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Authors: Mills, A.A.S., Izydorczyk, M., Choo, T.M. (Alek), Durand, J., Mountain, N., et al.

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ARTICLE

Cultural practices to improve malt barley quality in the northeast with focus on the craft sector

A.A.S. Mills, M. Izydorczyk, T.M. (Alek) Choo, J. Durand, N. Mountain, M. Sorrells, and S.A.E. Fillmore

Abstract: Demand is increasing for locally grown malt barley (*Hordeum vulgare* L.) in northeastern North America, driven primarily by growth in the craft beer sector. A multi-site experiment was conducted to evaluate how variety (V), seeding rate (S), and nitrogen (N) fertilizer affect malt quality in the northeast. Two barley varieties (Cerveza and Newdale), two seeding rates (200 and 400 seeds m^{-2}), and five rates of actual applied N fertility (0, 30, 60, 90, and 120 kg ha^{-1}) were tested at Charlottetown, PE, Canada, Ithaca, NY, US, Princeville, QC, Canada, and New Liskeard and Ottawa, ON, Canada. Basic agronomic data were collected from all environments including yield, thousand kernel weight, and hectoliter weight. Barley of suitable quality was micromalted and subjected to malt quality analysis. Both V and S resulted in small effects on malt quality, however, N had the greatest effect on most measured variables. Increased rates of N application resulted in increased yield, hectoliter weight, and thousand kernel weight but had a negative effect on most quality traits, especially with increased protein content, reduced fine extract, Kolbach index, and friability, though it increased wort β-glucans. This study shows that for most years at most sites, it is possible to achieve malt quality in the northeast; however, excessive protein and the prevalence of preharvest sprout damage are the main barriers. The results of this study have implications for increased malt barley production for the craft sector as well as potential access to commodity markets for northeastern producers.

Key words: nitrogen, seeding rate, malt barley, craft malt.

Résumé : La demande d'orge brassicole (*Hordeum vulgare* L.) cultivée localement est à la hausse dans le nord-est de l'Amérique du Nord. On le doit principalement à la prolifération des brasseries artisanales. Les auteurs ont réalisé une expérience à plusieurs endroits en vue d'établir comment la variété (V — « variety »), la densité des semis (S — « seeding rate ») et les amendements azotés (N — « nitrogen ») affectent la qualité du malt dans cette région. Ils ont ainsi testé deux cultivars d'orge (Cerveza et Newdale), deux taux d'ensemencement (200 et 400 semences m^{-2}) et cinq taux d'application réel de N (0, 30, 60, 90 et 120 kg ha^{-1}) à Charlottetown (Île-du-Prince-Édouard), Ithaca (État de New York), Princeville (Québec), New Liskeard (Ontario) et Ottawa (Ontario). Des données agronomiques fondamentales ont été recueillies aux différents sites (rendement, poids de mille grains, poids d'un hectolitre). L'orge de qualité adéquate a été maltée en micro quantité, puis les auteurs ont analysé la qualité du malt. Les paramètres V et S exercent peu d'influence sur la qualité du malt. Des trois paramètres, c'est N qui a le plus d'effets sur la majorité des variables jaugées. Augmenter le taux de fertilisation accroît le

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A.A.S. Mills. Charlottetown Research and Development Centre, Agriculture and Agri-Food Canada, 440 University Avenue, Charlottetown, PE C1A 4N6, Canada.

M. Izydorczyk. Grain Research Lab, Canadian Grains Commission, 303 Main Street, Winnipeg, MB R3C 3G8, Canada.

T.M. Choo. Ottawa Research and Development Centre, Agriculture and Agri-Food Canada, 960 Carling Avenue, Ottawa, ON K1A 0C6, Canada.

J. Durand. Semican Research Centre, Semican, 1290 route 116 Ouest, Princeville, PQ G6L 4K7, Canada.

N. Mountain. New Liskeard Agricultural Research Station, Guelph University, 340 Armstrong Street N., New Liskeard, ON P0J 1P0, Canada.

M. Sorrells. Plant Breeding and Genetics Section, School of Integrative Plant Science, Cornell University, 240 Emerson Hall, Ithaca, NY 1485, USA.

S.A.E. Fillmore. Kentville Research and Development Centre, Agriculture and Agri-Food Canada, 32 Main Street, Kentville, NS B4N 1J5, Canada.

Corresponding author: A.A.S. Mills (email: aaron.mills@canada.ca).

rendement, le poids d'un hectolitre et celui de mille grains, mais on note des conséquences négatives sur la plupart des caractères qualitatifs (hausse de la teneur en protéines, diminution de la concentration d'extraits fins, indice de Kolbach, friabilité, plus forte teneur en bêta-glucanes dans le moût). Selon l'étude, il est possible d'obtenir un malt de qualité à la plupart des sites, la majorité des années, dans le nord-est, les principaux obstacles demeurant une trop grande concentration de protéines et les dommages attribuables à la germination sur pied. Les résultats de ces travaux pourraient concourir à une production accrue d'orge brassicole pour les brasseries artisanales et offrir de nouveaux débouchés aux agriculteurs du nord-est. [Traduit par la Rédaction]

Mots-clés : azote, taux d'ensemencement, orge brassicole, malt artisanal.

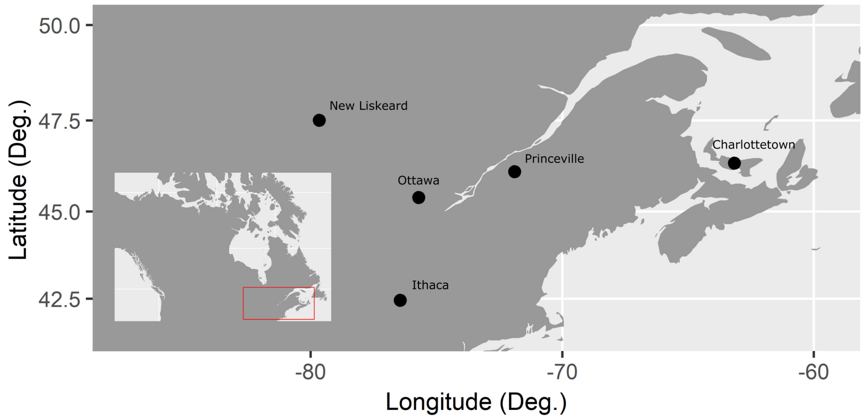
Introduction

Barley (*Hordeum vulgare* L.) is an excellent rotation crop for eastern North America. It serves to break pest and disease cycles when included in rotation with higher value legume or vegetable crops and requires relatively few inputs (Garstang et al. 2011). Depending on the specific area in the northeast, barley for feed has traditionally been grown in rotation with potato (*Solanum tuberosum* L.), canola (*Brassica napus* L.), soybean [*Glycine max* (L.) Merr.], or a pulse-like field pea (*Pisum sativum* L.). Despite the benefits of improving cropping system diversity by growing barley in the northeast, barley acreage has been decreasing steadily and is being replaced by shorter rotations that include more economically viable crops such as corn and soybean. If barley is grown in the northeast it is usually feed-type, and malt barley is not commonly grown in the region. The main reasons for the lack of malt barley production in the northeast is a combination of the distance to the nearest industrial processor, a lack of locally adapted germplasm, and insufficient management information to achieve acceptable malt quality. Therefore, it is essential to evaluate, validate, and modify agronomic production techniques for the region so that malt quality can be achieved.

