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Martin, Peter; Shah, S.s.m.; Chang, X

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Effect of nitrogen, phosphorous, potassium, plant growth regulator and artificial lodging on grain yield and grain quality of a landrace of barley

S.S.M. Shah [a], X. Chang [b*], and P. Martin [c]

[a] Agrii, Andoversford, Cheltenham, GL54 4LZ, UK
[b] Royal Agricultural University, Cirencester, GL7 6JS, UK
[c] The Agronomy Institute, Orkney College, UHI, KW15 1LX, UK
* Corresponding author e-mail address: Xianmin.chang@rau.ac.uk

Abstract

Landraces of different crops are still preferred due to their stable yields under low inputs and adverse climatic conditions to which most modern varieties are not adapted. In the UK, a landrace of barley called *Bere* is currently grown in extreme climatic conditions of Orkney to which most of the modern varieties are not adapted. Although this landrace is probably the oldest barley under cultivation in the UK, very little research has been conducted. In this paper the effects of nitrogen, phosphorous, potassium, plant growth regulator and artificial lodging on grain yield and quality of Bere were investigated in the Orkney's short growing season. Higher nitrogen application resulted in a higher lodging incidence but grain yield was not reduced by the severity of lodging. The artificial lodging applied at Zadoks growth stage 77 resulted in the greatest yield losses which indicated that control measures may be required to avoid lodging at this critical growth stage. Phosphorous and potassium had no significant effect on lodging resistance. Whilst plant growth regulator improved lodging resistance it was less effective in controlling lodging at the highest nitrogen level (90 kg ha^{-1}). The trials indicated that higher level of N caused marginal increase in grain yield when nitrogen level was raised from 45 kg to 90 kg ha^{-1}. This tended to suggest the use of medium N-level (45 kg N ha^{-1}) for producing Bere. Plant growth regulator increased lodging resistance but had an inconsistent effect on grain yield. This study recommended the use of plant growth regulator as a means of easing harvesting rather than for enhancing yield and quality. The study concluded that phosphorous and potassium could be used to improve disease resistance and grain yield but not for lodging control.

Key words: Landrace, Bere, nitrogen level, plant growth regulator, artificial lodging

1.0 Introduction

Until the arrival of modern plant breeding in the 19th Century, landraces and old varieties significantly contributed to meeting the world food needs (Harlan, 1975). However, the development of high yielding modern varieties led to the virtual disappearance of landraces in the 20th Century in developed countries (Newton *et al.,* 2009). In several developing countries and a few peripheral areas in developed countries, landraces of different crops are still preferred due to their stable yields under low inputs and adverse climatic conditions to which most modern varieties are not adapted (Pswarayi *et al.,* 2008). In Orkney, Scotland, a landrace of barley, Bere, is cultivated on a very small scale for milling (Theobald *et al.,* 2006) and to supply a niche market for distilling (Martin and Chang, 2008; Martin, Wishart and Scott, 2013; Martin and Wishart, 2015). It has been reported that growing season in Orkney is short (4 to 5 months) (Bond and Hunter, 1987). The wetness of the climate coupled with low temperature can complicate early field preparation and sowing. Harvesting can become increasingly difficult through September as a result of increasing rainfall. Most of the modern varieties are not suitable to produce grain crop in the short growing season of Orkney. The best strategy would be planting of a short duration variety which can make rapid growth. Bere grows rapidly in spring and matures early (Martin and Chang, 2008) and this is probably one of the reasons why a few farmers still grow Bere in Orkney. However, farmers are generally concerned about its susceptibility to lodging due to its long and weak straw (Peachy, 1951; Martin *et al*., 2008). Lodging is undesirable because of its detrimental effects on grain yield and quality (Pinthus, 1973; Stanca *et al.,* 1979; Birggs, 1990). Plant growth regulator (PGR) can reduce stem length and improve the standing ability of the barley (Kust, 1985; Sanvicente *et al.,* 1999) and wheat (Jung, 1964; Tripathi *et al.,* 2003). A few researches have used phosphorous (P) and potassium (K) for controlling lodging (Casserly, 1957; Arnold *et al.*, 1974). However, the effect of these treatments under a range of N-levels has not been investigated on Bere. There are also no published estimates of lodging related yield losses that could help to predict cost and benefits of integrating lodging control measures. It is difficult to accurately estimate yield and quality losses caused by lodging under natural conditions due to the unpredictable nature of lodging events (Kelbert *et al.,* 2004). Several researchers have used artificial lodging inducement as a mean to estimate yield and quality losses (Bauer, 1964; Stanca *et al.*1979). This paper reports the results obtained from two different trials. The first trial investigated the effects of a range of treatments on lodging related traits, yield components, grain yield and grain quality. In the second trial, yield and quality losses associated with lodging were estimated by inducing artificial lodging at two critical growth stages.

2.0 Materials and methods

Two separate trials were carried-out in 2009 and 2010 using standard seed rate (160 kg ha^{-1}) recommended by Martin *et al.* (2008) at an experimental site near Orkney College, Kirkwall, Orkney (Grid reference: HY 456 114). The soil of the experimental plot was classified as clay loam, with organic matter (3.9 %), NO_3-N (17.25 mg kg^{-1}) and NH_4^+ (0.96 mg kg^{-1}), P (28.2 mg kg^{-1}), K (70mg kg^{-1}) and acidic in nature (pH=5.5). Plots were planted using a Pneumatic Accord Combine Seed Drill. Weed control was achieved in all trials by applying a mixture of Mecoprop (1.5 l ha^{-1}) and 4-chloro-2-methylphenoxy acetic acid (MCPA) (1.0 l ha^{-1}) in 200 l of water by a tractor-mounted hydraulic nozzle sprayer (RAU-SPRiMAT L, Netherlands) having a 12 m boom length. A knapsack sprayer was used to apply the PGR (*Upgrade*) [{chlormequat chloride + chloroethylphosphonic acid}, Bayer CropScience, a.i 360:180 g l^{-1}] at Zadoks growth stage (ZGS) 31 in *Trial 1* and ZGS 37 in *Trial 2*. Ears m^{-2} (EPSM) was recorded by counting the number of fertile ears (ears with at least one fully filled grain) in a representative 50 cm x 50 cm quadrat in each plot. A representative sample of 20 stems was manually harvested from each treatment plot. A sub-sample (10 stems) was used to record stem length (StL) from the bottom of the stem to the base of ear as described by Schittenhelm and Hartmann (2006). The remaining stems were dissected into ear and stem and then dried separately at 80^{0}C for 72 hrs. Stem weight (SW) was used to calculate stem weight per cm (SWCM) by dividing SW by StL. Ears were weighed to record ear weight (EW) and then manually threshed to record grains ear^{-1} (GPE). A random sample of 10 stems was selected from each plot at ZGS 71 to assess the severity of disease. A scoring system developed by Large and Dolling (1962) was used to describe the severity of disease from 1 (disease not present) to 9 (dead leaves with no green area left) of the top four leaves. To record the onset of lodging all plots were visually monitored after every rainfall event. Final lodging assessments were made just before harvest. A frame marked with different angles was used to visualize the angle of deviation of stems from the vertical. The percentage area of the crop that was leaning at various angles was made. These observations were then converted into lodging index (LI) with slight modification to the formula developed by Berry *et al.* (2003) so that intermediate angles of 0-15, 15-30, 30-45, 45-60, 60-75, and 75-90 could be included.

