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ARTICLE

Effects of plant growth regulator applications on malting barley in western Canada

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Abstract: Malting barley is important in western Canada, yet many malting cultivars do not meet malt quality standards, in part due to lodging. Lodging can decrease barley yield and quality thereby reducing the acceptability for malting. In other countries, plant growth regulator (PGR) applications are used to mitigate lodging. Chlormequat chloride (chlormequat), trinexapac-ethyl (trinexapac), and ethephon were tested at five locations over 3 yr in western Canada for their ability to limit lodging, as well as their effects on yield, agronomic traits, and pre-malt quality characteristics. PGR applications occurred between Zadoks growth stage (GS) 30–33 for chlormequat and trinexapac and GS 37–49 for ethephon. Seeding rates of 200, 300, and 400 seeds m^{-2} of CDC Copeland barley were used to increase the likelihood of lodging. Increased seeding rate decreased tillers per plant, height, days to maturity, kernel protein, and kernel weight. Ethephon increased the number of tillers per plant and decreased plant height, kernel plumpness, and kernel weight. Trinexapac decreased plant height and kernel weight. Days to maturity was investigated across site-years, with ethephon increasing maturity in 60% of comparisons. Trinexapac and chlormequat had limited effects on maturity. Lodging was investigated across site-years, with trinexapac showing the largest number of lodging reductions and scale of reductions. Ethephon reduced lodging in 36% of comparisons, while chlormequat had inconsistent effects. None of the products affected yield or grain protein. The results suggest PGRs may not be the solution to lodging for CDC Copeland barley on the Canadian Prairies; however, trinexapac shows the most promise of the products tested.

Key words: plant growth regulators, malting barley, pre-malt quality.

Résumé : L'orge brassicole est une culture importante dans l'ouest du Canada. Pourtant, de nombreux cultivars ne parviennent pas à la qualité requise pour servir de malt, en partie à cause de la verse. En effet, la verse réduit le rendement et la qualité de la céréale, la rendant moins acceptable pour un usage brassicole. Les agriculteurs d'autres pays recourent à des régulateurs de croissance (PGR — « plant growth regulator ») pour atténuer le problème. Les auteurs ont testé le chlorure de chlorméquat (chlorméquat), le trinexapac-éthyle (trinexapac) et l'éthéphon pendant trois ans à cinq endroits, dans l'Ouest canadien, pour déterminer dans quelle mesure ces produits réduisent la verse et en préciser les effets sur le rendement, sur les paramètres agronomiques et sur la qualité du grain avant maltage. PGR ont été appliqués entre les stades (GS — « growth stage ») 30 et 33 pour le chlorméquat et le trinexapac, et entre GS 37 et 49 pour l'éthéphon. Pour accroître la probabilité de la verse, les chercheurs ont semé 200, 300 et 400 graines d'orge CDC Copeland par mètre carré. La plus forte densité des semis

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a réduit le nombre de talles par plant, la hauteur du plant, le nombre de jours jusqu'à maturité, la teneur en protéines du grain et le poids des grains. L'éthéphon augmente le nombre de talles par plant, mais réduit la hauteur du plant, rend les grains moins charnus et en diminue le poids. Le trinexapac diminue la hauteur du plant et le poids du grain. Les auteurs ont examiné le nombre de jours nécessaires pour que l'orge parvienne à maturité aux différents sites-années et les comparaisons révèlent que l'étéphon accélère la maturité dans 60 % des cas. Le trinexapac et le chlorméquat agissent relativement peu sur ce paramètre. La verse a aussi été examinée aux divers sites-années et c'est le trinexapac qui entraîne les réductions les plus intenses ainsi que les plus étendues. L'éthéphon a atténué la verse dans 36 % des comparaisons, tandis que les effets du chlorméquat étaient trop variables. Aucun des produits à l'étude n'affecte le rendement ni la teneur en protéines du grain. Les PGR ne semblent pas constituer la solution au problème de la verse pour la variété CDC Copeland cultivée dans les Prairies canadiennes. Le trinexapac paraît être le plus prometteur des produits testés. [Traduit par la Rédaction]

Mots-clés : régulateurs de croissance des plantes, orge brassicole, qualité avant maltage.

Introduction

Barley (*Hordeum vulgare* L.) was grown on over 2.5 million hectares in western Canada in 2018, with 56.3% of the area seeded to malt barley cultivars (McMillan et al. 2018). CDC Copeland and AC Metcalfe were the most common malting barley cultivars grown, with an increased prevalence of AAC Synergy (McMillan et al. 2018). Only a portion of the barley grown, however, meets minimum malting quality standards, which include germinative energy, varietal purity, protein content (11%–12.5%), plump kernels, and a maximum moisture content of 13.5% (Brewing and Malting Barley Research Institute 2010). Cultivar choice, agronomic decisions, and environmental conditions throughout the growing season impact many of these factors. Plant lodging is one factor that can negatively affect grain quality and crop yield (Jung 1984).

Lodging in cereals typically occurs between head emergence and harvest (Rademacher 2015) and is more severe under conditions that are conducive to plant growth such as high fertility and higher precipitation (Berry et al. 2004). Lodging can occur due to breakages or buckling in the stem or a dislodging of the rooting system from the ground (Mulder 1954; Berry et al. 2004). Stem lodging often results from weather events with high wind speeds and substantial rain, whereby the force exerted by the weather causes stem breakage or buckling (Rademacher 2015). Both stem and root lodging can occur, sometimes in combination (Berry et al. 2004). Increased lodging not only provides harvest challenges but also causes yield losses (Jedel and Helm 1991), increased disease presence (Langseth and Stabbetorp 1996), and decreased grain quality (Berry et al. 2004). Overall impacts of lodging depend on how early a plant lodges (Jedel and Helm 1991), weather events following lodging, and disease inoculum levels. Lodging risks can be cultivar specific (Clark and Fedak 1977) but are also affected by agronomic decisions such as seeding date or rate (O'Donovan et al. 2012), seeding depth (Pinthus 1974), fertilization strategies (O'Donovan et al. 2011), and potentially disease management (Turkington et al. 2015; Perrott et al. 2018) that affect plant height, plant health, and, likely as a result, stem strength. Reductions in nitrogen fertilization and growth of short-statured cultivars can limit plant lodging (Wiersma et al. 1986); however, reducing nitrogen fertilizer also reduces crop yield potential. For this reason, particularly in high yield potential areas, alternative strategies to manage lodging in crops such as malt barley would be useful for producers.

Plant growth regulators (PGRs) are used internationally in many crop species to impart a number of effects including increased yield, breaking of bud dormancy, fruit maturation prevention or initiation, and, of particular interest here, plant height management and lodging mitigation (Dahnous et al. 1982; Green 1986; Rademacher 2015). Application of PGRs to reduce lodging is highly prevalent in some countries in cereal crops; in the United Kingdom in 2016, 90% of spring wheat (*Triticum aestivum* L.), 71% of winter rye (*Secale cereal* L.), and 83% of the winter barley (*Hordeum vulgare* L.) acreage was treated with anti-lodging products (Garthwaite et al. 2016). They are less commonly used on spring barley in the United Kingdom, and were applied on only 36% of the acreage in 2016 (Garthwaite et al. 2016). Three PGRs used globally, or in other non-barley crops in Canada, to prevent lodging are chlormequat chloride (hereafter referred to as chlormequat), ethephon, and trinexapac-ethyl (hereafter referred to as trinexapac). None of these products are currently registered for use in barley in western Canada; however, ethephon is registered as Ethrel (Bayer CropScience 2019) and chlormequat is registered as Manipulator (Belchim Canada 2019) in wheat.