Since 2010, the craft beer industry in North America has grown appreciably. In 2017, the increase of breweries in the United States has exceeded the all-time high levels achieved in 1875 (Hmielowski 2017), and although openings of new breweries have slowed, the market share of craft breweries in the US continues to grow (Brewers Association 2019*b*). In Canada, there were approximately 1000 breweries in 2018, which was a 21% increase over the previous year (Beer Canada 2019). A relatively high per capita number of breweries in the northeast has resulted in an increased demand for locally produced malt barley (Hmielowski 2017). In eastern Canada, from Ontario to Atlantic Canada, there are now approximately 650 craft breweries (Beer Canada 2019). In the northeastern US, there were approximately 1800 breweries in 2018, with the vast majority of growth observed in the craft sector (Brewers Association 2019*b*). Unlike the industrial brewing sector, which relies primarily on adjunct materials including rice and corn as beer ingredients, the craft sector uses malt barley as the principal ingredient. The craft sector in the US consumes approximately 40% of the malt barley purchased by brewers, despite only occupying 13% of the total market share and only 4% by volume (Brewers Association 2019*b*). In 2014, the Brewers Association (2019*a*) published a report outlining desirable qualitative aspects specific to the craft beer sector that described the ideal specifications for malt destined for the craft brewing sector. These specifications included lower levels of diastatic power (DP), α-amylase, free amino nitrogen (FAN), and total protein compared with the requirements of the industrial brewing sector. Despite the rapidly expanding number of breweries in northeastern North America, the number of malt houses has not seen a similar growth rate. One of the main causes of this reduced rate of growth is likely due to an overall lack of availability of locally sourced malt barley of acceptable quality. This limit in the supply of malt barley in the northeast is due to many factors, however, the general lack of region-specific data on the implications of agronomic cultural practices on malt quality is a key element.

There has been a significant amount of work done in western Canada and the midwestern US to measure the effects of various management factors on malt barley quality. Agronomic practices including fertility and seeding rate (McKenzie et al. 2005; Edney et al. 2012; O'Donovan et al. 2012, 2015, 2017*a*), variety (Laidig et al. 2014), and the effects of the previous crop (O'Donovan et al. 2017*b*) have all been previously reported. In western Canada, seeding rate has been previously shown to influence tiller number as well as grain plumpness (McKenzie et al. 2005; O'Donovan et al. 2009, 2011, 2012, 2017*a*). The body of previous research has been done under western Canada growing conditions that are marked by high temperatures, lower rainfall, and soils with higher organic matter and higher pH. There are currently no data available on the effects of cultural practices on malt barley quality in the northeast where seasonal growing temperatures are generally cooler and wetter, and both soil organic matter and pH are lower than in most areas of western Canada (Marshall et al. 1999). Another major difference between production data generated in western North America compared with eastern North America is the use of primary tillage in the east. The majority of agricultural production in mid-west to western North America is under no-till conditions. Finally, for most experiments evaluating the effects of malt barley management on qualitative analysis, studies have focused on the industrial brewing sector; however, there is a growing need for management data

Fig. 1. Map showing the geographical location of five sites participating in the study. Figure was created using the R packages ggplot2 (version 3.3.2), ggmaps (version 3.0.0), maps (version 3.3.0), and mapdata (version 2.3.0) and assembled using data from maps (version 3.3.0) and mapdata (version 2.3.0) databases under the GPL2 license. [Colour online.]



specifically for the craft sector, particularly in the northeast (Shrestha and Lindsey 2019).

To achieve malt quality barley, producers in the northeast need to understand the appropriate management techniques to use and they need to know whether the data generated for the industrial brewing sector in western Canada and the US is relevant to the emerging production of malt barley in the region. Data for the comparison of locally available varieties, selected seeding rates, and the appropriate rates for nitrogen fertilizer are needed. The primary research objective of this study was to measure the effects of cultural practices on malt barley quality in the northeast, including variety selection, appropriate seeding rates, and the effects of increasing nitrogen fertility, and to evaluate if the achieved quality is suitable for the craft sector.

Materials and Methods

Sites and climate

The experiment was conducted over 3 yr (2014–2016) at five sites across northeastern North America. Sites included Agriculture and Agri-Food Canada research farms in Charlottetown, PE, and Ottawa, ON, a site in Quebec located at the Semican Research Farm in Princeville, a University of Guelph research site located in New Liskeard, ON, and a site at Cornell University located in Ithaca, NY (Fig. 1). Sites were chosen based on geographic locale, the diversity of soil types, their capacity to conduct the field experiment, and the relative interest in each area with regard to the production of malt barley for the craft market (Table 1).

Historical weather data were taken from Environment Canada for all Canadian sites (http://climate.weather.gc.ca/historical_data/search_historic_data_e.html). Weather data for the Ithaca site were taken from the Northeast Regional Climate Center (http://www.nrcc.cornell.edu/wxstation/ithaca/ithaca.html). Cumulative precipitation and growing degree days (GDD; 5 °C base) were calculated individually for each site and treated as a random factor under the "site" stratum.

The experiment was conducted under a Latinized design comprised of three replicates per treatment. The treatments included two malt barley varieties, two seeding rates, and five levels of actual nitrogen (N). The two spring malt barley varieties chosen for the study were Cerveza (Legge et al. 2013) and Newdale (Legge et al. 2008). Newdale was developed in western Canada. These were selected for evaluation as they are popular varieties for those growing for the craft malt sector, primarily based on their relatively high yields and reported preharvest sprout and disease resistance when grown in the region. These varieties were also readily available to most growers in the northeast.