Lodging Index = {1/6 (% at 0^0-15^0) +2/6(% at 15^0-30^0)+3/6(% at 30^0-45^0)+ 4/6(% at 45^0-60^0)+5/6(% at 60^0-75^0)+(% at 75^0-90^0)}.

The grain nitrogen content (GNC) was estimated on a grain sample of 300 g using Infratec Grain Analyzer (FOSS, Denmark). Grain yield (GY) was estimated by harvesting the plots either manually or by combine harvester. A sub-sample (100 g) of grain was drawn to measure grain moisture content (GMC). A Contador counter (Hoffman Manufacturing Inc, Germany) was used to count the grains required for 1000-grain weight (TGW). The GY and TGW were adjusted to 15 % GMC. Statistical analysis of the data was performed separately for each of the trials using Genstat 9.1. Means of treatments were compared using Fischer's protected least significant differences (LSD) at 5% level of probability. The relationships between yield, yield components, lodging and lodging related traits were investigated by regression analysis.

2.1 Trial 1

In this trial Bere was planted on 28th April 2009 in a strip-split plot design with 5 replications. There were 24 treatments resulting from the factorial combination of three levels of nitrogen (N), two levels of phosphorous (P) and potassium (K) and two levels of plant growth regulator (PGR) (Table 1). The N treatments were randomly allocated to 3 columns and the combination of P and K (P0K0, P0K45, P45K0, and P45K45) were assigned to four double rows. The fertilizer treatments were drilled along with the seed.

The PGR treatments (GR0 and GR1) were randomly assigned to sub-plots. Sub-plot size was 3m x 6 m with a 6 m wide guard between replicates. Data were collected on stem length (StL), stem weight (SW), stem weight per cm (SWCM), lodging index (LI), disease score (DS), ears m^{-2} (EPSM), ear weight (EW), grains ear^{-1} (GPE), 1000-grain weight (TGW), grain yield (GY) and grain nitrogen content (GNC). GY and EPSM were determined by harvesting a 1m x 1m quadrat from each plot on 8th September 2009. Ears were counted and threshed manually to record GY.

2.2 *Trial 2*

This trial was sown on 27th April 2010 in a randomized block design with 4 replications. A basal fertilizer treatment i.e 45 kg ha^{-1} N and 30 kg ha^{-1} each of P and K was drilled along with the seed. There were six treatments resulting from the factorial combination of plant growth regulator (PGR) at two levels and lodging treatment (LT) at three levels (Table 2) which were randomly assigned to individual plot (3m x 12m). The artificial lodging (AL) treatments were applied by walking through the crop while rolling a barrel on the plot flatten the crop. This method was advantageous in that it required few resources in terms of cost, equipment, time and skills compared with other methods such as wind tunnel, airplane propeller or weighted plywood board used by other researchers Bauer (1964); Harrington and Waywell (1950); Stanca *et al.* (1979). LI was assessed immediately following application of artificial lodging treatment and again at harvest. Other data collected from all the plots were StL, LI, EPSM, GPE, GY, TGW and GNC. GY was estimated by combine harvesting of one strip 2.3 m wide and 12 m long on 11th September 2010.