Chlormequat was introduced to the global market in 1965 (Rademacher 2015) and was the first PGR used to manage cereal lodging on a large scale in Europe (Rademacher 2015). Chlormequat applications inhibit gibberellin biosynthesis in the early stages of gibberellin metabolism (Jung 1984; Ma and Smith 1992*c*). Timing of application can be critical for chlormequat's effects on crop yield; early application (Zadoks growth stage (GS) 13) can increase barley yield through an increase in the number of tillers (Ma and Smith 1992*a*). In some cases, however, the increase in tillers only leads to the same number of yield-bearing spikes as in untreated plants (Ma and Smith 1992*c*). In different cultivars or years, PGR applications made at the same growth stage can result in differential effects to yield and number of productive tillers due to differences in apical development even at the same visible growth stage (Ma and Smith 1991*a*). The chlormequat label for a single application in spring wheat in western Canada directs application between GS 31 and 32 (Belchim Canada 2019), while applications to spring barley in Europe can be applied from GS 23 to GS 32 (BASF 2019). Split applications are possible in spring wheat from GS 12 to 39 (Belchim Canada 2019). There are differential responses between cereal crops to applications of chlormequat. Barley has been shown to be less responsive than other cereals to chlormequat application (Rajala and Peltonen-Sainio 2002). Barley's reduced sensitivity has been related in part to reduced spray droplet retention and absorption and reduced translocation (Baker and Hung 1985; Berry et al. 2004). As a result, chlormequat is less commonly used on barley than on other cereals. Chlormequat effects on barley have also been shown to be cultivar specific (Clark and Fedak 1977). It is possible that this is due to varietal differences in timing of apical development at the same visible growth stage (Ma and Smith 1991*a*). Chlormequat reduced lodging in winter barley through a reduction of plant height as well as through increasing the stem diameter and strengthening the stem wall (Jung 1984). The stem stabilizing properties of chlormequat are less effective in winter barley than in wheat (Jung 1984), possibly suggesting lower efficacy in spring barley as well. Chlormequat has been shown to reduce spring barley height without significantly affecting lodging in Ontario and Alberta (Ma and Smith 1991*b*; Perrott et al. 2018). Chlormequat applications have been shown to increase test weight and reduce kernel protein in Alberta, although protein reductions were likely related to increased grain yield (Perrott et al. 2018).

Trinexapac also inhibits gibberellin biosynthesis, but at a later stage in the gibberellin biosynthesis pathway than chlormequat, and also inhibits flavonoid biosynthesis (Rademacher 2015). Trinexapac is more commonly used than chlormequat to reduce lodging in barley in Europe due to a higher likelihood of responsiveness in barley (Rajala and Peltonen-Sainio 2002; Rademacher 2015). Studies with trinexapac on wheat in the United States have shown limited effects on kernel weight, but applications have reduced lodging, increased straw strength, and increased days to heading, particularly at the highest rates tested (Wiersma et al. 2011). Trinexapac has been shown to effectively reduce lodging in spring barley in Finland (Rajala and Peltonen-Sainio 2002).

Ethephon acts on a different biochemical pathway than chlormequat and trinexapac. After absorption, and when in an acidic environment, it decomposes into ethylene and byproducts (Ma and Smith 1992*c*; Rademacher 2015). Ethylene is a naturally occurring plant hormone that is involved in a number of plant processes. Application of ethephon and the subsequent release of ethylene, if timed properly, can reduce stem elongation in barley (Ma and Smith 1992*c*; Rajala and Peltonen-Sainio 2002). Ethephon is commonly used in cereals in Europe and has been shown to increase barley yield when lodging occurs (Dahnous et al. 1982; Simmons et al. 1988), but it has also been shown to induce late tillering (Foster et al. 1991); however, ethephon has shown more negative effects in barley than chlormequat, including decreased kernel weight and delayed maturity (Ma and Smith 1992*a*). Under stress conditions in particular, ethephon application can inhibit barley main stem growing points, resulting in increased tiller production (Ma and Smith 1991*b*). In spring and winter wheat, ethephon application is recommended between GS 37 and 45 (Bayer CropScience 2019).

Seeding rates have been studied for their effect on malt barley agronomics and quality in western Canada (McKenzie et al. 2005; O'Donovan et al. 2012). In that research, a rate of 200–300 seeds m^{-2} was identified as the optimal seeding rate for malting barley in western Canada, whereas seeding above these rates resulted in a risk of reduced yield and kernel plumpness. Rates below the optimal had higher protein levels, less uniform kernels, and typically lower yield (McKenzie et al. 2005; O'Donovan et al. 2012). Seeding rate alone (range of 100–500 seeds m^{-2}) was not shown to impact lodging; however, at later seeding dates, increased lodging was observed with higher seeding rates (O'Donovan et al. 2012). In other research, increased seeding rates have been shown to increase lodging risk (Kirby 1967; Berry et al. 2000). Seeding rates were therefore incorporated into the current study to try to create a scenario with increased probability of lodging. Additionally, recent research has found interactions between seeding rate and PGR application (Perrott et al. 2018). The effect of chlormequat chloride on spike length, test weight, and acid detergent fibre in feed barley in Alberta was different between target plant densities of 240 and 355 plants m^{-2} (Perrott et al. 2018). With chlormequat application, the lower seeding rate showed increased test weight and acid detergent fibre, while the higher seeding rate showed increased spike length (Perrott et al. 2018).

The objective of this study was to determine (*i*) if ethephon, chlormequat, or trinexapac application can mitigate malt barley lodging in western Canada, (*ii*) if seeding rate interacts with PGR application, and (*iii*) if there are any nontarget effects on agronomics such as yield or plant height and pre-malting quality.

Materials and Methods

A field experiment with PGR applications in CDC Copeland malt barley (Canadian Food Inspection Agency 1999; Secan 2015) was conducted at five rain-fed locations across the Canadian Prairies: Lacombe (52°28′N, 113°46′W) and Lethbridge (49°41′N, 112°46′W), Alberta;

Indian Head (50°32′N, 103°40′W) and Scott (52°21′N, 108°51′W), Saskatchewan; and Brandon (49°50′N, 99°57′W), Manitoba. Experiments were conducted in 2014, 2015, and 2016 at each location. Malt barley was direct-seeded into standing cereal stubble at each location. In each treatment, 120 kg ha^{-1} of nitrogen was applied as granular fertilizer at seeding, with other nutrients (phosphorous, potassium, and sulfur) supplied as per soil test recommendations at each site. Fertilizer was either side-banded or seed-placed, location and equipment dependent. Soil tests were conducted either the previous fall or prior to seeding in the cropping season spring, weather and accessibility dependent. Herbicides were applied across all treatments as required based on the weed pressure at each location during each year, while propiconazole (Tilt, Syngenta Canada) was applied each year at 499 mL ha^{-1} with 85 L ha^{-1} water volume at flag leaf emergence to limit the potential confounding effects of disease development.