The production of malt barley is relatively new in the northeast; although seeding rates have been previously shown to have an effect on malt barley qualitative parameters, this factor remains untested in the region. Therefore, seeding rates of 200 and 400 seeds m^{-2} were chosen for this particular study as 200 seeds m^{-2} is lower than the average rate for the region and 400 seeds m^{-2} is higher (OMAFRA 2017). These rates were selected to cover a range of responses from low to high. Nitrogen application rates in malt barley has been studied in other regions of North America, particularly in western Canada where moisture tends to be limited through most growing seasons. This work has not been done under the higher moisture conditions of the northeast, and rates of 0, 30, 60, 90, and 120 kg ha^{-1} were selected as increasing levels of nitrogen. Plot sizes and the equipment used for the implementation of the experiment varied by site and depended on the equipment available; however, urea (46–0–0) was used as a nitrogen source, hand-applied at all sites and soil was incorporated prior to seeding the experiment. Weed control at all sites consisted of a single application of MCPA (2-methyl-4-chlorophenoxyacetic acid) at the appropriate time and rate for each site

Table 1. Site attributes, crops grown previous to malt barley, and results of preliminary screening for malt suitability.

Site	Soil classification	Year	Previous crop	Suitable for malting
Charlottetown	Orthic humic ferro podzol	2014	Red clover	Yes
		2015	Red clover	No (high protein)
		2016	Buckwheat	Yes
Ithaca	Luvicgleysol	2014	Buckwheat	Yes
		2015	Buckwheat	Yes
		2016	Fallow	Yes
New Liskeard	Lacustrine gleysol	2014	Soybean	Yes
		2015	Soybean	No (low GE, pregerminated)
		2016	Red clover	No (high protein)
Ottawa	Orthic melanic brunisol	2014	Soybean	Yes
		2015	Soybean	No (low GE, pregerminated)
		2016	Soybean	No (low GE, pregerminated)
Princeville	Orthic eutricbrunisol	2014	Flax	Yes
		2015	Soybean	Yes
		2016	Winter wheat	Yes

Note: GE, germination energy.

depending on local recommendations; no fungicide was applied at any site through the duration of the experiment. Following harvest, each site measured agronomic components including yield, thousand kernel weight (TKW), and hectoliterweight before samples were sent for malt quality analysis.

Barley samples (1 kg per site) for all replicates including variety (Cerveza and Newdale), seeding rate (200 and 400 seeds m^{-2}), and nitrogen rate (0, 60, and 120 kg ha^{-1}) were sent to the Canadian Grain Commission, Grain Research Laboratory in Winnipeg, MB, Canada, for barley and malt quality analyses. To reduce testing costs and capture the full range of treatment effects, samples from treatments receiving nitrogen application rates of 30 and 90 kg N ha^{-1} were not submitted for analysis. Barley grown in all environments was tested for protein content (ASBC Barley-7B), TKW (ASBC Barley-2D), plumpness (ASBC Barley-2C), and germinative energy (ASBC Barley-3A) using methods described by the American Society of Brewing Chemists (ASBC) Methods of Analysis (ASBC 2004). Germination index (GI) was calculated from germinative energy results according to Riis and Bang-Olsen (1991). Barley that met the specifications of appropriate protein levels and germination energy was malted and subjected to various malting quality tests (Table 1). Barley that was determined as not suitable for malting exhibited either very high concertation of proteins (>140 g kg^{-1}) and (or) reduced germination energy (<95%) due to preharvest sprouting (pregermination) as determined by the rapid viscosity analysis (Table 1) (Izydorczyk 2010). Barley was malted in a Phoenix Automated Micromalting machine (Adelaide, SA, Australia). Steep-out moisture was calculated from the difference in weight between dry matter barley and steeped barley.

Malt analysis was performed according to the procedures outlined in the ASBC Methods. Malt samples were analyzed for moisture content (ASBC Malt-3) and malt modification by friability with a Pfeuffer friabilimeter (ASBC Malt12). Wort viscosity was determined with an Anton PaarLovis ME rolling-ball viscometer (ASBC Wort-13B), wort FAN concentration was determined by segmented flow analysis (ASBC Wort-12B), and wort colour was determined spectrophotometrically at 430 nm (ASBC-Wort-9). The content of β-glucan in wort was determined by measuring fluorescence from calcofluor binding with β-glucan polymers by segmented flow analysis (Skalar, the Netherlands) (ASBC Wort-18B). Protein in unhopped wort (soluble protein) was determined by spectrophotometry based on the differing ultraviolet absorption of protein at 215 and 225 nm (ASBC Wort-17). Malt protein content was measured by nitrogen combustion with a LECO protein analyzer (ASBC Malt-8B).

Data analysis

All analyses were performed using GENSTAT version 19 (VSN International, Harpenden, UK). A mixed model ANOVA was used to measure the influence of treatment factors on barley yield and quality parameters. Agroclimatological factors (precipitation and accumulated GDD), site, and year factors were all included as random effects; variety, seeding rate, and nitrogen application rate were included as fixed effects. Multivariate analysis, including principal component analysis (PCA), was used to further elucidate differences between treatments and trends in the data. Using means from ANOVA REML datasets, PCA incorporating Euclidian distances were used to evaluate barley yield and agronomic components as well as malt qualitative parameters. All line graphs were created using R version 4.0 including the package's ggmap version 3.0.0 (Kahle and Wickham 2013), maps version 3.3.0, mapdata version 2.3.0, and ggplot2 version 3.3.2; biplots were prepared using Sigmaplot version 13.0.0.83.

Results and Discussion

Climate

Accumulated GDD calculated with 5 °C base temperature (GDD5) and monthly precipitation were evaluated for each site and included under the "site" stratum for the analyses. Across all sites, 2014 was wetter and cooler than the other years of the study; 2016 was hotter and dryer than the other years (Figs. 2*a* and 2*b*). Monthly precipitation and GDD5 were largely determined to be site dependent, and so were only correlated to the first stratum of the analysis, which is where the variation of year and site were also are determined. All the treatments are below this stratum, so there is no additional variation that has not already been removed by the year and site differences.

Yield and barley quality data

Overall effects of treatment factors on barley agronomic variables were consistent across sites. Variety, seeding rate, and nitrogen application rates had all had a significant effect on yield, TKW, and hectoliterweight (Table 2). Yield averaged over sites and years was 2918 kg ha^{-1} with a range of 870–5049 kg ha^{-1} (Ottawa = 0 kg N ha^{-1} at 200 seeds m^{-2}; New Liskeard = 120 kg N ha^{-1} at 400 seeds m^{-2}). Generally, yields showed a quadratic increase associated with increasing nitrogen application rates (Fig. 3). A seeding rate of 200 seeds m^{-2} tended to have slightly higher yields than 400 seeds m^{-2} (2961 vs. 2876 kg ha^{-1}) and Cerveza consistently resulted in significantly higher average yields than Newdale (2943 vs. 2893 kg ha^{-1}). The optimum yield in response to nitrogen application was 90 kg ha^{-1}.