3.0 Results

3.1 Trial 1

StL was significantly affected by N (*P*< *0.001*) and PGR (*P*< *0.001*) while the effects of P and K were not significant. N increased the length of stem (28 % for N45 and 33 % for N90) compared with the N0 treatment. A decrease of 13% in StL (averaged over all treatments) resulted from the GR1 treatment when compared with GR0 (Table 3). There were no significant interactions amongst treatments (Tables 4 and 5). SW was significantly affected by N (*P*< *0.001*) and PGR (*P*< *0.001*) but not by P and K. The heaviest SW was obtained from the N45 treatment and the lowest from N0. The GR1 treatment resulted in 12 % reduction in the SW compared with GR0 (averaged over all other treatments) (Table 3).There were no significant interactions amongst the treatments for SW (Tables 4 and 5). SWCM was significantly (*P*= *0.021*) affected by N but not by PGR, P and K (Table 3). The no-nitrogen plots (N0) had the highest SWCM, which declined as N-level increased (averaged over the other treatments). There was a significant (*P*= *0.002*) PGR x N interaction because, without PGR, the SWCM was constant at all N-levels, where as when PGR was added, it decreased as N-level increased (Fig 1). There were no significant interactions amongst the remaining treatments (Tables 4 and 5). The LI assessments made on 1st September 2009 indicated significant effects of N (*P*< *0.001*) and PGR (*P*< *0.001*). However, there were no significant effects of P and K (Table 3). LI rose as the level of N increased. A significant (*P*< *0.001*) PGR x N interaction was caused by the proportionately larger reductions in LI when GR1 was applied at N0 than at the other N-levels (Fig 2). There were no significant interactions amongst the remaining treatments for LI (Tables 4 and 5). There were significant effects of N ($P< 0.001$), P ($P= 0.041$) and K ($P= 0.008$) on DS while PGR had no significant effect (Table 3). The DS increased with the application of N and was higher in the N90 (6.6) and N45 (6.0) treatments than with N0 (5.7). Small but significant reductions in DS were obtained from the P45 and K45 treatments compared with P0 and K0 respectively. There were no significant interactions amongst the treatments for DS (Tables 4 and 5). N ($P< 0.001$), PGR ($P= 0.008$) and K ($P= 0.041$) had significant effects on EPSM while P had no significant effect (Table 3). EPSM increased from 296 (N0) to 412 (N90) with increasing N-level. This increase corresponded to 16% for N45 and 40% for N90 compared with N0. The K45 treatment increased EPSM by 4% compared with K0 while the GR1 treatment resulted in 5% higher EPSM (averaged over all treatments) compared with the GR0 treatment. There were no significant interactions amongst the treatments (Tables 4 and 5). EW was significantly affected by N ($P= 0.016$) and K ($P= 0.035$) but not by P and PGR. The highest EW was from the N45 treatment (1.25 g) compared with 1.13 g for the N0 and N90 treatments. The K45 treatment increased the EW by 5 % compared with the K0 treatment (Table 3). There were no significant interactions amongst the treatments (Tables 4 and 5). GPE was significantly ($P< 0.001$) affected by N but not by P, K and PGR. Averaged over all treatments, the N45 treatment increased the GPE by 17 % compared with the N0 treatment. However, doubling the N-level to 90 kg ha^{-1} caused a non-significant 3 % reduction in GPE compared with N45 (Table 3). There were no significant interactions amongst the treatments (Tables 4 and 5). TGW (g) was significantly ($P< 0.001$) affected by N but not by P, K and PGR. Averaged over all other treatments, values of TGW were 35.3, 33.4 and 30.9 g for N0, N45 and N90 respectively, indicating a decrease in TGW with increasing level of N (Table 3). There was a significant ($P = 0.020$) N x PGR interaction which resulted because application of GR1 at N90 decreased TGW while at N0 and N45, the GR1 treatment increased TGW (Fig 3). There was a significant (P= 0.039) interaction effect of N x P x K x PGR on TGW due to the different effect of PGR at different N-levels (Fig 4). The GR1 treatment had a significant negative effect on TGW at N90 with high levels of P and K but not at N0 or N45. There were no significant interactions amongst the remaining treatments (Table 4 and 5). GY (kg ha^{-1}) was significantly affected by N ($P < 0.001$), K ($P = 0.011$) and PGR ($P = 0.013$) while there was no significant effect of P. Averaged over all treatments, there was a 26 % increase in yield from the N45 and a 38% from the N90 treatment compared with N0. The application of K45 and GR1 treatment increased GY by 8% and 6% compared with K0 and GR0 treated plots respectively (Table 3). There were no significant interactions amongst the treatments (Table 4 and 5). GNC was significantly affected by N ($P < 0.001$) but not by P ($P = 0.834$), K or PGR. The mean values for GNC (averaged over P, K and PGR) were 1.62, 1.71 and 1.99 from the N0, N45 and N90 treatments respectively. An increase in GNC when GR1 was applied with K45 resulted in a significant ($P < 0.001$) interaction. There were no significant interactions amongst the remaining treatments (Tables 4 and 5). Simple linear correlation analysis between yield and its components for individual plot data from all the treatments revealed that EPSM accounted for the largest amount of variation in GY, while EW, GPE, and TGW had lower values for coefficient of determination (R^2) (Table

6). When these components were fitted against GY by stepwise multiple linear regression, the combination of EPSM and GPE or EW accounted for 73 % of the variations in GY. The inclusion of TGW in the regression model had very little impact on the coefficient of determination which was due to the negative association between TGW and EPSM (Fig 8). GNC was also negatively associated with TGW (Fig 9). Variation in StL accounted for 61 % of the variation in LI (Table 7). LI was also significantly (*P< 0.001*) associated with EPSM (R^2= 0.41), SW (R^2= 0.28) and SWCM (R^2= 0.08). However, there was no significant association between EW and LI (Table 7). A step wise inclusion of additional variables into the regression model improved the correlation and a maximum of 70 % of the variation in LI was explained by the combinations of (1) StL, SWCM and EPSM and (2) StW, SW and EPSM.

3.2 Trial 2

StL was significantly affected by PGR (*P*< *0.001*) and LT (*P*< *0.001*) (Table 8). The GR1 treatment resulted in 14 % shorter stems compared with GR0 (averaged over lodging treatments). Plots subjected to AL treatments produced shorter stems than from the AL0 treatment. The overall reductions in StL (averaged over PGR treatment) due to the AL59 and AL77 treatments were 18 % and 5 % respectively compared with AL0. There was a significant (*P*< *0.001*) LT x PGR interaction which was due to StL not being affected by GR1 when AL59 had been applied (Table 9). There was a significant (*P*= *0.023*) effect of LT on SWCM (mg cm^{-1}). The highest SWCM was recorded from the AL59 treatment (10.71 mg cm^{-1}) and the lowest from the AL77 (9.64 mg cm^{-1}) which was not significantly different from AL0 (9.79 mg cm^{-1}) (Table 8). The PGR treatment had no significant effect and the interaction of PGR x LT was also not significant (Table 9). LI was significantly affected by PGR (*P*< *0.001*) and LT (*P*< *0.001*). Averaged over LT, the GR1 treatment improved the standing ability of the crop compared with the GR0 treatment (Table 8). There was a considerable recovery following the AL59 treatment and LI of AL0 and AL59 were almost similar. However, AL77 was the most severe lodging treatment. There was a significant (*P*< *0.001*) LT x PGR interaction because with AL77, the LI of the GR1 treatment was very similar to that of the GR0 treatment while with AL59 and AL0, the GR1 treatment always resulted in a significantly lower LI than GR0 (Table 9). Ear sprouting was noticed at harvest in the plots subjected to the AL77 treatment. There were no significant effects of PGR and LT on EPSM but GPE was significantly (*P*= *0.011*) reduced by LT and the AL77 treatment caused the largest reductions (11 %) compared with AL0 (Table 8). There were no significant interactions amongst the treatments (Table 9). PGR and LT had no significant effect on TGW, GMC and GNC but GY was significantly affected by LT and the AL59 and AL77 treatment caused 9 % and 17 % reductions in GY respectively, compared with AL0 (averaged over PGR treatment) (Table 9).