Treatments

The experiment was designed as a randomized complete block design with four replicates at each location. There were 12 treatments (three PGRs plus an untreated, combined with three seeding rates). The seeding rates were 200, 300, and 400 seeds m^{-2}. The three PGRs were chlormequat, trade name Manipulator (620 g L^{-1}; Belchim Crop Protection Canada), ethephon, trade name Ethrel (240 g L^{-1}; Bayer CropScience Canada), and trinexapac (250 g L^{-1}; Moddus formulation) currently undergoing registration review in Canada. Chlormequat and trinexapac were applied between GS 30 and 32 (Zadoks et al. 1974) at 1532 and 100 g a.i. ha^{-1}, respectively. Ethephon was applied between GS 37 and 45 at 240 g a.i. ha^{-1}. Actual calendar dates of application and crop growth stages are provided in Table 1. Stage and rate of application were based on labels in other cereals (Ethrel label for wheat, Manipulator label for spring wheat for chlormequat stage, and Moddus label in the United Kingdom for trinexapac stage) or by company recommendation (chlormequat and trinexapac rates). Sprayers were calibrated to a deliver a carrier volume of 100 L ha^{-1}, with pressure and nozzles chosen as appropriate for each location.

Data collection

An area of 2 rows × 2 m was staked early in the season (~2 wk after crop emergence) and the plant population was determined. Days to maturity was recorded using GS 92 as mature and calculated by using the Julian date when 90% of the plot reached GS 92 and subtracting the Julian date at crop seeding. Days to maturity was not collected at Brandon in 2015 and at Lethbridge in 2015 and 2016. At crop maturity, tiller production per plant was measured through counting productive heads removed from the premarked 2 rows × 1 m area in each plot. Based on the number of productive tillers in the area and the known population, we calculated an average number of tillers per plant. Plant height excluding awns was also determined at maturity through measurement of an average height at the front and back of every plot, approximately 1 m from the front and back edges and in the approximate center from each of the sides. A lodging index was used to evaluate lodging area and severity at each location (eq. 1):

$$\text{(1)} \qquad \text{Lodging index} = S \times I \times 0.2$$

where S is the area of surface lodged (on a scale of 1 to 9, where 1 = none and 9 = total) and I is the intensity of lodging (on a scale of 1 to 5, where 1 = upright and 5 = flat) (Wiersma et al. 1986). Lodging was only collected in those site-years in which lodging occurred and was recorded at maturity (Indian Head 2014 and 2015, Lacombe 2014 and 2016, Scott 2014 and 2016, and Brandon 2015 and 2016).

Grain yield was adjusted to 13.5% moisture. Quality parameters evaluated included 1000-kernel weight, percent plump, and percent protein. The 1000-kernel weight was determined through counting and weighing 250 kernels from each treatment and then multiplying that value by four. Percent protein was measured via NIR with a Foss 6500 (Foss Analytics, Denmark) using previously developed calibration equations from the barley breeding program of Alberta Agriculture in Lacombe, AB, using standard whole grain NIR protein analysis methods (i.e., American Society of Brewing Chemists Methods of Analysis, Barley-7D). Percent plump was determined by following the USDA grain grading procedure and evaluating a subsample of the barley grain for the percentage of kernels that did not pass through a 6/64 slotted sieve (USDA 2013).

Statistical analysis

An ANOVA using the Proc MIXED procedure in SAS version 9.4 (SAS Institute Inc., Cary, NC, USA) was conducted in which PGR, seeding rate, and their interaction were fixed effects and site-year, replicate nested in site-year, and the interaction of site-year with the fixed effects were considered random effects. The proportion of variance for each measured variable associated with the interaction between site-year and the fixed effects was calculated as [(variance estimate for site-year interaction of interest)/(variance estimate for site-year + site-year interactions with fixed effects)] × 100 (Littell et al. 2006; O'Donovan et al. 2012). As the goal of agronomic studies is to use results to determine predicted effects at future locations and in future years, it may be most appropriate to consider site-year as random (Yang 2010). Consistent with other malt barley research in western Canada using 10 site-years as a threshold for the effect of site-year to be considered random (Yang 2010; O'Donovan et al. 2011, 2012), our 15 site-years makes this approach appropriate. Variables that

Table 1. Precipitation for each site-year growing season in comparison with the long-term average (1981–2010) along with details of the materials and methods at each location.

		Precipitation			Soil description (%)								
Location	Year	April–October (mm)	Long term-average[a] (LTA) (mm)	LTA (%)	pH	OM	Sand	Silt	Clay	Seeding date	Ethephon application	Chlormequat application	Trinexapac application
Brandon	2014	447	322	139	7.8	4.3	37	32	31	26 May	9 July (GS 43)	25 June (GS 30)	25 June (GS 30)
	2015	195		61	7.9	4.8	37	32	31	12 May	25 June (GS 37)	18 June (GS 30)	18 June (GS 30)
	2016	305		95	7.9	4.5	36	34	30	6 May	28 June (GS 37–41)	9 June (GS 30)	9 June (GS 30)
Indian Head	2014	488	310	158	7.4	3.0	13	21	66	13 May	8 July (GS 49)	24 June (GS 31)	24 June (GS 31)
	2015	284		92	8.0	3.4	13	24	63	5 May	29 June (GS 45)	25 June (GS 33)	25 June (GS 33)
	2016	309		100	7.3	3.2	14	24	61	16 May	8 July (GS 49)	30 June (GS 32)	30 June (GS 32)
Lacombe	2014	287	348	82	8.3	9.7	44	32	24	15 May	3 July (GS 41)	17 June (GS 31)	17 June (GS 31)
	2015	351		101	7.6	9.2	41	34	25	11 May	29 June (GS 45)	22 June (GS 30)	22 June (GS 30)
	2016	366		105	6.9	8.9	52	35	13	10 May	30 June (GS 45)	14 June (GS 30)	14 June (GS 30)
Lethbridge	2014	406	293	139	7.8	4.8	N/A	N/A	N/A	23 May	20 July (GS 49)	24 June (GS30)	24 June (GS 30)
	2015	189		64	7.8	4.8	39	36	25	1 May	20 July (GS 49)	22 June (GS 30)	22 June (GS 30)
	2016	275		94	7.7	3.5	38	35	26	30 Apr.	30 June (GS 49)	3 June (GS 30)	3 June (GS 30)
Scott	2014	306	256	120	5.7	4.9	36	53	11	28 May	16 July (GS 47)	4 July (GS 32)	4 July (GS 32)
	2015	250		98	6.0	4.9	36	53	11	18 May	6 July (GS 49)	29 June (GS 32)	29 June (GS 32)
	2016	296		116	6.0	3.4	37	49	14	18 May	5 July (GS 43–49)	20 June (GS 32)	20 June (GS 32)

Note: Zadoks growth stage (GS) for each plant growth regulator application is given following the application date. OM, organic matter; N/A, not available.
[a]Source: Environment Canada.

showed >10% of variance associated with a site-year and treatment interaction were analyzed and are presented below by site-year. Lodging was only analyzed at those site-years in which lodging occurred to eliminate the confounding effect of lack of PGR effect on lodging in years where no lodging occurred. Due to non-normality, lodging was analyzed in Proc Glimmix. Model selection was conducted using the Laplace method and selected via the lowest Akaike's Corrected Information Criterion. A gamma distribution was utilized in an ANOVA using the same fixed and random effects as stated above, and the proportion of variance associated with the different effects calculated as above. Variables that were analyzed by site-year due to high variance associated with site-year and a fixed effect used ANOVA in Proc Mixed or Proc Glimmix and included PGR, seeding rate, and their interaction as fixed effects and replicate as a random effect. A Dunnett's test was used in all ANOVAs to compare treatment means with the untreated controls. Seeding rate was tested to determine if variable responses were linear or quadratic in nature. The α level for significance for all statistical tests was $\alpha = 0.05$.