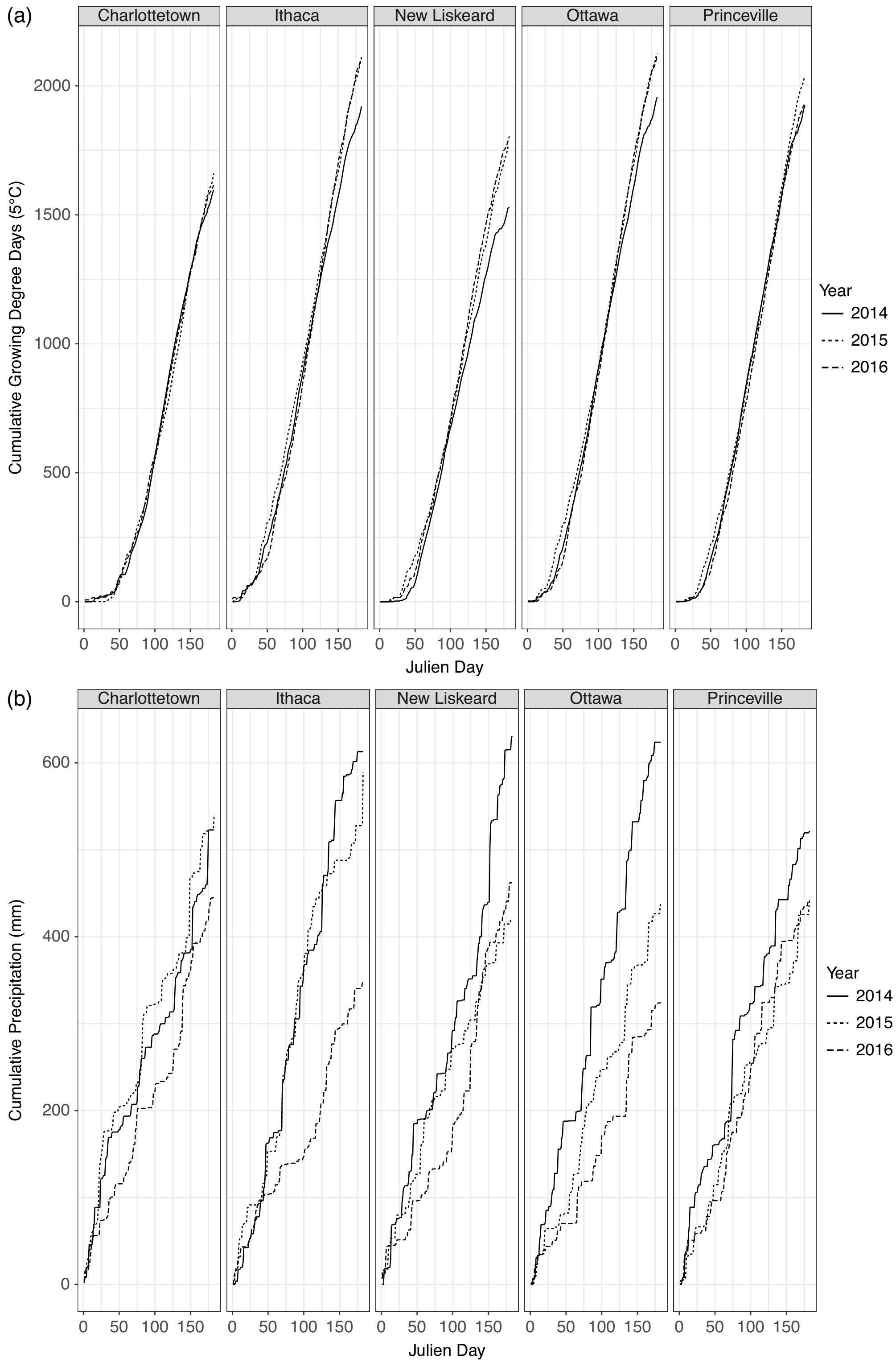
TKW increased with increasing nitrogen application rates and ranged from 34.7 to 46.4 g (Ottawa = 0 kg N ha^{-1} applied to Newdale seeded at 400 seeds m^{-2}; New Liskeard = 60 kg N ha^{-1} applied to Cerveza seeded at 200 seeds m^{-2}). Cerveza had significantly higher TKW than Newdale (41.9 vs. 40.3 g) and 200 seeds m^{-2} had significantly higher TKW than 400 seeds m^{-2} (41.9 vs. 40.4 g). Both of these traits have been previously reported from western Canada (O'Donovan et al. 2011; Legge et al. 2013). Finally, hectoliterweight also increased with increasing rates of nitrogen application and ranged from 54.89 to 65.5 kg hL^{-1} (Princeville = 60 kg N ha^{-1} applied to Cerveza seeded at 400 seeds m^{-2}; Ithaca = 0 kg N ha^{-1} applied to Cerveza seeded at 400 seeds m^{-2}). There was an interaction between variety and nitrogen rate on TKW ranging from 39.7 to 42.7 g (Newdale = 30 and 90 kg N ha^{-1}; Cerveza = 0, 60, and 120 kg N ha^{-1}) and on hectoliterweight (60.4 kg hL^{-1} for Newdale with 0, 60, and 120 kg N ha^{-1} vs. 61.9 for Cerveza with 30 and 90 kg N ha^{-1}). No other interactions were observed (Table 2).

The findings of the present study are largely consistent with what has been reported in previous studies. Increasing the rate of nitrogen application has been shown to have cultivar-specific responses (Edney et al. 2012), with an overall increase in kernel size and hectoliterweight. With increasing nitrogen, the relative rate of increase can vary on a variety-by-variety basis, but the actual optimum nitrogen rate is similar with the two varieties tested. The effect of seeding rate on yield has been shown to have negative or neutral effects (Spaner et al. 2001; O'Donovan et al. 2009, 2011; Edney et al. 2012) as well as positive effects (McKenzie et al. 2005; O'Donovan et al. 2012). McKenzie et al. (2005) report optimum seeding rates in western Canada to be approximately 150–200 seeds m^{-2}, whereas in the northeast 250–350 seeds m^{-2} are recommended (OMAFRA 2017). In western Canada, slight yield gains have been reported at higher seeding rates and there have been reports suggesting that there are negative effects on malt quality (McKenzie et al. 2005; Edney et al. 2012; O'Donovan et al. 2012). O'Donovan et al. (2017*a*) reported higher seeding rates resulted in reduced plumpness, yet uniformity in kernel size. This effect resulted in a quicker start to germination, lower protein and β-glucan, and higher friability values, indicating more uniform kernel modification. For malt barley production in the northeast, increased seeding rates needs to be combined with an aggressive fungicide program as a combination of increased canopy and limited airflow may result in an increase in *Fusarium* pressure (Choo et al. 2014). Although early planting tends to result in higher feed barley yields in eastern Canada (Choo et al. 2014), when the seeding date is delayed due to weather then the seeding rate is increased to compensate for a reduced yield (O'Donovan et al. 2012). A study published from western Canada showed that there was no effect of planting date on malt quality, nor did the interaction between planting date and seeding rate have any effects on malting quality (O'Donovan et al. 2017*a*). Although higher seeding rates have been shown repeatedly to result in lower hectoliterweight and TKW, the authors suggest that the evenness of kernel size is more important than the percentage of plump kernels overall.