4.0 Discussion

In cereals, several morphological characteristics such as StL (Pinthus, 1973), EW (Tripathi *et al.,* 2003) and SWCM (White, 1991) are related to lodging. The results in *Trial 1* showed that StL was the main characteristic strongly associated with lodging. Higher N-levels (N45 and N90) increased StL and the propensity of Bere to lodge compared with the untreated plots. Together with StL, EW is associated with lodging (Pinthus, 1967). When plant is displaced from its vertical position due to wind a second bending moment results from the force of gravity which rises with increase in StL and EW (Pinthus, 1973). This consequently increases lodging incidence. In the present research EW and StL increased when N-level was raised from N0 to N45 which consequently increased lodging incidence. Increasing N-level also increases tiller density (Lauer and Partridge, 1990) which results in the production of taller and weak stems which are susceptible to lodging (Crook and Ennos, 1995). This study obtained similar results and the reduction in strength, measured as SWCM, due to the higher levels of N may have been a consequence of higher EPSM. This resulted in higher LI in the N90 treated plots compared with N45 and the untreated control plots. PGR reduces lodging risk by decreasing StL (Tripathi *et al.,* 2003). In this research the PGR also reduced StL and resulted in a lower LI compared with the untreated control plots. But the PGR was less effective in controlling lodging at the highest N-level (N90). This outcome was partly due to changes in crop density in response to PGR and N. Higher application of N-level and PGR increases stems per plant and per unit area (Christensen and

Killorn, 1981; Foster *et al.,* 1991; Ma and Smith, 1992). As stems per plant increases, the risk of root lodging increases (Baker *et al.,* 1998). This is attributed to the increased leverage on the anchorage system of the aerial parts of all the stems belonging to one plant (Berry *et al.,* 2007). In this study the plots which received combined treatment of N90 and GR1 had higher EPSM but weaker stems which consequently increased lodging risk and incidence. This partly explained why the PGR was less effective in lodging control at N90 than at N45 or N0. P and K have been reported to improve lodging resistance (Casserly, 1957). However in this trial the two elements had no effect on LI. This outcome was partly because the two elements increased EPSM which consequently reduced stem strength resulting in a higher LI than the plots which did not receive P and K. This tended to suggest that the two elements may not be ideal for lodging control which is in agreement with the findings of Mulder (1954) and Gasper *et al.* (1994) on cereals.

N application can increase disease incidence due to changes in crop density (Jordan and Stinchombe, 1988). One mechanism for this could be increased tillering which can result in favourable conditions for disease spread (Howard *et al.,* 1994). Results reported in *Trial 1* showed that DS rose with increased N-levels which was probably associated with increased EPSM. Increased DS may also be attributed to higher lodging incidence (Kono, 1995). PGR can reduce disease incidence by protecting the crop from lodging (Jordan and Stinchcombe, 1986). However, in this study, the PGR tended to increase DS (although statistically not significant). This outcome may have been due to increased tillering and short stems which favoured disease spread and development. Johnston and Macleod (1987) have proposed a similar explanation to this outcome for spring barley. P and K have the potential in lowering the DS (Mitchell and Walters, 2004; Amtmann *et al.,* 2008). In this study P addition tended to reduce DS which may have been the result of changes in plant metabolism reducing food supply to pathogens (Walters and Bingham, 2007). K application reduced the incidence of powdery mildew partly because the soil was deficient in K and its application may have allowed the crop to grow and defend itself against biotic and abiotic stresses better than the crop which did not receive K. The study concluded that the addition of P and K would be useful in improving resistance in Bere against powdery mildew.

It has been reported that when available N-levels in soil are low the relationship between GY and added N is linear (Kramer, 1979). In this study, there was a 26 % increase in GY when N-level was raised from N0 to N45. This increase was attributable to increased EPSM and high TGW. Doubling the N-level from N45 to N90 caused only a 12 % increase in GY. This limited increase was due to reduced TGW and decreased GPE probably caused by the negative association of EPSM with GPE and TGW (Foster *et al.,* 1991). Moreover, the higher LI from the highest N-level (90 kg ha^{-1}) may have reduced GPE and TGW (Jedel and Helm, 1991). P and K can have significant positive effect on GY (Gately, 1968). The results reported in this paper indicated that K had a significant effect on GY while the effects of P were not detected. This outcome was due to a difference in the availability of the two elements as the soil of the experimental site was deficient in K but contained sufficient in P. Perrenoud (1990) and Gately (1968) gave similar explanations for the non-significant effects of P and K respectively on GY. The results indicated that the combination of high levels of N, P and K produced a higher yield than when either was applied individually alone. This was partly due to the positive effect of N on

EPSM and a higher TGW due to the application of P and K. PGR had a significant positive effect on GY in *Trial 1* but not in *Trial 2.* This may have resulted from differences in the timing of application of PGR. The earlier (ZGS 31) application of PGR in *Trial 1* significantly increased EPSM which resulted in high yields. This is in agreement with the findings of Tripathi *et al.* (2003) on several wheat varieties. The later application (ZGS 37) in *Trial 2* had no significant effect on EPSM and therefore the yield enhancing effects of PGR were not consistently observed. Higher levels of N result in higher lodging incidence in susceptible varieties (Jordan and Stinchcombe, 1986; Newton *et al.,* 1998) which negatively affect GY (Fischer and Stapper, 1987). In this study LI increased with N-level but GY was not lowered by its detrimental effects probably due to late occurrence of lodging. It has been reported that when lodging occurs at heading, grain number ear^{-1} and grain yield may be reduced (Day, 1957; Weibel and Pendleton, 1964; Briggs, 1990). Lodging at the early milk stage can cause the highest yield losses while lodging at the soft dough to hard dough stages has a negative effect on grain weight, but a less severe effect on yield reduction (Jedel and Helm, 1991). The low level yield losses from lodging at heading may be associated with the ability of crop to regain its vertical position (Stanca *et al.,* 1979). The results reported in *Trial 2* obtained similar results in which Bere was able to recover its erect position following the AL59 treatment. This recovery may have allowed the crop to photosynthesize normally which resulted in a lower yield depression compared with plots which were unable to recover from the AL77 treatment. The highest yield reduction (*ca* 20%) caused by AL77 treatment was attributed to grain germinating in the ear and the inability of the combine harvester to pick up lodged stems (personal observation). However, yield losses figure reported in this paper may not represent what would occur naturally because the barrel-method for inducing lodging may have caused stem breakage and stoppage of assimilates translocation towards ear. But the level of yield losses in this paper were either lower or comparable with the losses reported by Pinthus (1973) (34%), Stanca *et al.* (1979) (38%) and Briggs (1990) (21%) who also used artificial lodging techniques to estimate yield losses. Therefore, the predicted yield losses in this study were used for estimating cost and benefit of using a PGR for controlling lodging. Data of the present trial indicated that AL77 could have incurred a loss of £160 ha^{-1}. This estimate was based on the market price of Bere's grain in 2010 (£200 t^{-1}) and average GY (4.0 t ha^{-1}). The calculation indicated that an investment of £75 ha^{-1} to cover the cost of a PGR and its application may save up to £85 ha^{-1} farm income by protecting the crop from the lodging at ZGS 77. This figure may be over exaggerated because under natural conditions the type of damage caused by AL77 is unlikely to occur, and unless PGR results in significant yield enhancement it may not justify its cost of application.