Results and Discussion

Precipitation and PGR applications

During the 2014 growing season, all locations received higher precipitation than the long-term average, with the exception of Lacombe, which experienced a drier season (82% of long-term average) (Table 1). In contrast, most locations received close to normal precipitation in 2015 with the exceptions of Brandon and Lethbridge, which received substantially less than average (61% and 64% of long-term average respectively) (Table 1). Precipitation in 2016 was generally close to the long-term average, with some variation on both sides across sites (Table 1). Scott had the largest variation from the average precipitation in 2016 at 116% of the long-term average. Lodging is associated with high and (or) intense precipitation and storm events. In comparison with the long-term average, the generally near average precipitation years and the low incidence of intense storms during this study may have limited the incidence and severity of lodging.

Generally, locations were able to apply chlormequat and trinexapac at the intended timing (GS 30–32); however, only 53% of the ethephon applications were made at the correct growth stages (37–45), with the rest being applied late (Table 1). Ethephon applications at Lethbridge occurred later than intended (GS 49), while the ethephon in Scott in 2014 and 2015 was applied late (GS 47 and 49, respectively), and the staging for the application in 2016 was variable to late (GS 43–49). Indian Head applied trinexapac in 2015 slightly later than recommended (GS 33) and applied ethephon later than intended in 2014 and 2016 (GS 49). These inaccuracies in application timing may have affected the results in terms of response to ethephon at affected locations and to trinexapac at Indian Head in 2015.

Site-year effects

The ANOVAs indicated that site-year was, unsurprisingly, the largest source of variation for the variables measured (data not shown); however, the interaction of site-year and the fixed effects, and the proportion of variance explained by these interactions, is of greater interest in this study. For most of the variables, this proportion of variance explained was <10% (Table 2), with days to maturity and lodging showing a higher proportion of variance associated with the interaction of site-year and PGR application (12% and 16%, respectively) (Table 2). This is still relatively low compared with the overall variances associated with the effects of site-year for lodging, but it is high enough to warrant further investigation into the effects of PGRs on days to maturity and lodging at individual site-years (presented below).

Seeding rate effects

Seeding rate had a significant effect on tiller production per plant (including main head tillers), plant height, plant maturity, kernel weight, and protein across locations (Table 2). Increased seeding rate caused a linear decrease in tillers per plant, height, days to maturity, protein, and kernel weight (Table 3). All of these effects are consistent with those reported by O'Donovan et al. (2011, 2012) within the range of seeding rates contained in this study. McKenzie et al. (2005) also reported decreased protein and decreased kernel size in response to increased seeding rate. In some cases, the pattern of response in O'Donovan et al. (2012) was found to be quadratic, whereas the only response pattern in this study was linear; however, O'Donovan et al. (2012) were working with a larger range of seeding rates than was considered in this study. O'Donovan et al. (2011, 2012) did not investigate the effect of seeding rate on height so we cannot compare with those results. In this study, height decreased in a linear fashion as seeding rate increased. There was no interaction of seeding rate with PGR application on any of the measured variables across locations (Table 2). In contrast, Perrott et al. (2018) found an interaction between chlormequat application on barley and plant density on spike length and test weight, neither of which are reported in our study. Seeding rate interaction with PGRs on days to maturity and lodging at individual site-years are described in the PGR effects on the respective variable sections below.

PGR effects

PGR applications had a significant effect on tillers per plant, plant height, kernel plumpness, and kernel weight (Table 2). Plant maturity was close to significant (Table 2) but was not under $\alpha = 0.05$; however, as the variance associated with site-year and PGR for maturity was >10%, maturity was also analyzed by location and is

Table 2. Statistical significance of plant growth regulator (PGR) and seeding rate (SR) treatments, as well as their interactions on measured agronomic variables.

Factor	Tillers	Height	Lodging[a]	Maturity	Yield	Kernel plumpness	Protein	Kernel weight
PGR	**0.0069**	**<0.0001**	0.0767	0.0554	0.1856	**0.0008**	0.2677	**<0.0001**
SR	**<0.0001**	**0.0006**	0.5324	**<0.0001**	0.5259	0.7485	**0.0032**	**<0.0001**
PGR × SR	0.6368	0.6758	0.3108	0.2254	0.4223	0.8254	0.5310	0.8007
	Variance estimate							
Site-year	0.90	206.33	1.05	70.84	470 978	127.15	0.54	20.01
Site-year × PGR	0.04	8.48	0.22	9.96	27 160	8.87	0.027	0.41
Site-year × SR	0.09	1.25	0.01	1.18	13 729	0.87	0.008	0.29
Site-year × PGR × SR	0	0.13	0.01	0.42	5 306.77	0	0.0001	0
	Proportional variance estimate[b] (%)							
Site-year	87.0	95.4	81.2	86.0	91.1	92.9	93.9	96.7
Site-year × PGR	4.4	4.0	16.8	12.0	5.5	6.5	4.7	2.0
Site-year × SR	9.3	0.6	1.1	1.6	2.8	0.7	1.5	1.4
Site-year × PGR × SR	0	0.07	0.9	0.6	1.1	0	0.02	0

Note: Bold values indicate significance at $\alpha = 0.05$. Variance estimates for the effect of site-year on the measured variables are also given.

[a]Lodging was analyzed using a gamma distribution in Proc Glimmix (SAS version 9.4). Variance was calculated using the same equation as above.

[b]Proportional variance estimate was calculated as [(variance estimate for site-year interaction of interest)/(variance estimate for site-year + site-year interactions with fixed effects)] × 100.

presented below. PGRs also did not significantly affect yield, protein, or lodging across site-years. Yield effects of PGRs have been shown to be year, staging, cultivar, and environment specific (Ma and Smith 1992*a*, 1992*b*). Both positive (Rajala and Peltonen-Sainio 2002; Perrott et al. 2018) and negative (Caldwell et al. 1988; Simmons et al. 1988; Ma and Smith 1991*b*; Ramburan and Greenfield 2007) effects have been demonstrated for different products in barley. Although the across site-year analysis for PGR effects on lodging was not significant, the variance associated with the interaction between site-year and PGR application was >10% and so lodging by site-years is reported below.

Tillers per plant

Of the three PGRs applied, only ethephon caused a significant difference in the number of productive tillers produced per plant (Table 3); however, tiller production was only increased by less than half a tiller per plant on average and may not be agronomically significant. In other studies, ethephon has been shown to increase barley tillering, in particular production of tillers that do not produce grain (Foster et al. 1991; Ma and Smith 1992*a*, 1992*c*). Non-productive tillers were not counted in this study and may have been increased, particularly with late ethephon applications. There has been some varietal specificity shown in terms of tillering response to ethephon application; however, increased tillering has been the response in the varieties tested (Foster et al. 1991). The varietal specificity was in how much of an increase in tillering was observed (Foster et al. 1991) or the timing of application and genetics of the cultivars (Ma and Smith 1992*c*). Increased late tillering increases variability in barley maturity and can also impact harvest operations (Foster et al. 1991). We did not test the timing of tillering in this study; however, plant maturity was not significantly changed by any tillers that may have occurred late in the season. Neither trinexapac nor chlormequat caused a significant increase in productive tillers in this study. This is consistent with previous research on chlormequat in barley (Ma and Smith 1992*c*). Trinexapac has been shown to increase tillering of barley under greenhouse and (or) growth chamber conditions (Rajala and Peltonen-Sainio 2001); however, application of trinexapac in that study occurred at a much earlier growth stage (three leaves, GS 13) than in our study. Increased tillering can result in delayed maturity, which can increase the need for desiccants that are not accepted by the Canadian malt barley industry, or in a later harvest, which can cause exposure to weather that causes quality loss in the grain. In our study, the increased tiller number is not likely to have been agronomically significant.