Grain quality parameters relevant to maltsters

Malt quality data were only analyzed based on sites which met preliminary selection criteria based on protein level, values for germination energy, and the degree of pregermination (Table 1). If samples were deemed suitable for malting, all replicates were sent for individual analysis (three replicates per treatment). As mentioned above, samples from treatments receiving application rates of 30 and 90 kg N ha^{-1} were not submitted for analysis to reduce experimental costs. Pregermination was the most common reason for malting rejection

Fig. 2. Plots indicating annual (*a*) cumulative growing degree days (5 °C) and (*b*) monthly precipitation for each study location.



(Table 1). This results from increased moisture in the environment (heavy dew, rain events) after barley has reached physiological maturity (Gordon 1970). This response is exacerbated for varieties from western North American breeding programs, where enzymatic activity has been part of the breeding selection criteria (Henson et al. 2018). Mitigation of pregermination in the northeast can be accomplished by planting varieties that were bred under similar environmental conditions (i.e., UK, France, Scandinavian countries) and combining

Table 2. Analysis of variance mixed models analysis for barley agronomic response to applied nitrogen (N), variety (V), and seeding rate (S) as sources of variance.

Source	Yield	TKW	HLW
N	***	***	***
Linear	***	***	***
Quadratic	***	***	***
Deviations	NS	NS	NS
V	**	***	***
S	***	***	***
N × V	NS	**	***
Linear	NS	*	NS
Quadratic	NS	NS	NS
Deviations	NS	*	**
N × S	NS	NS	NS
Linear	NS	NS	NS
Quadratic	NS	NS	NS
V × S	NS	NS	NS
V × S × N	NS	NS	NS
Linear	NS	NS	NS
Quadratic	NS	*	NS

Note: Results are presented for all sites and years for yield, thousand kernel weight (TKW), and hectoliter weight (HLW). *, **, and ***, significant at $P \leq 0.05$, $P \leq 0.01$, and $P \leq 0.001$, respectively; NS, not significant.

with appropriate harvest timing, whereby grain is harvested at a higher moisture value and dried using forced air.

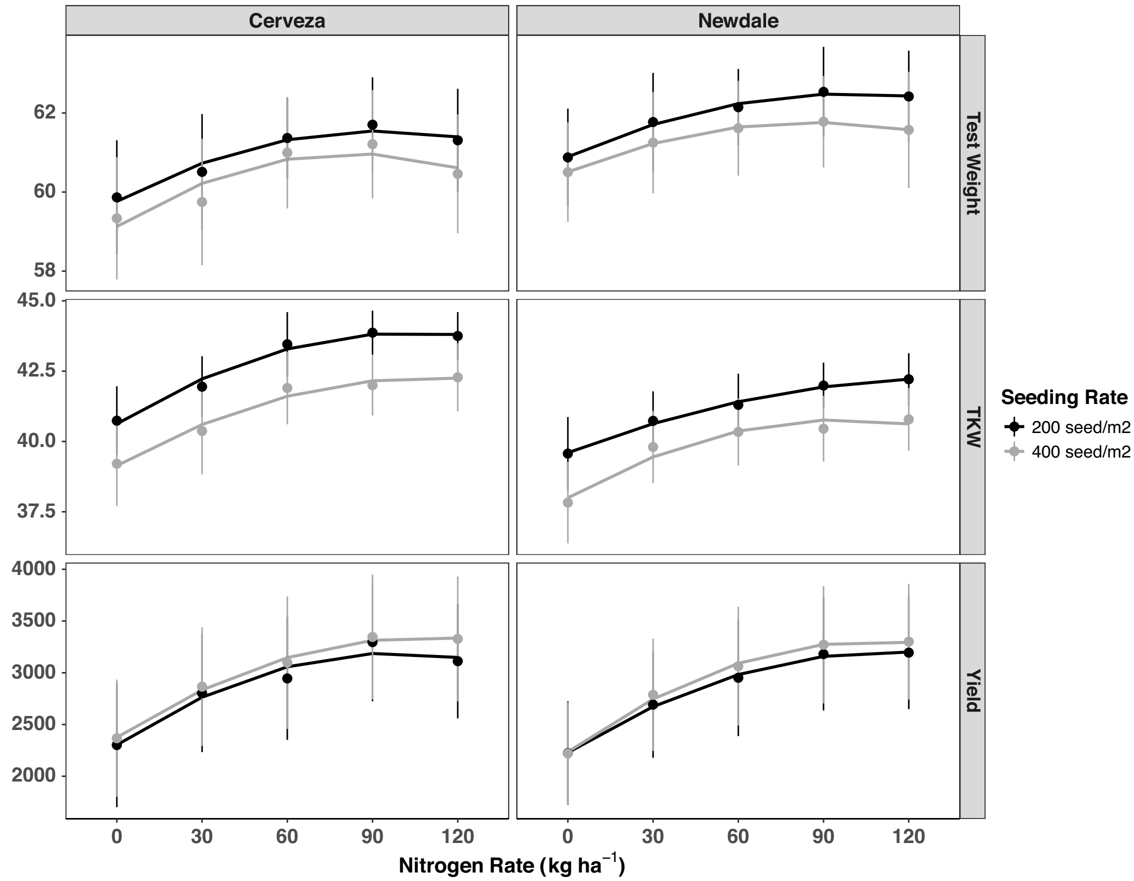
Variety had a significant effect on the percentage of plump kernels (78.1% vs. 79.4% for Newdale and Cerveza), protein (119 g kg^{-1} for Cerveza vs. 122 g kg^{-1} for Newdale), germination energy (4 mL; 84.9% for Cerveza vs. 90.4% Newdale), and GI values (6.8 and 7.3 for Cerveza and Newdale, respectively) (Table 3). Seeding rate had a highly significant effect on the percentage of plump kernels (79.7% vs. 77.9% for 200 and 400 seeds m^{-2}, respectively) and GI, with values ranging from 7.0 to 7.4 (200 vs. 400 seeds m^{-2}) (Fig. 4). Seeding rate also had a significant effect on barley protein (12.3 vs. 12.2 for 200 vs. 400 seeds m^{-2}) and germination (4 mL) with values ranging from 92.4% to 92.8% (200 vs. 400 seeds m^{-2}). Increased nitrogen application rate had a significant effect on the percentage of plump kernels (76.6%–80.1%), barley protein (112–135 g kg^{-1}), germination (4 mL; 93.2%–91.8% for 0–120 kg N ha^{-1}), GI (7.4–7.0, 0–120 kg N ha^{-1}), and percent moisture (9.6%–9.7%) (Fig. 4). The interaction between variety and nitrogen showed an effect on the percentage of plump grains (78.1%–80.0%) and on germination (4 mL; 91.3%–93.4%). The interaction between variety and seeding rate had an effect on the percentage of plump kernels (77.3%–80.9% seeded at 200 seeds m^{-2} for Cerveza vs. Newdale, respectively), kernel size, and germination energy (4 mL). The interaction between nitrogen rate and seeding rate had an effect on germination (4 mL) with values ranging from 90.8%–94.3% for 60 kg N ha^{-1} seeded at 200 seeds m^{-2} vs. 60 kg N ha^{-1} seeded at 400 seeds m^{-2}. Interaction between all three factors influenced grain percent moisture (9.66%–9.73% for Cerveza seeded with 0 kg N ha^{-1} at 200 seeds m^{-2} vs. 400 seeds m^{-2}) (Table 3).