Higher inputs of N to increase yield can reduce malting quality by affecting TGW and GNC (Widdowson *et al.,* 1982). Higher N-levels reduce TGW (Christensen and Killorn, 1981) and may raise GNC due to low carbohydrates accumulation (Lauer and Partridge, 1990), which is undesirable for malting (Grashoff and d'Antuono, 1997; Conry, 1997). GNC followed the increasing level of N in *Trial 1* which was also associated with decreased TGW. Moreover, high N-levels can result in increased translocation of N from vegetative parts to grains which raises GNC (Papakosta and Gagianas, 1991). P and K had no significant effect on GNC, an outcome consistent with the results of Gately (1968) for malting barley. The non-significant effect of the PGR treatment on GNC suggested that it could not be used to manipulate grain quality. Lodging can decrease TGW which may raise GNC (Caierao, 2006) due to low carbohydrates content in the grain (Grashoff and d'Antuono, 1997). However in this *Trial 2* there were no significant alterations in TGW and GNC in response to artificial lodging treatments. It is possible that the grain sample used for TGW and GNC determination may not have been representative of a lodged flat crop. Since combine harvester was unable to pick-up all lodged stems and sprouted ears, it is possible that the sample from the lodged flat plot did not contain poor quality grain. This consequently resulted in a non-significant effect of artificial lodging treatment on TGW and GNC.

5.0 Conclusion

Based on the results reported in this paper it can be concluded that Bere responds positively to N and K. However, the marginal increase in crop yield from N45 to N90 suggested the adoption of N45 to achieve reasonable yield (*ca* 4.0 t ha^{-1}) and acceptable grain quality (GNC< 1.80 %). The results indicated that an adequate supply of P and K may be required to improve disease resistance and GY; however, these nutrients did not contribute to control lodging. PGR resulted in low LI but did not result in higher yield. Although, in the absence of severe lodging or significant yield enhancement, the PGR application may not justify its expenditure, it may facilitate easier harvesting operations. In Orkney controlling pre-harvest lodging is very important because rain can delay the harvesting operation for several days which may result in severe yield and quality losses. Considering the susceptibility of Bere to lodging, PGR may not be applied for enhancing yield and quality but to avoid late-season lodging. Its inclusion in the production guidelines is recommended to avoid pre-harvest ear sprouting and to ease harvesting operation.

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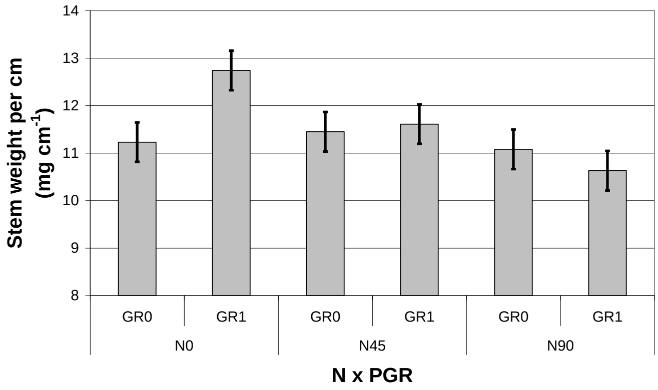