Plant height

Plant height was significantly affected by PGR application (Table 2). Both ethephon and trinexapac reduced plant height compared with the no PGR treatment (Table 3). Ethephon had the largest effect at 5 cm while trinexapac reduced height by 4 cm. Ethephon has previously been shown to reduce height in barley, albeit with some cultivar and application stage specificity (Dahnous et al. 1982; Caldwell et al. 1988; Simmons et al. 1988; Foster et al. 1991; Ma and Smith 1992*a*). Chlormequat

Table 3. LSmeans for each measured variable as a result of seeding rate (SR) and plant growth regulator (PGR) treatments.

	SR (no. m^{-2})					PGR			
	200	300	400	Linear *p*	Quadratic *p*	None	Chlormequat	Ethephon	Trinexapac
Tillers (no. plant^{-1})	3.98	3.08	2.54	**<0.0001**	0.1207	3.08	3.13	**3.43**	3.16
Height (cm)	79.19	78.06	76.70	**0.0001**	0.8136	80.86	79.78	**75.17**	**76.14**
Maturity (d)	99.97	98.58	97.58	**<0.0001**	0.2254	97.65	97.86	100.69	98.64
Yield (kg ha^{-1})	4738.29	4790.30	4797.36	0.3027	0.6479	4734.76	4796.51	4709.77	4860.22
Protein (%)	12.74	12.64	12.56	**0.0008**	0.9426	12.68	12.57	12.64	12.69
Plump (%)	86.96	87.34	87.01	0.9366	0.4531	88.63	88.85	**84.09**	86.84
Kernel weight (g per 1000 seeds)	43.58	42.85	42.26	**<0.0001**	0.7616	43.83	43.53	**41.25**	**42.98**
Lodging[a] (lodging index)	1.04	1.01	1.13	0.4289	0.4333	1.28	1.44	0.83	0.83

Note: Bolded *p* values indicate significance compared with $\alpha = 0.05$. Bolded LSmeans indicate significant difference from None treatment based on a Dunnet's comparison of means. PGR applications were between GS 30 and 33 for chlormequat and trinexapac and between GS 37 and 49 for ethephon.

[a]Lodging was analyzed using a gamma distribution in Proc Glimmix (SAS version 9.4). LSmeans have been back-transformed for presentation.

did not significantly reduce plant height, which contrasts with research conducted with chlormequat in Alberta (Perrott et al. 2018) but is consistent with research in South Africa (Ramburan and Greenfield 2007) on barley. When barley height reductions have been measured after chlormequat application, they have generally been relatively small but significant (Ma and Smith 1992*a*; Perrott et al. 2018). It has also been shown that chlormequat height reductions are cultivar specific in barley (Clark and Fedak 1977). It is possible that CDC Copeland is a variety that shows limited response to chlormequat application and other varieties may be more affected. Trinexapac has been shown to reduce barley height in Poland (Miziniak et al. 2017), consistent with our study in western Canada. It has also reduced shoot growth in a controlled environment (greenhouse and (or) growth chamber) when applied at GS 13 (three leaf) (Rajala and Peltonen-Sainio 2001), significantly earlier than applications in this study. Reduced plant height can sometimes result in reduced lodging, therefore the height reductions by ethephon and trinexapac are positive agronomic effects.

Kernel plumpness

PGR application had a significant effect on kernel plumpness (Table 2). Neither trinexapac nor chlormequat significantly affected kernel plumpness, but ethephon reduced kernel plumpness by 4%. The malt quality standard for kernel plumpness is 90% (G. Feist, Executive Director, Brewing and Malting Barley Research Institute, Saskatoon, SK, personal communication), a level that was sometimes achievable in our study at individual site-years (data not shown) but not when averaged across site-years (based on untreated averages). With barley around a threshold level, a reduction in plumpness of 4% resulting from ethephon application could make the difference between meeting that threshold or not. It is possible that this scale of reduction could impact malt barley acceptability; however, only 8 of the 15 site-years had applications of ethephon within the target window; late applications may impact ethephon effects on kernel plumpness. Product selection and proper application timing for that product may be critical to mitigating negative quality effects of PGR applications.

Kernel weight

PGR application had a significant effect on kernel weight (Table 2). Both ethephon and trinexapac reduced kernel weight. Ethephon reduced kernel weight by over 2.5 g per 1000 seeds. Trinexapac also reduced kernel weight but by under 1 g per 1000 seeds. The scale of these differences was small but significant. Previous research with ethephon has shown limited impacts on kernel weight in barley (Ma and Smith 1992*a*). Trinexapac has been previously shown to have limited effect on wheat kernel weight, causing limited reductions unless used at high rates at later growth stages (i.e., GS 37)

Table 4. The p values for plant growth regulator (PGR) and seeding rate (SR) treatment effects on days to maturity across site-years.

Site-year	PGR p	SR p	PGR × SR p	Regression significance[a]	
				Linear	Quadratic
Brandon 2014	**<0.0001**	1.000	0.8794	N/A	N/A
Brandon 2016	**0.0076**	**<0.0001**	**0.0112**	**<0.0001**	0.6357
Indian Head 2014	**0.0016**	**<0.0001**	0.3078	**<0.0001**	0.6930
Indian Head 2015	**<0.0001**	**0.0004**	**0.0446**	**<0.0001**	0.4590
Indian Head 2016	0.4598	0.2242	0.1305	N/A	N/A
Lacombe 2014	**<0.0001**	**<0.0001**	**0.1126**	**<0.0001**	**0.0005**
Lacombe 2015	0.6363	**<0.0001**	0.0667	**<0.0001**	0.0998
Lacombe 2016	0.9810	**<0.0001**	0.5705	**<0.00001**	**0.0041**
Lethbridge 2014	**<0.0001**	**0.0017**	**0.0219**	**0.0005**	0.4176
Scott 2014	0.3909	**0.0009**	0.8576	**0.0002**	0.8214
Scott 2015	**<0.0001**	0.2905	0.3606	N/A	N/A
Scott 2016	**0.0014**	**<0.0001**	0.7847	**<0.0001**	0.3430

Note: Bolded p values indicate significance at an $\alpha = 0.05$.
[a]Regression significance only given if seeding rate has a significant effect on lodging.

(Wiersma et al. 2011). In previous research, chlormequat has also had limited impact on barley kernel weight (Clark and Fedak 1977; Perrott et al. 2018). Kernel weight is another malt quality parameter, so reductions in kernel weight may put achieving malt quality at risk.