Malting quality relevant to brewers

Variety had a significant effect on all malting quality attributes with the exception of colour and friability (Table 4). When averaged across all environments and growing conditions, Cerveza had a slightly higher malt yield (90.5% vs. 90.1%) and hydrated to a slightly lower steep-out moisture (46.1% vs. 46.5%) compared with Newdale (Fig. 5). There were significant differences between Cerveza and Newdale in malt protein (116 and 119 g kg^{-1}, respectively), wort soluble protein (53 and 57 g kg^{-1}, respectively), Kolbach index (46.7 and 48.1, respectively), and FAN (241.5 and 253.3 mg L^{-1}, respectively). Genetic variability in grain protein between varieties has been well documented previously (Laidig et al. 2014, 2017*a*, 2017*b*). Increasing application rate from 0 to 120 kg N ha^{-1} significantly increased malt protein (107–129 g kg^{-1}) and wort soluble protein (54–56 g kg^{-1}) but decreased the Kolbach index (50.7–43.9). FAN decreased slightly from 250 to 246 mg kg^{-1} with increasing nitrogen rates. Increasing seeding rates from 200 to 400 seeds m^{-2} had no effect on malt proteins, but significantly increased wort soluble protein (54–56 g kg^{-1}), Kolbach index (46.8–47.9), and FAN (241–253 mg kg^{-1}). The interaction between variety and seeding rate significantly increased Kolbach index and soluble protein. Also, interactions between variety and nitrogen rate had an effect on soluble protein (an average increase from 5.3% to 5.8%) and Kolbach index (an average increase from 46.4 to 48.9) with increased rates of nitrogen showing associated increases in soluble protein and decreasing values for the Kolbach index (Table 4).

When averaged across environments and growing conditions Cerveza produced a significantly higher level of malt extract compared with Newdale (81.3% vs. 79.7%, respectively). Overall, the malt extract was negatively and significantly affected by increasing nitrogen application and decreased from 81.1% to 79.9% when nitrogen rate increased from 0 to 120 kg ha^{-1}. There were no detected effects of increasing seeding rate on malt extract. The results of this study corroborated previous findings indicating that the malt extract may be influenced by barley genotype and is inversely related to barley protein concentrations (Edney et al. 2012; O'Donovan et al. 2017*a*).

Fig. 3. Variable response to the tested factors of variety, seeding rate, and nitrogen application rate. Points represent mean values and error bars represent standard error values from the mixed model analysis for site-year averages. Units for test weight are kg hL^{-1}, thousand kernel weight (TKW) is g, and yield is kg ha^{-1}.



Excessive protein is not desirable in malting barley for several reasons. As the relationship between the proportion of starch and protein in grain is inverse, higher levels of protein result in a lower amount of starch that can be converted into fermentable sugars, resulting in lower malt extract. Higher protein levels in barley tend to produce higher levels of proteolytic enzymes which can lead to over modification and excessive solubilization of proteins (Schwarz and Li 2011). The increase in the ratio of soluble to total protein has been reported to lead to "chill haze" in beer (Leiper and Miedel 2009). In the craft brewing sector, depending on the brewing style, haziness is not necessarily considered to be a negative attribute; however, if the desired outcome is for a clear and light pilsner style, haziness is detrimental and removing proteins from the beer would result in increased costs for filtering.

FAN is a group of protein-derived, low-molecular-weight nitrogenous compounds present in wort. The level of FAN is determined primarily by the extent to which the proteolytic enzymes are able to act on grain proteins. These low-molecular-weight nitrogenous compounds can also affect beer colour through the Maillard reaction (Bathgate 1973). Slightly higher FAN levels are desired in adjunct brewing, in which a large proportion of starchy adjuncts do not contribute much to the overall FAN level. FAN compounds are essential for yeast nutrition and the overall brewing performance (Pierce 1982). In craft all-malt brewing, FAN holds the same importance for yeast health; however, excessive levels of FAN can lead to premature spoilage, thereby limiting the shelf life and geographical distribution of the beer. The Brewers Association (2019*a*) recommends wort FAN levels below 150 ppm to maintain flavor stability and beer shelf-life. FAN levels for both genotypes used in this study were relatively high and showed a tendency to increase with both higher seeding rates and higher fertility, suggesting that cultural practices are a driver of FAN concentrations. Both of these varieties were developed for the adjunct-based industrial brewing sector, which requires higher wort FAN concentration. Variety aside, it is clear that FAN is influenced by nitrogen application and protein management.

Enzymatic activity in malt is important for both malting and brewing processes. The α-amylase is an essential enzyme responsible for the initial breakdown of starch molecules during malting and brewing processes. On average, the level of malt α-amylase in Cerveza

Table 3. Analysis of variance mixed model analysis for the response of grain quality parameters relevant to malting as affected by applied nitrogen (N), variety (V), and seeding rate (S) as sources of variance.

Source	Plump (%)	Moisture (%)	Protein (%)	Germination energy (4 mL) (%)	Germination index
N	***	**	***	***	***
Linear	***	NS	***	***	***
Quadratic	**	*	***	NS	NS
V	***	NS	***	***	***
S	***	NS	**	*	***
N × V	***	NS	NS	**	NS
Linear	***	NS	NS	NS	NS
Quadratic	NS	NS	NS	**	NS
N × S	NS	NS	NS	*	NS
Linear	NS	NS	NS	*	*
Quadratic	NS	NS	NS	NS	NS
V × S	*	NS	NS	***	NS
V × S × N	NS	*	NS	*	NS
Linear	NS	**	NS	*	NS
Quadratic	NS	NS	NS	NS	*

Note: *, significant at $P \leq 0.05$; **, significant at $P \leq 0.01$; ***, significant at $P \leq 0.001$; NS, not significant.