Fig 1 Effect of N x PGR interaction on SWCM

Bars on columns represent standard error of differences of means

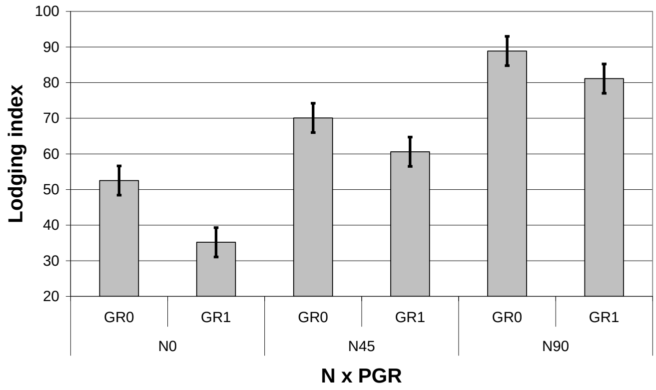


Fig 2 Effect of N x PGR interaction on lodging index

Bars on columns represent standard error of differences of means

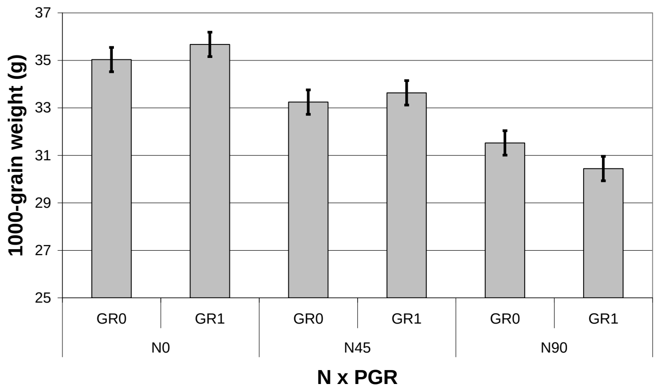


Fig 3 Effect of N x PGR on 1000-grain weight

Bars on columns represent standard error of differences of means

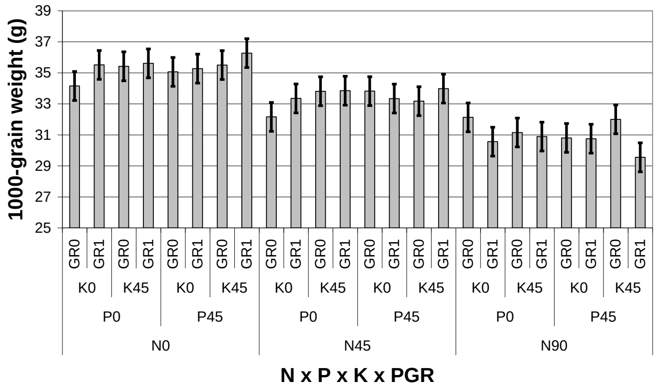


Fig 4 1000-grain weight as affected by the interaction of N x P x K x PGR

Bars on columns represent standard error of differences of means

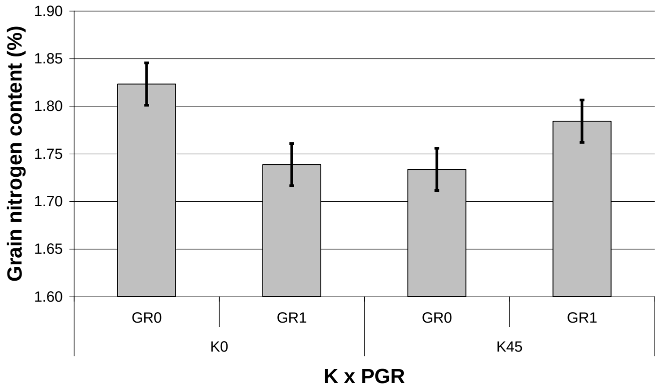


Fig 5 Grain nitrogen content as affected by the interaction of PGR x K

Bars on columns represent standard error of differences of means

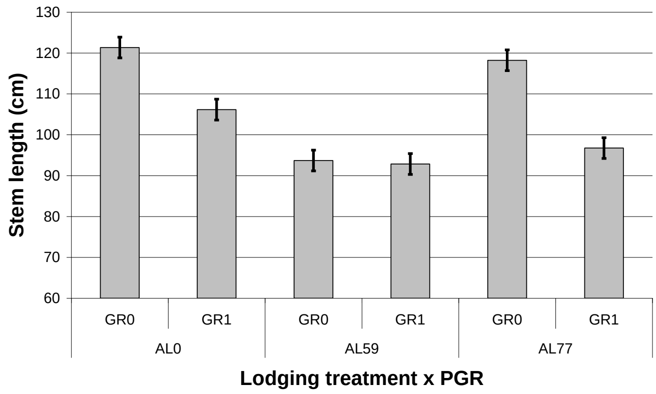
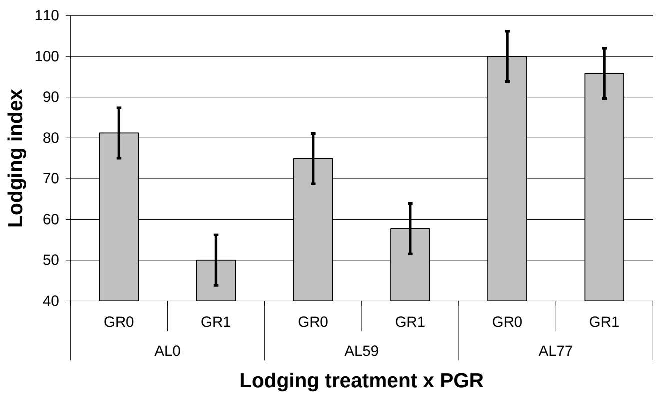


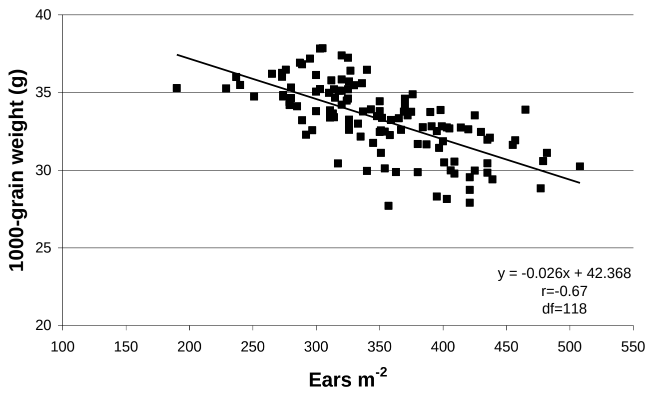
Fig 6 Stem length as affected by interaction of lodging treatment x PGR

Bars on columns represent standard error of differences of means

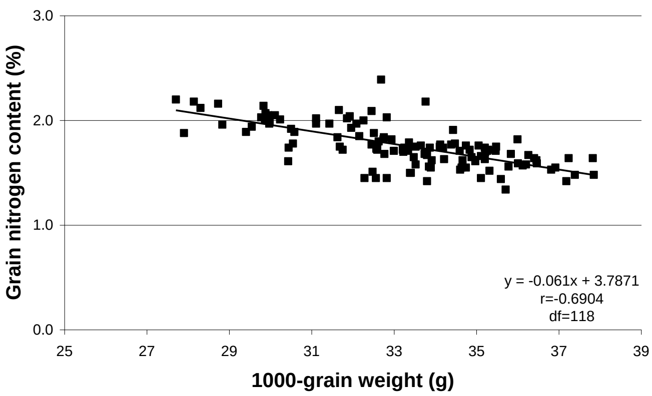


<u>Fig 7 Lodging treatment x PGR effect on lodging index</u>

Bars on columns represent standard error of differences of means



<u>Fig 8 Correlation between 1000-grain weight and ears m^{-2}</u>



<u>Fig 9 Correlation between grain nitrogen content and 1000-grain weight</u>

Table 1 List of treatments and their abbreviations

Treatment	Level	Abbreviation
Nitrogen (N)	0 kg ha^{-1}	N0
	45 kg ha^{-1}	N45
	90 kg ha^{-1}	N90
Phosphorous (P)	0 kg ha^{-1}	P0
	45 kg ha^{-1}	P45
Potassium (K)	0 kg ha^{-1}	K0
	45 kg ha^{-1}	K45
Plant growth regulator (PGR)	No-PGR	GR0
	PGR at ZGS 31	GR1

