDGS protein from wheat grain protein was not found. Nevertheless, it seems that the amino acid profile of triticale is not different enough to that of wheat to expect a substantially different composition of DDGS.

Grain quality for pig feed

To understand the implications of the grain quality results from the Innovate UK project for pig nutrition, work was commissioned by AHDB Pork. The project aimed to demonstrate the economic value of triticale grain in grower and finisher pig rations, using grain samples and analyses generated in separate Innovate UK and AHDB Cereals & Oilseeds projects. Grain samples from experiments comparing triticale and wheat were analysed for Dry Matter (DM; %), Total oil (Oil B; %), Ash (%), Neutral Detergent Fibre (%) and Crude Protein (N x 6.25; Dumas; %) and Pig DE (MJ/kg) and Pig NE (MJ/kg) were calculated. Amino Acid contents were also determined and Standardised Ileal Digestibility calculated. Grower (30-60 kg) and Finisher (60-100kg) diets were 'least cost' formulated using raw materials prices from 2014 and 2015. Diets were run under different scenarios: Run 1 – wheat only, no triticale offered; Run 2 – no restrictions; Run 3 – 30% forced in wheat; Run 4 – restrict triticale to max. 20% (growers) or 25% (finishers); and Run 5 – restrict triticale, restrict barley 30% max., min 15% hipro soya. The diets were also run using a £5 and £0/t price differential between wheat and triticale and no other restrictions. Calculated Pig DE levels were slightly higher for triticale (16.33 MJ/kg) than wheat (16.30 MJ/kg) on a DM basis but slightly lower for triticale (14.57 MJ/kg) than wheat (14.59 MJ/kg) on an as fed basis. Pig NE (as fed) was 0.01 MJ/kg lower for triticale than wheat. Ration formulations showed some cost savings when using triticale (assuming a £10/t discount to wheat) but these are dependent on costs of other raw materials; triticale was able to make greater cost savings in the finisher diet when raw material prices were more expensive. Where diets were formulated with no cereal minimum/maximum level set (run 2), triticale was the preferential cereal used with subsequent diet cost savings compared to diets formulated with wheat only (run 1). When the diets were run using a £5 and £0/t price differential between wheat and triticale, the grower diet used triticale as the preferential cereal, but the finisher diet replaced triticale with wheat when the wheat price was equal to triticale. Further work is required on the perceived negative effects of feeding triticale due to anti-nutritional factors and also current diet inclusion limits.

4.11. Bioethanol yields and greenhouse gas savings

Grain samples from the project experiments were taken and bioethanol yields determined for wheat and triticale grain at ADAS (2011 and 2012 samples) and Südzucker (2014 samples). The ADAS results did not show a significant difference between the alcohol yields of triticale and wheat, but the Südzucker results showed triticale to give a lower alcohol yield than wheat (Figure 15). This is in contrast to results found in previous studies (Weightman *et al*., 2011). The relationship between protein and alcohol yield is also much poorer than in previous studies (Smith *et al*., 2006; Kindred *et al*., 2008; Sylvester-Bradley *et al*., 2010). When the data were combined, analyses indicated that the alcohol yields for triticale were generally slightly lower than wheat for the experiments tested.

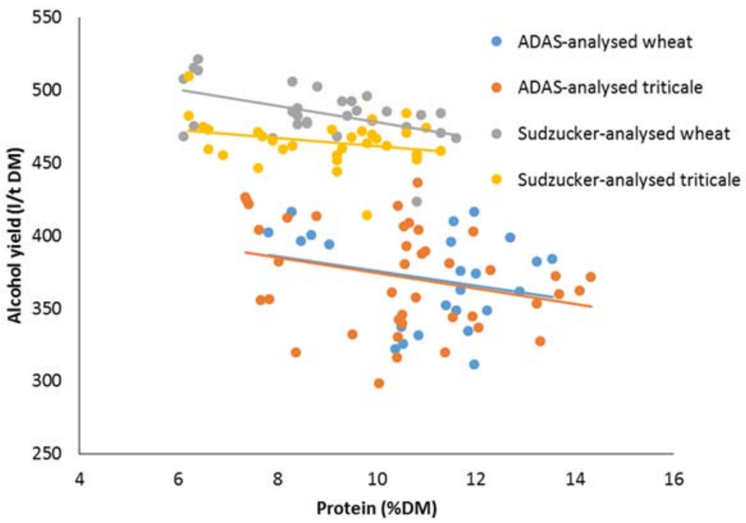

Figure 15. The relationship between grain protein concentration and alcohol yields of grain samples analysed by ADAS (grain from 2011 and 2012 harvest season experiments) and Sudzucker (grain from 2014 harvest season experiment). Grain samples were taken from experiments described above.