Days to maturity

As the variance associated with the site-year and PGR interaction for maturity was >10%, maturity has been analyzed by site-year. PGR had a significant effect on days to maturity at 8 of the 12 site-years (67%) where days to maturity was recorded and (or) there were differences in maturity (Table 4). Seeding rate had a significant effect on days to maturity at 9 of 12 site-years (75%) with linear effects in most cases (Table 4). There was a significant interaction of PGR and seeding rate at 4 out of 12 site-years (33%) (Table 4). At all locations where seeding rate had a significant effect, days to maturity decreased as seeding rates increased (Table 5). Out of the 20 total comparisons for PGRs (PGR alone and PGR × seeding rate when the interaction was significant), chlormequat only had a significant effect twice, once resulting in increased days to maturity and once resulting in decreased days to maturity (Table 5). This inconsistency in effect suggests that chlormequat effects on maturity are limited. Chlormequat has not been shown to affect barley maturity in the past, which is consistent with these conclusions (Ma and Smith 1992*a*; Perrott et al. 2018). Ethephon significantly affected days to maturity compared with the no PGR treatment in 12 out of 20 comparisons (60%), increasing days to maturity each time. At Scott in 2015, maturity was increased by 28 d; however, application of ethephon at that location occurred at a late plant stage (GS 49), and timing of PGR application is known to be critical (Rajala and Peltonen-Sainio 2002). The large impact on days to maturity could be related to the mistimed application; however, at a number of other locations where ethephon was also applied late, maturity was not significantly affected (i.e., Indian Head 2016, Scott 2014 and 2016) (Tables 1 and 5). Previous studies have shown delayed maturity in barley with ethephon applied at GS 39, which is within the label recommendations, or at early applications (GS 30) in 1 yr (Ma and Smith 1992*a*). Trinexapac significantly affected days to maturity in 4 out of 20 comparisons with the untreated malt (20%). Days to maturity were increased for three out of four of those comparisons. Previous studies have shown delays in wheat maturity with trinexapac, although scale of effect was dependent on rate and timing of application (Wiersma et al. 2011; Grijalva-Contreras et al. 2012).

Lodging

The goal of this study was to evaluate PGRs as a tool to mitigate lodging in malt barley on the Canadian Prairies. There was no significant effect of PGR application on lodging averaged across sites in this study (Table 2). Lodging only occurred at 8 out of 15 site-years, thus limiting the number of site-years in which PGR application may have affected lodging. Furthermore, in those site-years when lodging did occur, effects were generally limited, with lodging scores averaging ≤3.6 on a scale of 0.2–9 in all but 1 site-year (data not shown); however, because of the high variance associated with the interaction of site-year and PGR for lodging (16.8%), data were analyzed across site-years. Of the 8 site-years in which lodging occurred, PGR had a significant effect on lodging at 6 of them (75% of the time) (Table 6). Seeding rate had an effect in 3 out of 8 site-years (38%), and there was interaction between PGR and seeding rate in 3 out of 8 site-years (38%) (Table 6). At the three locations where seeding rate was significant, Scott 2014 showed

Table 5. LSmeans of days to maturity for plant growth regulator (PGR) and seeding rate (SR) treatment effects across site-years.

	SR (no. m^{-2})				PGR			
Site-year	200	300	400	SR for interactions	None	Chlormequat	Ethephon	Trinexapac
Brandon 2014	87.3	87.3	87.3		85.7	85.6	89.0*	89.0*
Brandon 2016	99.0	97.8	96.3	200	97.3	99.0*	101.0*	98.8
				300	97.8	97.5	99.0	97.0
				400	96.8	96.5	96.0	96.0
Indian Head 2014	96.1	94.6	93.4		93.8	94.3	96.0*	94.5
Indian Head 2015	106.6	105.1	102.5	200	103.0	103.8	107.5*	112.0*
				300	102.8	102.3	109.5*	106.0
				400	100.5	101.8	104.5*	103.3
Indian Head 2016	103.7	103.3	103.4		103.5	103.3	103.7	103.4
Lacombe 2014	104.4	101.1	101.0	200	104.0	103.0	107.5*	103.0
				300	101.0	99.0*	105.5*	99.0*
				400	99.0	99.0	106.0*	100.0
Lacombe 2015	120.1	114.1	110.9		114.3	115	115.3	115.6
Lacombe 2016	110.8	108.4	108.2		109.3	109.1	109.1	109.1
Lethbridge 2014	90.9	90.6	89.8	200	90.8	91.3	92.3*	89.5
				300	90.5	90.0	91.3	90.5
				400	89.3	88.5	91.3*	90.0
Scott 2014	94.3	92.3	90.6		92.7	91.8	91.8	93.3
Scott 2015	112.9	111.6	108.6		102.4	106.2	129.5*	106.1
Scott 2016	87.6	86.4	85.8		86.3	86.2	86.4	87.7*

Note: * indicates a significant difference compared with the None treatment (compared within seeding rates for which interaction is significant) based on a Dunnett's test and an $\alpha = 0.05$.

Table 6. The p values for plant growth regulator (PGR) and seeding rate (SR) treatment effects on lodging across site-years.

				Regression significance[a]	
Site-year	PGR p	SR p	PGR × SR p	Linear	Quadratic
Brandon 2015	**<0.0001**	0.7034	0.8379	N/A	N/A
Brandon 2016	**0.0017**	0.7255	0.5924	N/A	N/A
Indian Head 2014	**<0.0001**	0.0580	**0.0210**	N/A	N/A
Indian Head 2015	0.0893	0.1783	**0.0043**	N/A	N/A
Lacombe 2014	**0.0031**	**0.0227**	0.0842	0.0088	0.3962
Lacombe 2016	0.8071	0.2377	0.4052	N/A	N/A
Scott 2014	**<0.0001**	**0.0378**	0.5328	0.0146	0.4140
Scott 2016	**0.0096**	**0.0269**	**0.0003**	0.0505	0.0547

Note: Bolded p values indicate significance at an $\alpha = 0.05$.
[a]Regression significance only given if seeding rate has a significant effect on lodging.

increased lodging with increased seeding rate, Lacombe 2014 showed decreased lodging with increased seeding rate, and Scott 2016 showed minimal differences in lodging (Table 7). Chlormequat showed relatively limited effects on lodging, increasing lodging in 1 site-year (Brandon 2016) and increasing lodging in 2 additional site-years for one seeding rate, while reducing lodging in 2 site-years for one seeding rate (Table 7). Out of the 14 comparisons made of chlormequat to the control (including the seeding rate interactions), 3 increased lodging (21%), while 2 decreased lodging (14%) (Table 7). The scale of lodging increase or decrease is a maximum of a point on the lodging scale, showing fairly limited effect. This limited effect on lodging in barley is consistent with previous research (Ramburan and Greenfield 2007; Perrott et al. 2018). Chlormequat efficacy has been

Table 7. LSmeans of lodging for plant growth regulator (PGR) and seeding rate (SR) treatments based on a lodging index.

	SR (no. m^{-2})			SR for	PGR			
Site-year	200	300	400	interactions	None	Chlormequat	Ethephon	Trinexapac
Brandon 2015	4.8	5.1	5.6		7.6	5.7	6.0	2.7*
Brandon 2016	1.8	1.7	1.8		1.5	2.5*	1.5	1.7
Indian Head 2014	0.3	0.5	0.6	200	0.8	0.2*	0.2*	0.4
				300	1.2	0.9	0.2*	0.2*
				400	1.8	0.9	0.2*	0.3*
Indian Head 2015	0.2	0.23	0.24	200	0.2	0.2	0.2	0.2
				300	0.4	0.2*	0.2*	0.2*
				400	0.2	0.4*	0.2	0.2
Lacombe 2014	1.9	1.1	1.0		1.0	1.4	2.5*	0.8
Lacombe 2016	3.1	2.3	3.4		2.5	2.9	2.9	3.3
Scott 2014	0.9	1.6	1.8		3.2	3.8	0.3*	1.1*
Scott 2016	0.3	0.2	0.2	200	0.2	1.0*	0.2	0.2
				300	0.2	0.2	0.2	0.2
				400	0.2	0.2	0.2	0.2

Note: Lodging index = $S \times I \times 0.2$, where S is the area of surface lodged (on a scale of 1 to 9, where 1 = none and 9 = total), and I is the intensity of lodging (on a scale of 1 to 5, where 1 = upright and 5 = flat).