Table 2 List of treatments, their abbreviations and application dates

Treatment	**Abbreviation**	**Date of application**
PGR treatment		
No-PGR	GR0	-
PGR (Upgrade) (2 l ha^{-1}) at ZGS 37	GR1	21 June 2010
Lodging treatment		
No AL (Natural lodging)	AL0	-
AL at fully emerged ear stage	AL59	4th July 2010
AL at milk stage	AL77	21st July 2010

Table 3 Main effect of N, P, K and PGR on lodging, yield and quality related traits of Bere in 2009

Treatment	StL (cm)	SW (g)	SWCM (mg)	LI	DS	EPSM	EW (g)	GPE	TGW (g)	GY (Kg ha^{-1})	GNC (%)
N0	86.9	1.04	11.98	43.8	5.7	296.4	1.13	32.77	35.35	3060	1.6218
N45	111.2	1.3	11.53	65.3	6.0	344.0	1.25	38.23	33.44	3860	1.7007
N90	115.3	1.26	10.85	85.0	6.6	412.1	1.13	37.14	30.98	4297	1.9867
F-Probability	<0.001	<0.001	0.021	<0.001	<0.001	<0.001	0.016	<0.001	<0.001	<0.001	<0.001
LSD (5%)	4.6	0.10	0.73	8.19	0.36	31.6	0.08	2.05	0.93	284.4	0.14
P0	104.6	1.21	11.6	66.7	6.2	349.4	1.18	36.3	33.22	3715	1.7682
P45	104.6	1.17	11.31	63.8	6.1	352.4	1.17	36.86	33.29	3763	1.7713
F-Probability	NS	NS	NS	NS	0.041	NS	NS	NS	NS	NS	NS
LSD (5%)	3.3	0.08	0.65	5.41	0.12	12.4	0.06	1.71	0.59	200.1	0.05
K0	103.5	1.17	11.35	64.7	6.2	344.4	1.14	35.24	33.08	3599	1.778
K45	105.7	1.22	11.56	64.7	6.0	357.4	1.20	36.86	33.43	3879	1.7615
F-Probability	NS	NS	NS	NS	0.008	0.041	0.035	NS	0.011	0.207	NS
LSD (5%)	3.3	0.08	0.65	5.41	0.12	12.4	0.06	1.71	0.59	200.1	0.05
GR0	112.3	1.79	11.25	70.9	6.1	342.8	1.18	36.3	33.26	3633	1.7805
GR1	96.8	1.72	11.66	58.9	6.1	357.4	1.16	35.79	33.25	3845	1.759
F-Probability	<0.001	<0.001	NS	<0.001	NS	0.008	NS	NS	0.014	NS	NS
LSD (5%)	2.9	0.06	0.45	3.39	0.14	11.7	0.05	1.32	0.52	168.1	0.04

NS: Not significant (*P> 0.05*)

Table 4 Interaction effects of N, P and K on lodging, yield and quality related traits of Bere in 2009

Treatment			StL (cm)	SW (g)	SWCM (mg)	LI	DS	EPSM	EW (g)	GPE	TGW (g)	GY (Kg ha^{-1})	GNC (%)
N0	P0	K0	87.81	0.99	11.41	42.42	5.55	291.0	1.14	33.47	34.83	2842	1.62
		K45	87.20	1.07	12.24	45.83	5.77	311.3	1.10	31.66	35.52	3158	1.63
	P45	K0	92.96	0.96	11.67	39.17	5.82	284.1	1.10	31.94	35.16	2966	1.62
		K45	89.71	1.13	12.62	47.92	5.66	299.3	1.21	34.03	35.89	3272	1.62
N45	P0	K0	108.54	1.34	12.34	66.92	6.23	337.9	1.21	37.91	32.75	3714	1.73
		K45	114.11	1.26	11.06	67.75	5.94	347.5	1.32	39.90	33.83	4049	1.66
	P45	K0	111.17	1.23	11.08	67.33	6.04	348.6	1.21	36.68	33.58	3851	1.71
		K45	112.20	1.31	11.62	59.33	5.87	342.1	1.26	38.43	33.57	3826	1.71
N90	P0	K0	116.29	1.31	11.24	90.75	6.95	389.4	1.06	34.38	31.35	4057	2.0
		K45	113.73	1.29	11.29	80.25	6.64	419.0	1.23	40.51	31.02	4468	1.97
	P45	K0	113.99	1.19	10.37	81.83	6.63	415.2	1.13	37.06	30.78	4162	1.99
		K45	117.36	1.23	10.51	87.17	6.34	424.9	1.10	36.61	30.77	4503	1.98
F-Probability			NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
LSD (5%)			7.887	0.173	1.335	12.521	0.382	39.16	0.146	2.427	1.377	469.8	0.149

NS: Not significant (*P> 0.05*)

Table 5 Interaction effects of N, P, K and PGR treatment on lodging, yield and yield related characteristics of Bere in 2009