Previous work has shown a good relationship between grain protein and alcohol yield (Sylvester-Bradley *et al*., 2010) so bioethanol yields are calculated using the formulas below. However, due to the results indicating a difference between species, the intercept of the relationship was adjusted for triticale based on regression analyses of the alcohol yield data from these experiments:

Wheat: Bioethanol (l/t) = 520 – (7.2 x % protein)

Triticale: Bioethanol (l/t) = 509 – (7.2 x % protein)

Bioethanol yields were then expressed per ha, using grain yield data. Despite the difference in relationship between bioethanol yields and grain protein of the different species, estimated bioethanol production per ha was higher for triticale varieties than wheat varieties (Figure 16), principally because of the higher grain yield of triticale.

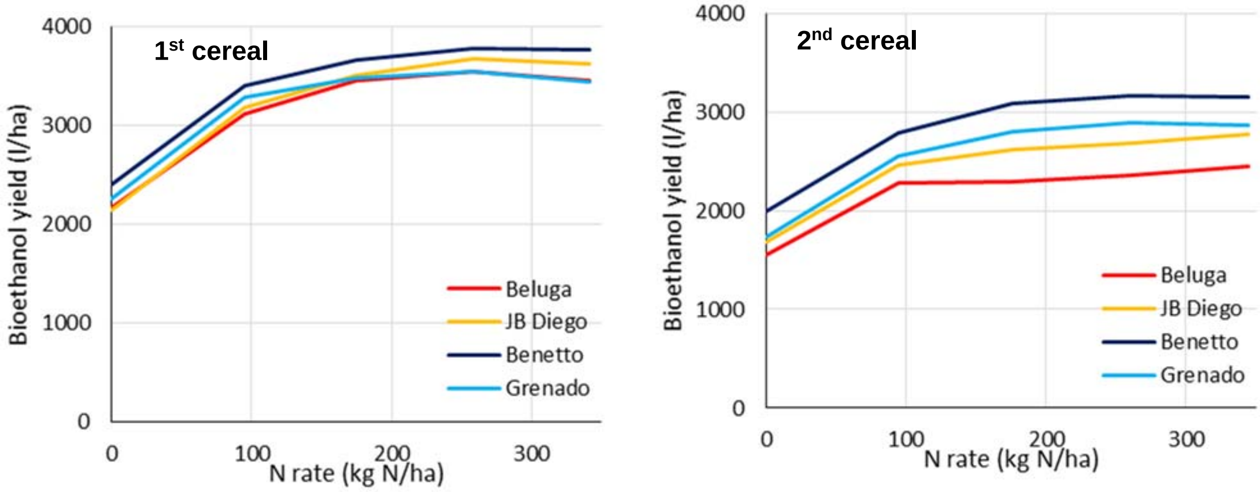

Figure 16. Bioethanol yield (l/ha) of wheat varieties Beluga and JB Diego and triticale varieties Benetto and Grenado, averaged across six 1st cereal experiments and seven 2nd cereal experiments.

Greenhouse gas emissions were calculated using the assumptions listed in Table 27, combined with N rates and grain or bioethanol yields. Greenhouse gas emissions per t grain produced (Figure 17) and per l bioethanol (Figure 18) were lower for triticale than for wheat, because triticale produced more grain and therefore more bioethanol then wheat at a given N rate.

Table 27. Assumptions used to calculate greenhouse gas emissions. Figures are taken from Sylvester-Bradley et al., (2015).