Fig. 4. Variable responses to the tested factors of variety, seeding rate, and nitrogen application rate. Points represent mean values and error bars represent standard error values from the mixed models analysis of site-year averages. Germ., germination.

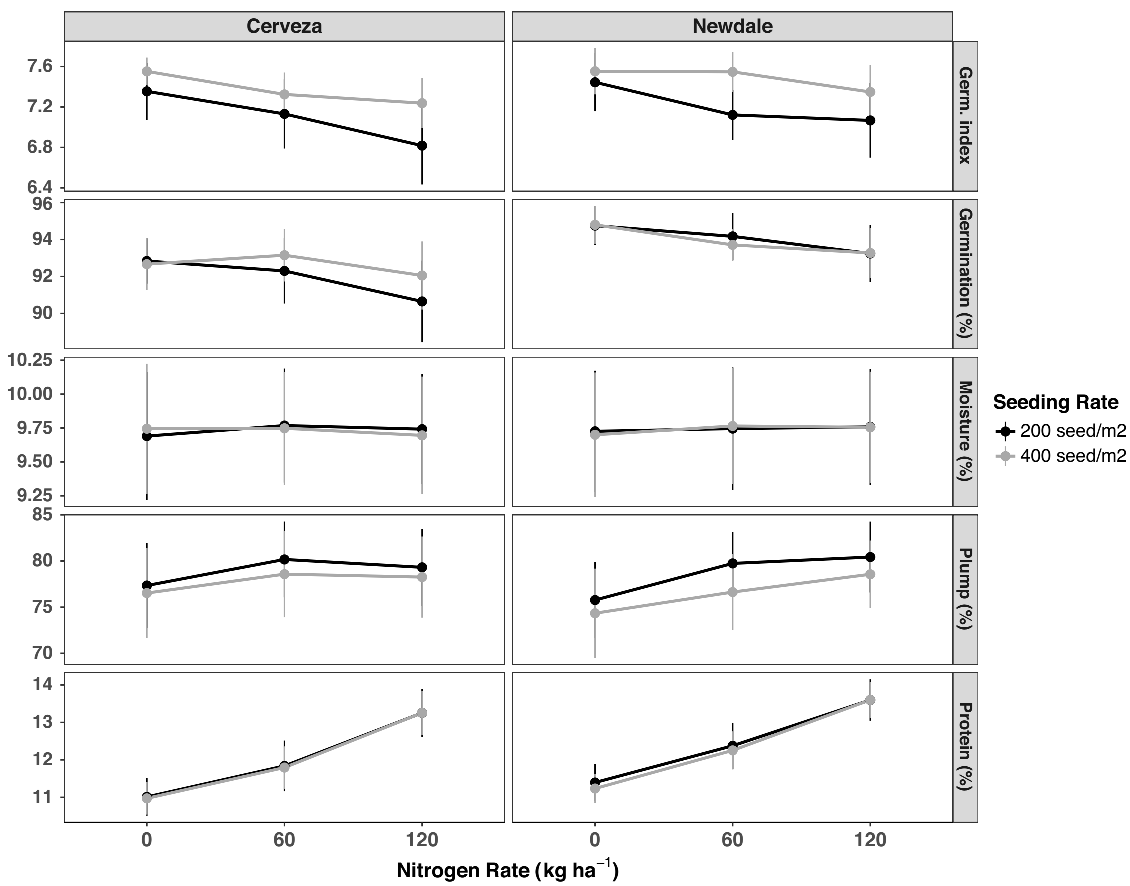


Table 4. Mixed model analysis of variance for malt quality.

Source	Steep-out moisture (%)	Malt yield (%)	Fine extract (%)	Malt protein (%)	Soluble protein (%)	Kolbach index (%)	β-glucan (mg kg^{-1})	Viscosity (cP)	Diastatic power (°L)	α-amylase (DU)	Colour (°L)	FAN (mg kg^{-1})	Friability (mg g^{-1})
N	***	**	***	***	***	***	***	***	***	***	***	*	***
Linear	***	**	***	***	***	***	***	***	***	***	***	**	***
Quadratic	**	NS	***	**	NS	NS	***	**	NS	NS	NS	NS	***
V	***	***	***	***	***	***	***	***	***	***	NS	***	NS
S	***	NS	NS	NS	***	***	***	**	NS	NS	***	***	NS
N × V	*	*	*	NS	***	**	***	*	*	NS	NS	*	*
Linear	*	NS	*	NS	NS	NS	***	NS	**	NS	NS	*	NS
Quadratic	NS	*	NS	NS	***	***	***	*	NS	NS	NS	*	*
N × S	NS	*	NS	NS	NS	NS	***	NS	NS	***	NS	NS	**
Linear	NS	*	NS	*	NS	NS	***	NS	NS	**	NS	NS	**
Quadratic	NS	NS	NS	NS	NS	NS	***	NS	NS	*	NS	NS	NS
V × S	NS	NS	NS	NS	**	***	NS	NS	NS	*	*	NS	***
V × S × N	**	NS	NS	NS	NS	NS	**	NS	**	NS	NS	NS	NS
Linear	*	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Quadratic	*	NS	NS	*	NS	NS	**	NS	**	NS	NS	NS	NS

Note: N, nitrogen; V, variety; S, seeding rate; FAN, free amino nitrogen; *, significant at $P \le 0.05$; **, significant at $P \le 0.01$; ***, significant at $P \le 0.001$; NS, not significant.