Treatment				StL (cm)	SW (g)	SWCM (mg)	LI	DS	EPSM	EW (g)	GPE	TGW (g)	GY (Kg ha^{-1})	GNC (%)
N0	P0	K0	GR0	98.20	1.05	10.67	53.50	5.705	279.2	1.13	33.99	34.15	2648	1.66
			GR1	77.42	0.94	12.15	31.33	5.395	302.8	1.14	32.94	35.51	3036	1.59
		K45	GR0	93.52	1.12	11.95	51.17	5.884	326.0	1.08	31.28	35.42	3202	1.62
			GR1	80.89	1.01	12.53	40.50	5.655	296.6	1.12	32.04	35.61	3115	1.63
	P45	K0	GR0	93.97	0.98	10.30	48.33	5.735	279.2	1.09	31.66	35.06	2937	1.68
			GR1	71.95	0.941	13.04	30.00	5.902	289.0	1.12	32.22	35.27	2996	1.56
		K45	GR0	101.86	1.22	11.98	57.00	5.435	285.4	1.17	33.60	35.50	3040	1.60
			GR1	77.55	1.03	13.25	38.83	5.890	313.2	1.23	34.46	36.27	3504	1.63
N45	P0	K0	GR0	112.65	1.35	12.03	71.00	6.300	334.8	1.25	39.70	32.16	3611	1.83
			GR1	104.42	1.32	12.66	62.83	6.255	341.0	1.18	36.12	33.35	3818	1.63
		K45	GR0	121.09	1.33	10.99	70.67	5.930	340.6	1.32	39.62	33.81	4151	1.64
			GR1	107.12	1.19	11.13	64.83	5.955	354.4	1.33	40.18	33.85	3948	1.68
	P45	K0	GR0	116.92	1.30	11.13	67.50	6.000	327.8	1.16	35.12	33.82	3577	1.77
			GR1	105.42	1.16	11.04	67.17	6.085	369.4	1.25	38.24	33.34	4124	1.64
		K45	GR0	121.04	1.41	11.64	71.17	5.850	333.6	1.23	38.16	33.17	3550	1.66
			GR1	103.35	1.20	11.60	47.50	5.895	350.6	1.29	38.70	33.98	4101	1.75
N90	P0	K0	GR0	121.68	1.45	11.92	94.83	7.135	374.6	1.15	36.38	32.13	3976	2.02
			GR1	110.90	1.17	10.56	86.67	6.770	404.2	0.97	32.38	30.56	4137	1.98
		K45	GR0	121.02	1.37	11.30	81.00	6.560	409.4	1.23	40.54	31.15	4292	2.00
			GR1	106.44	1.21	11.29	79.50	6.720	428.6	1.22	40.48	30.89	4600	1.95
	P45	K0	GR0	122.29	1.30	10.68	89.17	6.682	416.8	1.13	36.76	30.80	4203	1.98
			GR1	105.68	1.07	10.07	74.50	6.585	413.6	1.13	37.36	30.75	4121	2.00
		K45	GR0	124.36	1.29	10.42	90.50	6.160	406.6	1.21	38.80	32.00	4405	1.90
			GR1	110.36	1.17	10.60	83.83	6.530	443.2	1.01	34.42	29.55	4644	2.06
F-Probability				NS	NS	NS	NS	NS	NS	NS	NS	0.039	NS	NS
LSD (5%)				10.44	0.239	1.700	14.830	0.5608	616.7	0.195	5.169	1.85	616.7	0.166

NS: Not significant (*P*> *0.05*)

Table 6 Values of co-efficient of determination (R^2) and probability (P) and degrees of freedom (df) for linear regression of yield and its components

Traits	No. of independent variables	R^2	Probability (P) Df
Ears m^{-2} (EPSM)	1	0.6565	<0.001,df=118
Grains ear^{-1} (GPE)	1	0.2351	<0.001,df=118
Ear weight (EW)	1	0.2431	<0.001,df=118
1000-grain weight (TGW)	1	0.1950	<0.001,df=118
EPSM,GPE	2	0.7291	<0.001,df=117
EPSM,TGW	2	0.6760	<0.001,df=117
EPSM, EW	2	0.7311	<0.001,df=117
EPSM,TGW,GPE	3	0.7422	<0.001,df=116

NS: Not significant (*P*> *0.05*)

Table 7 Values of co-efficient of determination (R^2), probability (P) and degrees of freedom (df) for linear regression of LI and lodging related characteristics

Traits	No. of independent variables	R^2	Probability (P)
Ear weight (EW)	1	0.001	NS, df=118
Stem length (StL)	1	0.6059	<0.001,df=118
Stem weight (SW)	1	0.2794	<0.001,df=118
Stem weight per cm (SWCM)	1	0.0816	<0.001,df=118
Ears m^{-2} (EPSM)	1	0.4101	<0.001,df=118
EW, StL	2	0.6242	<0.001,df=117
EW,SW	2	0.3084	<0.001,df=117
EW,SWCM	2	0.0851	<0.005,df=117
EW,EPSM	2	0.4111	<0.001,df=117
StL,SW	2	0.6206	<0.001,df=117
StL,SWCM	2	0.6203	<0.001,df=117
StL,EPSM	2	0.6894	<0.001,df=117
SWCM,EPSM	2	0.4433	<0.001,df=117
StL,SW,EPSM	3	0.6985	<0.001,df=116
StL,SWCM,EPSM	3	0.6996	<0.001,df=116

NS: Not significant (*P*> *0.05*)

Table 8 Main effect of PGR and LT on lodging, grain yield and quality related traits of Bere in 2010.

Treatment	StL (cm)	SWCM (mg cm^{-1})	LI (%)	EPSM	GPE	GY (kg ha^{-1})	TGW (g)	GMC (%)	GNC (%)
GR0	111.1	10.3	85.4	390.0	43.7	3834	32.2	19.2	1.83
GR1	98.6	9.8	67.8	407.3	43.2	3862	31.8	19.0	1.81
F-Probability	<0.001	NS	<0.001	NS	NS	NS	NS	NS	NS
LSD (5%)	3.1	0.64	7.6	41.1	2.3	274.5	1.5	0.53	0.04
AL0	113.7	9.8	65.6	419.0	46.1	4220	31.6	19.3	1.82
AL59	93.3	10.7	66.3	396.0	42.6	3831	32.9	18.9	1.80
LT77	107.5	9.6	97.9	381.0	41.6	3493	31.5	19.1	1.85
F-Probability	<0.001	0.023	<0.001	NS	0.011	336.2	NS	NS	NS
LSD (5%)	3.8	0.79	9.3	50.3	2.8	475.4	1.8	0.65	0.06

NS: Not significant (*P*> *0.05*)

Table 9 Interaction effect of PGR x LT on lodging, grain yield and quality related traits of Bere in 2010.

Treatment		StL (cm)	SWCM (mg cm^{-1})	LI (%)	EPSM	GPE	GY (kg ha^{-1})	TGW (g)	GMC (%)	GNC (%)
	AL0	121.3	9.71	81.2	391.0	46.23	4259	31.96	19.58	1.85
GR0	AL59	93.7	11.26	74.9	399.0	42.13	3794	33.03	18.93	1.81
	LT77	118.2	9.95	100	380.0	42.82	3450	31.74	18.98	1.85
GR1	AL0	106.2	9.87	50	447.0	45.98	4182	31.31	18.95	1.79
	AL59	92.8	10.17	57.7	393.0	43.10	3868	32.94	18.97	1.80
	AL77	96.7	9.33	95.8	382.0	40.48	3536	31.25	19.21	1.85
F-Probability		<0.001	NS	0.025	NS	NS	NS	NS	NS	NS
LSD (5%)		5.4	1.1	13.2	71.1	4.1	475.4	2.7	0.92	0.08

NS: Not significant (*P*> *0.05*)