Input	Emissions per ha (kg CO_2e)	Emissions per kg N used (kg CO_2e)
Diesel	310	
Agrochemicals	81	
P, K and lime	292	
Seed	123	
N_2O emissions from residues	365	
N fertiliser manufacture		3.4
N_2O emissions from fertiliser		6.205

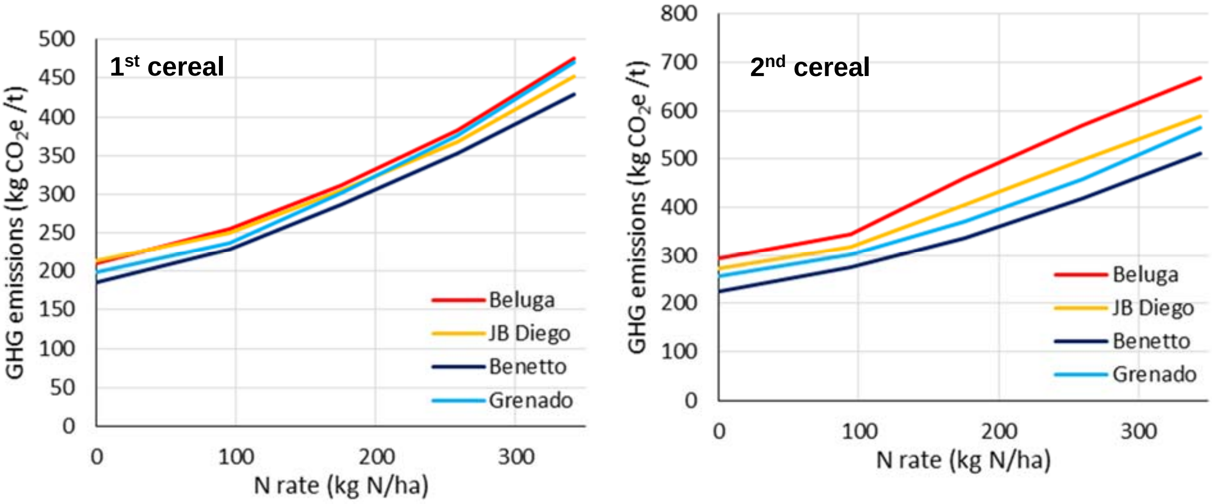

Figure 17. Greenhouse gas (GHG) emissions (kg CO_2e) per t grain, for wheat varieties Beluga and JB Diego and triticale varieties Benettp and Grenado, averaged across six 1st cereal experiments and seven 2nd cereal experiments.

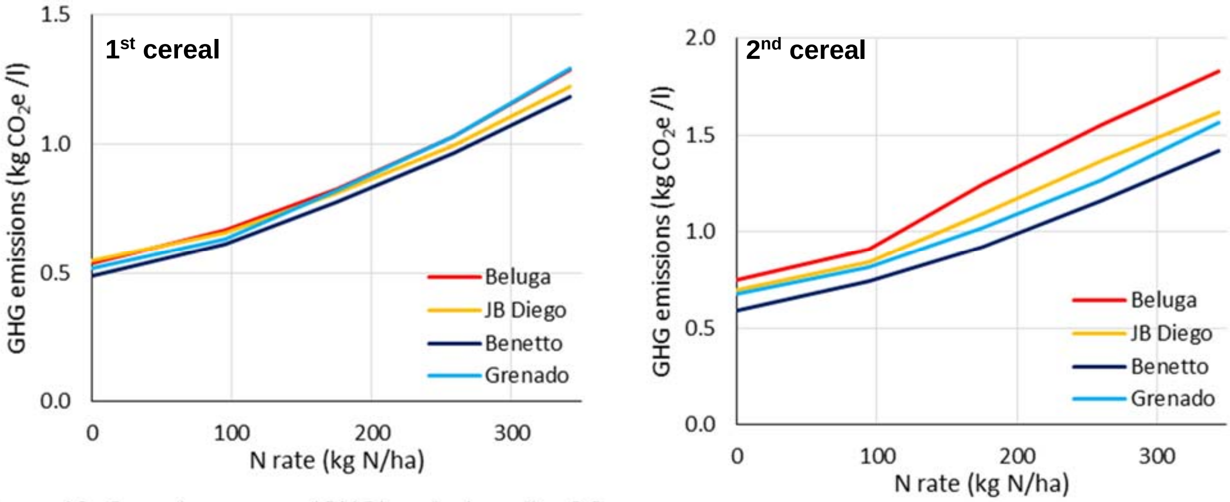

Figure 18. Greenhouse gas (GHG) emissions (kg CO_2e) per l bioethanol, for wheat varieties Beluga and JB Diego and triticale varieties Benettp and Grenado, averaged across six 1st cereal experiments and seven 2nd cereal experiments.