* indicates a significant difference compared with the None treatment (compared within seeding rates in which the interaction is significant) based on a Dunnett's test and an $\alpha = 0.05$.

shown to be cultivar specific, so it is possible that other cultivars would exhibit a response; however, reduced sensitivity of barley to chlormequat applications is likely responsible for the limited effects (Baker and Hung 1985; Berry et al. 2004). Ethephon reduced lodging in 5 out of the 14 comparisons made with the control (36%) and increased lodging in 1 site-year (Lacombe 2014) (Table 7). The reduced lodging occurred at two out of the three locations with lodging where ethephon was applied late. Trinexapac reduced lodging in 5 out of the 14 comparisons to the control (36%) and showed the largest scale reduction in lodging when looking at higher lodging site-years such as Brandon 2014 or Scott 2014 (Table 7); however, there were also site-years when trinexapac was associated with a non-significant increase in lodging (Brandon 2016 and Lacombe 2016) (Table 7). Generally, the scale of lodging reductions was fairly minor as a result of PGR application, in many cases less than a full point in the index (Table 7). PGRs have been previously shown to significantly affect barley plant height, without affecting plant lodging (Ma and Smith 1991*b*; Perrott et al. 2018). Results from the present study suggest that PGR-related crop shortening is not a guarantee that lodging will be reduced. Effects of PGR on lodging were variable and not always predictable, nor were they always effective. In some heavier lodging environments, trinexapac provided the largest benefit.

Conclusions

Lodging is a significant threat to malt barley production on the Canadian Prairies. This study investigated if PGR application would reduce the impact of lodging and thus mitigate its effects on malt barley yield and quality. Overall, while all PGRs did reduce lodging in some site-years, trinexapac showed the largest scale lodging reductions followed by ethephon, although the ethephon response was not consistent. Chlormequat effect was inconsistent and quite minor in terms of effects. In Finland, it was recommended that chlormequat not be used for control of lodging in commercial barley production due to highly cultivar specific responses (Rajala and Peltonen-Sainio 2002). Producers need to have appropriate expectations that PGRs do not have the same consistent efficacy as other plant protection products such as herbicides. In particular, as we cannot accurately predict which growing seasons will have lodging-conducive conditions, PGRs may be applied in growing seasons when they are unnecessary. In this sense, PGRs are more similar to fungicide applications than herbicides — the presence of the pest (disease inoculum or lodging) is inconsistent and risks of establishment are weather dependent, yet product applications need to be made prior to visual symptoms in some cases (i.e., sclerotinia and plant lodging) to be effective. As a risk mitigation strategy, trinexapac and ethephon were the products most likely to have an effect; however, in attempts to mitigate lodging, unintended consequences of PGR application, primarily ethephon in this case, including increased tillering, delayed maturity, and decreased kernel weight (also for trinexapac) and plumpness, may increase harvest frustrations and increase risk for meeting malt quality thresholds. Negative impacts with no or limited associated lodging mitigation will be hard to justify for producers. Different barley cultivars may have responded differently than CDC Copeland; however, as CDC Copeland is still the most commonly grown malt barley cultivar in western Canada, these results would be representative of what many current malt barley producers would experience. Unfortunately, environment and weather are still the dominating factors when determining if lodging will occur in malt barley or not. PGR products may help mitigate some of that risk; however, product choice is important and, even with choosing the best product, they are not a guaranteed solution for the problem.

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References

Baker, E.A., and Hung, G.M. 1985. Factors affecting the uptake of chlormequat into cereal leaves. Ann. Appl. Biol. **106**: 579–590. doi:10.1111/j.1744-7348.1985.tb03149.x.

BASF. 2019. 3C Chlormequat 750. BASF UK, Cheadle, UK. 7 pp.

Bayer CropScience. 2019. Ethrel liquid plant growth regulator. Bayer CropScience, AB, Canada. 18 pp.

Belchim Canada. 2019. Manipulator 620 plant growth regulator. Belchim Canada, ON, Canada. 8 pp.

Berry, P.M., Griffin, J.M., Sylvester-Bradley, R., Scott, R.K., Spink, J.H., Baker, C.J., and Clare, R.W. 2000. Controlling plant form through husbandry to minimise lodging in wheat. Field Crops Res. **67**: 59–81. doi:10.1016/S0378-4290(00)00084-8.

Berry, P.M., Sterling, M., Spink, J.H., Baker, C.J., Sylvester-Bradley, R., Mooney, S.J., et al. 2004. Understanding and reducing lodging in cereals. Pages 217–271 in D. Sparks, ed. Advances in agronomy. Vol. 84. Academic Press, Cambridge, MA, USA.

Brewing and Malting Barley Research Institute. 2010. Quality factors in malting barley. 2 pp. [Online]. Available from http://bmbri.ca/variety-development/quality-factors-in-malting-barley/ [13 Mar. 2018].

Caldwell, C.D., Norrie, J., and Mellish, D.R. 1988. A comparison of ethephon alone and in combination with CCC or DPC applied to spring barley. Can. J. Plant Sci. **68**: 941–946. doi:10.4141/cjps88-114.

Canadian Food Inspection Agency. 1999. Registered variety: CDC Copeland (barley). [Online]. Available from https://www.inspection.gc.ca/active/netapp/regvar/regvare.aspx?id=2481 [25 Feb. 2020].

Clark, R.V., and Fedak, G. 1977. Effects of chlormequat on plant height, disease development and chemical constituents of cultivars of barley, oats and wheat. Can. J. Plant Sci. **57**: 31–36. doi:10.4141/cjps77-005.

Dahnous, K., Vigue, G.T., Law, A.G., Konzak, C.F., and Miller, D.G. 1982. Height and yield response of selected wheat, barley and triticale cultivars to ethephon. Agron. J. **74**: 580–582. doi:10.2134/agronj1982.00021962007400030041x.

Foster, K.R., Reid, D.M., and Taylor, J.S. 1991. Tillering and yield responses to ethephon in three barley cultivars. Crop Sci. **31**: 130–135. doi:10.2135/cropsci1991.0011183X003100010031x.

Garthwaite, D., Barker, I., Ridley, L., Mace, A., Parrish, G., MacArthur, R., and Lu, Y. 2016. Pesticide usage survey report 271: arable crops in the United Kingdom 2016. Defra, London, UK.

Green, C.F. 1986. Modifications to the growth and development of cereals using chlorocholine chloride in the absence of lodging: a synopsis. Field Crops Res. **14**: 117–133. doi:10.1016/0378-4290(86)90051-1.

Grijalva-Contreras, R.L., Macia-Duarte, R., Martinez-Diaz, G., Robles-Contreras, F., and Nunez-Ramirez, F. 2012. Effects of trinexapac-ethyl on different wheat varieties under desert conditions of Mexico. Agric. Sci. **3**: 658–662. doi:10.4236/as.2012.35079.

Jedel, P.E., and Helm, J.H. 1991. Lodging effects on a semidwarf and two standard barley cultivars. Agron. J. **83**: 158–161. doi:10.2134/agronj1991.00021962008300010036x.

Jung, J. 1984. Plant bioregulators in cereal crops: action and use. Pages 29–43 in R.L. Ory and F.R. Rittig, eds. Bioregulators: chemistry and uses. American Chemical Society, Washington, DC, USA.

Kirby, E.J.M. 1967. The effect of plant density upon the growth and yield of barley. J. Agric. Sci. **68**: 317–324. doi:10.1017/S0021859600012806.

Langseth, W., and Stabbetorp, H. 1996. The effect of lodging and time of harvest on deoxynivalenol contamination in barley and oats. J. Phytopathol. **144**: 241–245. doi:10.1111/j.1439-0434.1996.tb01523.x.

Littell, R.C., Milliken, G.A., Stroup, W.W., and Wolfinger, R.D. 2006. SAS system for mixed models. 2nd ed. SAS Institute Inc., Cary, NC, USA. 813 pp.

Ma, B.L., and Smith, D.L. 1991*a*. Apical development of spring barley in relation to chlormequat and ethephon. Agron. J. **83**: 270–274. doi:10.2134/agronj1991.00021962008300020002x.

Ma, B.L., and Smith, D.L. 1991*b*. The effects of ethephon, chlormequat chloride and mixtures of ethephon and chlormequat chloride applied at the beginning of stem elongation on spike-bearing shoots and other yield components of spring barley (*Hordeum vulgare* L.). J. Agron. Crop Sci. **166**: 127–135. doi:10.1111/j.1439-037X.1991.tb00894.x.

Ma, B.L., and Smith, D.L. 1992*a*. Chlormequat and ethephon timing and grain production of spring barley. Agron. J. **84**: 934–939. doi:10.2134/agronj1992.00021962008400060005x.

Ma, B.L., and Smith, D.L. 1992*b*. Growth regulator effects on aboveground dry matter partitioning during grain fill of spring barley. Crop Sci. **32**: 741–746. doi:10.2135/cropsci1992.0011183X003200030033x.

Ma, B.L., and Smith, D.L. 1992*c*. Modification of tiller productivity in spring barley by application of chlormequat or ethephon. Crop Sci. **32**: 735–740. doi:10.2135/cropsci1992.0011183X003200030032x.

McKenzie, R.H., Middleton, A.B., and Bremer, E. 2005. Fertilization, seeding date, and seeding rate for malting barley yield and quality in southern Alberta. Can. J. Plant Sci. **85**: 603–614. doi:10.4141/P04-152.

McMillan, T., Izydorczyk, M.S., and Li, Y. 2018. Quality of western Canadian malting barley: annual harvest report. Canadian Grain Commission, Winnipeg, MB, Canada. ISSN: 1182-4417. 35 pp. [Online]. Available from https://www.grainscanada.gc.ca/en/grain-research/export-quality/cereals/malting-barley/2018/03-production.html [5 June 2019].

Miziniak, W., Matysiak, K., and Kaczmarek, S. 2017. Studies on trinexapac-ethyl dose reduction by combined application with adjuvants in spring barley. J. Plant Prot. Res. **57**: 36–42. doi:10.1515/jppr-2017-0005.

Mulder, E.G. 1954. Effect of mineral nutrition on lodging of cereals. Plant Soil, **5**: 246–306. doi:10.1007/BF01395900.

O'Donovan, J.T., Turkington, T.K., Edney, M.J., Clayton, G.W., McKenzie, R.H., Juskiw, P.E., et al. 2011. Seeding rate, nitrogen rate, and cultivar effects on malting barley production. Agron. J. **103**: 709–716. doi:10.2134/agronj2010.0490.

O'Donovan, J.T., Turkington, T.K., Edney, M.J., Juskiw, P.E., McKenzie, R.H., Harker, K.N., et al. 2012. Effect of seeding date and seeding rate on malting barley production in western Canada. Can. J. Plant Sci. **92**: 321–330. doi:10.4141/cjps2011-130.

Perrott, L.A., Strydhorst, S.M., Hall, L.M., Yang, R.C., Pauly, D., Gill, K.S., and Bowness, R. 2018. Advanced agronomic practices to maximize feed barley yield, quality, and standability in Alberta, Canada. I. Responses to plant density, a plant growth regulator, and foliar fungicides. Agron J. **110**: 1447–1457. doi:10.2134/agronj2017.12.0683.

Pinthus, M.J. 1974. Lodging in wheat, barley, and oats: the phenomenon, its causes, and preventive measures. Adv. Agron. **25**: 209–263. doi:10.1016/S0065-2113(08)60782-8.

Rademacher, W. 2015. Plant growth regulators: backgrounds and uses in plant production. J. Plant Growth Regul. **34**: 845–872. doi:10.1007/s00344-015-9541-6.

Rajala, A., and Peltonen-Sainio, P. 2001. Plant growth regulator effects on spring cereal root and shoot growth. Agron. J. **93**: 936–943. doi:10.2134/agronj2001.934936x.

Rajala, A., and Peltonen-Sainio, P. 2002. Timing applications of growth regulators to alter spring cereal development at high latitudes. Agric. Food Sci. **11**: 233–244. doi:10.23986/afsci.5721.

Ramburan, S., and Greenfield, P.L. 2007. Use of ethephon and chlormequat chloride to manage plant height and lodging of irrigated barley (cv. Puma) when high rates of N-fertiliser are applied. S. Afr. J. Plant Soil, **24**: 181–187. doi:10.1080/02571862.2007.10634806.

Secan. 2015. CDC Copeland 2-row malting barley. ON, Canada. 2 pp.

Simmons, S.R., Oelke, E.A., Wiersma, J.V., Lueschen, W.E., and Warnes, D.D. 1988. Spring wheat and barley responses to ethephon. Agron. J. **80**: 829–834. doi:10.2134/agronj1988.00021962008000050029x.

Turkington, T.K., O'Donovan, J.T., Harker, K.N., Xi, K., Blackshaw, R.E., Johnson, E.N., et al. 2015. The impact of fungicide and herbicide timing on foliar disease severity, and barley productivity and quality. Can. J. Plant Sci. **95**: 525–537. doi:10.4141/cjps-2014-364.

USDA. 2013. Grain inspection handbook: Book II, Chapter 2: barley. U.S. Department of Agriculture, Grain Inspection, Packers and Stockyards Administration, Federal Grain Inspection Service.

Wiersma, D.W., Oplinger, E.S., and Guy, S.O. 1986. Environment and cultivar effects on winter wheat response to ethephon plant growth regulator. Agron. J. **78**: 761–764. doi:10.2134/agronj1986.00021962007800050002x.

Wiersma, J.J., Dai, J., and Durgan, B.R. 2011. Optimum timing and rate of trinexapac-ethyl to reduce lodging in spring wheat. Agron. J. **103**: 864–870. doi:10.2134/agronj2010.0398.

Yang, R.-C. 2010. Towards understanding and use of mixed-model analysis of agricultural experiments. Can. J. Plant Sci. **90**: 605–627. doi:10.4141/CJPS10049.

Zadoks, J.C., Chang, T.T., and Konzak, C.F. 1974. A decimal code for the growth stages of cereals. Weed Res. **14**: 415–421. doi:10.1111/j.1365-3180.1974.tb01084.x.