4.12. Gross margin analysis

An exercise was carried out to compare the likely gross margins of typical wheat and triticale crops grown as second cereals (Table 28). The grain yield of the second wheat is the average seen in the UK, and the yield of triticale is based on the average advantage seen over 16 trials (8% yield advantage). The relative grain price is what is typically applied to triticale i.e. a £10/t discount compared to wheat. The lower price of triticale means that, although it gives a higher yield, the total grain outputs for the two crops are similar. The improved gross margin of the triticale comes from its higher straw yield and lower cost of inputs.

Table 28. Gross margin analysis for a typical wheat and triticale crop grown as a second cereal.

	2nd Wheat	Triticale
Grain yield (t/ha)	*7.5*	*8.1*
Grain price	£130	£120
Grain output (£/ha)	**£975**	**£972**
Straw output (£/ha)	**£140**	**£151**
Variable costs (£/ha)		
Seed & treatment	£70	£70
N fertiliser	£174	£174
Other fertilisers	£80	£86
Fungicides	£100	£70
Insecticides/ herbicides	£70	£70
PGRs	£15	£20
Total variable costs (£/ha)	**£509**	**£490**
Gross margin (£/ha)	£606	£633
Triticale advantage (£/ha)		**£27**

Typical variable costs have been applied to the wheat and triticale crops. Table 28 gives the yield advantage of triticale compared to wheat when the same N rate is applied. If a 40 kg N/ha lower N rate was applied to this example crop, the associated yield would be similar to that of the wheat (7.5 t/ha). Fungicide costs are lower for triticale as the crop is not susceptible to septoria tritici which is generally more expensive to control than yellow rust, which many triticale varieties are susceptible to. The difference in the 'other fertiliser' category is due to the higher offtake of phosphorous and potassium in triticale which would need to be replaced. Generally, PGR costs will be higher for triticale because triticale is around 20cm taller than wheat and has larger ears. Although triticale varieties generally have stiff straw, their height and ear size means that they are more prone to lodging than wheat.

Overall, it can be seen that growing triticale as opposed to a second wheat can make financial sense. The higher yield offsets the lower grain price and, even without the greater straw production, the lower input costs mean a greater gross margin for triticale.

4.13. Tramline trials

All farmers reported higher yields of triticale than wheat in their test fields. The experiences of two of the farmers were documented in case studies and yield maps were taken.

James and Sam Daw farm near Rugeley, Staffs., and compared triticale on two fields (light and heavy soils) and measured yields using yield mapping and a weighbridge.

On the light-land field, triticale was compared with a breadmaking wheat. Both species were established with the same seed rate (150 kg/ha), but James reported that ‘the triticale got ahead quicker and was always more advanced’ than the wheat.

The triticale received less nitrogen than the wheat; 30 kg N/ha less during the growing season and it did not receive the late 40 kg N/ha designed to increase protein concentration in the wheat. Despite this, the triticale gave higher yields. Weighbridge measurements showed the wheat yielded 5.9 t/ha and the triticale 9.1 t/ha with James commenting ‘I’ve never seen so much straw.’

Difficult conditions at establishment hampered drilling of the feed wheat and triticale on the heavy land field, but both crops established, albeit not as well as hoped. This was a 2nd cereal situation but there was no take-all evident in the wheat. ‘If take-all had been a problem in that field you would have seen a bigger advantage of triticale’ says James. When it came to harvest the triticale again out-yielded the wheat, this time by 0.75 t/ha.

James and Sam found no particular disease problems in the triticale, despite high pressure in the wheat, and they applied the same PGR programme to both species. ‘The biggest problem was the marketing’ says James. ‘Because 2014 was such a good season everyone wanted the grain cheaper so the merchants we spoke to heavily discounted the price of triticale’. ‘But we would certainly grow triticale again if the market was right’ he added.

Table 29. Yields of triticale and wheat in two fields of James Daw (Rugeley, Staffs.). Data are cleaned data from combine yield maps

Field	Triticale average yield (t/ha @ 15% mc)	Wheat average yield (t/ha @ 15% mc)
Princes (heavy soi)	9.89	8.74
Goldihays (light soil)	9.66	8.54

James Robinson farms near Peterborough, and compared triticale (Ragtac) to Relay feed wheat on a clay loam soil as a second cereal.

The wheat and triticale were established using the same methods and drilled at the end of September. The seed rate of the two crops were very similar – around 125 kg/ha. 'The triticale got away faster and looked more competitive right the way through the winter', says James. 'It had good ground cover'.

James tested two rates of nitrogen on different areas of the triticale – a standard rate the same as the wheat (220 kg/ha), and a half rate. 'The half rate looked a bit thin', he commented. 'If we did it again I think it would be OK to reduce the nitrogen by a quarter. I'd be a bit worried about it falling over if we put the full rate on'.

But the triticale did not suffer from lodging in the trial season. It received the same PGR programme as the wheat which comprised two applications – one in March and one in April.

It also received the same herbicide and fungicide regime as the wheat, and didn't suffer from any problems. 'Relay is susceptible to yellow rust, and there was a bit in the relay but it did not transfer into the triticale', reported James.

James applied Roundup pre-harvest and combined the triticale a couple of days later than the wheat on the 19th August. 'You could feel that there was a lot more going through the combine with the triticale. The volume was there but it didn't weigh as much as I'd expected – I think it had a low specific weight', he commented. James also reported that the straw was still quite green at harvest so they weren't able to bale it as they'd hoped

Overall, James was happy with how the triticale compared to the wheat. 'It was interesting watching it. It didn't cause me any trouble because I dealt with it like wheat. If it was proven to be good quality for poultry we would use it for our turkeys, and the straw would be useful'.

5. Conclusions and recommendations for further work

The work reported here clearly demonstrates that triticale regularly out-yields wheat across a range of soils, years and locations in both plot trials and field comparisons, by an average of 3% for first cereals and 8% in the second cereal position. This conclusion was not necessarily expected by the authors at our outset and is counter to common perceptions in the arable industry. The evidence points to triticale being a suitable alternative to wheat or barley in livestock diets and a satisfactory feedstock for bioethanol if its price was right and if there was sufficient supply for its use in the market.

This therefore raises some important questions and opportunities: if triticale was grown instead of wheat across 25% of the current UK wheat area (over half of current wheat production is used for animal feed) of 2 Mha and an average 5% yield advantage was achieved an additional 200,000 t of grain production would be expected, worth £24M per year to UK farmers at £120/t. It therefore seems worthwhile for the industry to spend some effort developing the market opportunities for triticale for the feed industry, by properly quantifying its value in a range of pig, poultry and ruminant diets. There is unlikely to be sufficient additional benefit from triticale for it to attract a premium or even to actively be sought out, but if it is priced at a slight discount to wheat then feed compounders are likely to be able to profitably use it, so long as there is sufficient volume available to make its inclusion worthwhile.

Given the results from the earliest experiment in 2009, where triticale had an N optima 20% lower than wheat despite a 20% higher yield, we were expecting subsequent studies to confirm the widely held assumption that triticale has a lower N requirement than wheat. The N response experiments reported here however have not provided evidence of lower N optima for triticale than wheat: from the responses the safest conclusion is that triticale achieves a higher yield without a higher nitrogen requirement. This contrasts however with conclusions from a separate ADAS study funded by Defra (Sylvester-Bradley *et al.*, in press) which compared N responses of 20 wheat varieties and one triticale (Grenado) across five site seasons in 2011 and 2012. Cross-site analysis here showed triticale to give among the lowest optima despite achieving among the highest yields of all varieties tested. It was concluded that triticale, alongside the Danish variety Mariboss, exhibit High Yield and Low Optima (HYLO) characteristics. The reasons for the different conclusion in N optima between the HYLO study and the reported work here could be due to the wider set of varieties tested in the HYLO work, and perhaps a difference in N optima between Grenado and Benetto: Grenado was seen to have a slightly lower optima in this study. Given the uncertainty here, and because of the greater risk of lodging with triticale, we have continued to advise growers to use a lower N rate for triticale than they would otherwise use for feed wheat. The Growers report suggests a reduction of 40 kg/ha compared to wheat, but there is considerable uncertainty in this. The experimental evidence would suggest that this is limiting triticale yields slightly below their optimum. Newer triticale varieties are generally shorter and more lodging resistant than Grenado and Benetto, but are still likely to be more lodging-prone than most wheat varieties. The question of how much less N should be applied to triticale relative wheat is therefore somewhat dependent on the attitude to the risk of the farmer, and our recommendation of 40 kg/ha less is rather arbitrary.

We have made some progress with understanding the physiological basis of the greater yield of triticale. It is clearly due to achieving a higher total biomass rather than through greater portioning to the grain; the harvest index of triticale is invariably lower. This greater total growth may be in part due to earlier development in triticale, starting stem extension earlier thus intercepting more light more quickly. Flowering is also reached more quickly in triticale, but maturity date is only slightly earlier, giving a longer duration for grain-filling.

Light interception of triticale is greater than wheat, though the GAI of triticale is not always greater. This implies a higher extinction co-efficient for triticale, each unit of GAI intercepting more light than wheat. This may be due to the greater height of triticale and greater ear size (including awns) giving a different canopy structure.

Triticale takes up more N than wheat. Grain N concentration of triticale is generally lower than that for wheat, indicating a higher N utilisation efficiency for triticale.

Contrary to expectations, there is little evidence that triticale has a bigger or deeper root system, though Benetto perhaps has more roots at the surface.

Triticale varieties generally showed lower incidence of take-all, with Benetto the least affected. However, variation in Take-All was great between seasons and rotational positions, with the difference between wheat and triticale being relatively small.

Triticale generally had lower grain protein concentrations than wheat, meaning that the amino acid contents, which were generally comparable to wheat on a % protein basis, were actually lower than wheat on a dry matter basis. However, as expected, lysine contents were slightly higher in triticale than wheat. There was also variety variation within species in the grain quality parameters measured. Specific weight is generally lower in triticale than in wheat, sometimes by a considerable margin. The importance of specific weight for animal feed value may be marginal but at the least it does affect how much grain can be stored in a bin, which may have real financial and logistical implications within the grain trade.

Alcohol yield results were inconsistent between years and testing labs, but when results were combined, triticale appeared to have a lower alcohol yield per tonne than wheat. However, when data were analysed on a per hectare basis, triticale gave higher yields because of its greater yields. These higher yields also led to greenhouse gas savings for triticale compared to wheat on a per tonne and per hectare basis, especially when grown as a second cereal. It therefore seems that triticale should be a valuable feedstock for bioethanol production, if its price is competitive.

5.1. Recommendations for further work

- A small number of on-farm trials of triticale have shown that triticale can out-yield wheat. Further large-scale trials should be carried out in different situations and grain taken through the feed or bioethanol supply chains to further illustrate the advantages of triticale and demonstrate this to the wider industry.
- Although take-all was measured in the experiments reported here, results were unclear. Further work to understand the differences between wheat and triticale in terms of their resistance or tolerance of take-all would be useful.
- The experiments reported here did not include investigations into weeds. The smothering ability of triticale vs. wheat and potential reduction in weed population should be investigated, as well as chemical weed control options.
- Yellow rust can be a problem in certain varieties of triticale, but this was not investigated in the project reported here. It is generally assumed that disease control is cheaper and easier in triticale but this should be investigated further.
- General optimal agronomic management of triticale requires further work, especially with regard to optimal spend on fungicides (including SDHIs) and PGRs.
- There is a real need to understand the underlying physiological cause of the greater yield achieved by triticale than wheat. Measurements here have started to provide some answers, but more detailed and comprehensive measures are needed to fully explain the difference, including measures of photosynthetic rate, respiration, sink strength etc. It is important to understand the cause of this in order to best target agronomic and genetic improvement of the wheat crop.
- There is a pressing need to engage the whole supply chain in the development of markets for triticale, especially for animal feed. This is somewhat difficult due to the lack of large financial benefit to the grain trade or to animal feed compounders, and the potentially disruptive logistical requirements for dealing with an additional crop eg for separate storage. However, the potential benefits to farmers through increased yields, reduced inputs and lower feed costs warrant co-ordinated action from industry representatives such as AHDB.

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