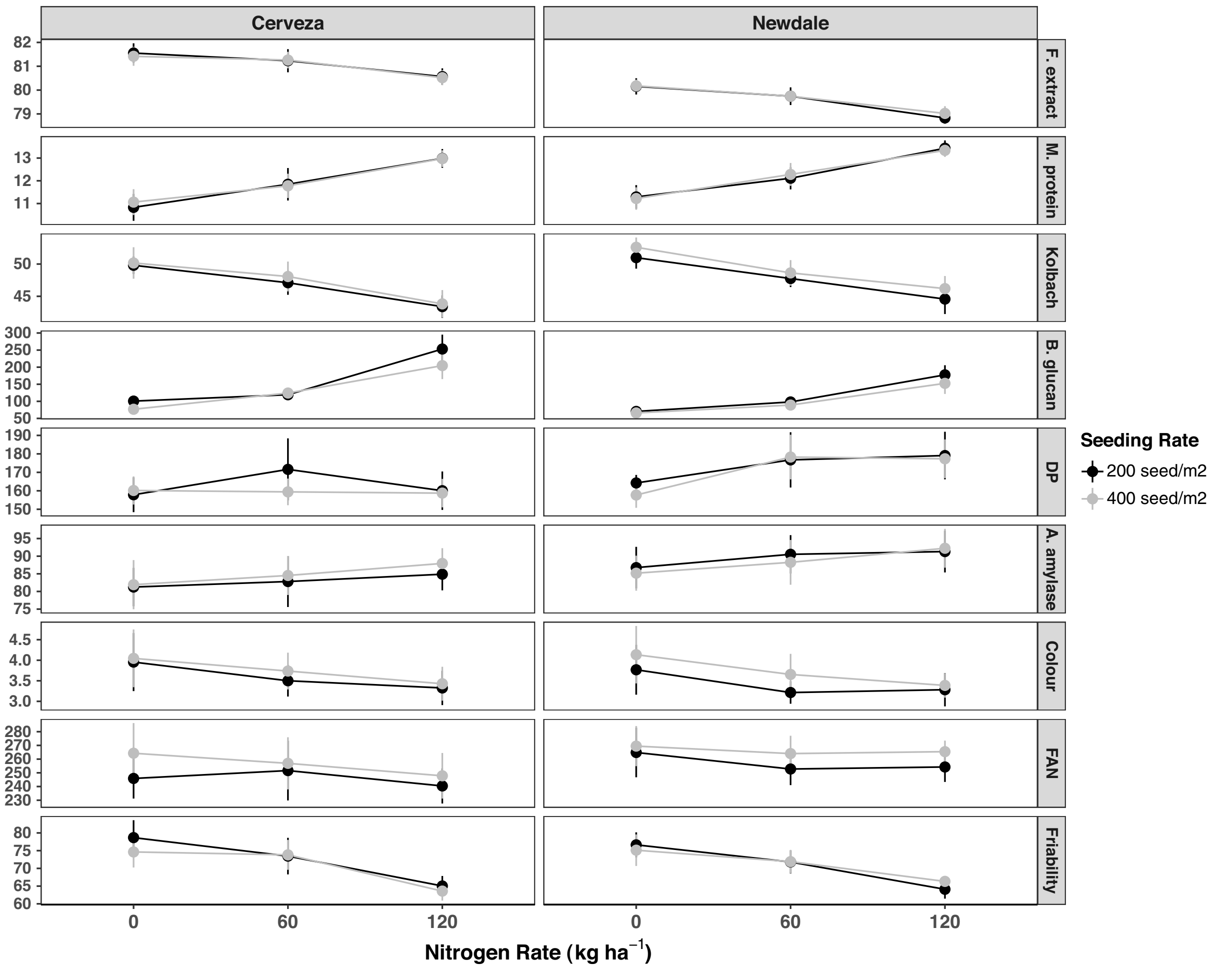
(85 mg kg^{-1}) was lower than in Newdale (89 mg kg^{-1}). Nitrogen application rate had a highly significant effect on α-amylase resulting in an increase from 84.8 to 88.4 mg kg^{-1} with increasing nitrogen application rate (0–120 kg ha^{-1}). Although seeding rate on its own did not show a significant effect on α-amylase activity, interactions including nitrogen × seeding rate (N × S) and variety × seeding rate (V × S) were significant. Mean concentrations of α-amylase in these interactions ranged between 82.2 and 90.1 mg kg^{-1} (200 seeds m^{-1}, 0 kg ha^{-1} and 400 seeds m^{-2}, 120 kg ha^{-1}, respectively) for N × S. Concentrations of α-amylase ranged between 86.6 and 87.9 mg kg^{-1} (Newdale vs. Cerveza seeded at 400 seeds m^{-2}).

Malt DP is a measure of the total activity of malt enzymes (α-amylase, β-amylase, limit dextrinase, and amyloglucosidase) that hydrolyze starch into fermentable sugars, with β-amylase having the biggest contribution to the overall DP level. Cerveza consistently exhibited lower DP values than Newdale (156.4° vs. 165.3°). The lower DP of Cerveza malt could be partly attributed to generally lower protein contents in barley and malt of this genotype compared with Newdale (Legge et al. 2008, 2013). In general, an increase in DP from 156.9° to 164.2° was observed with increasing nitrogen rates (0–120 kg ha^{-1}). These effects were compounded with the interaction N × V, where values ranged from 155.4 to 165.5 (Cerveza at 0 kg ha^{-1} vs. 60 kg ha^{-1}). Finally, these responses were also observed in V × S × N ($P = 0.006$) with values ranging from 152° to 172.1° for Cerveza seeded at 200 seeds m^{-2} with 0 kg N ha^{-1} vs. Newdale seeded at 400 seeds m^{-2} with 120 kg N ha^{-1} (Table 4).

The measurement of DP is important in both the malt house and the brewery. A high level of DP is normally desirable in adjunct brewing to ensure complete starch hydrolysis in unmalted adjunct material. For the craft all-malt brewing, lower DP levels are sufficient for complete conversion of malt starch into fermentable sugars. Increases in DP have previously been shown to be correlated with increased applied nitrogen fertility and corresponding increases in protein levels in barley (O'Donovan et al. 2011).

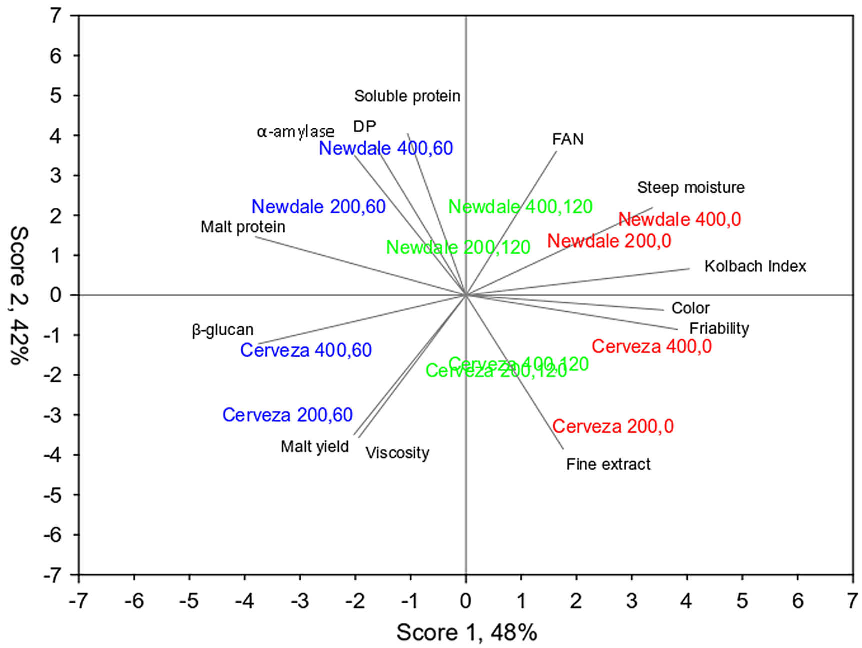
Malt friability, wort β-glucans, and wort viscosity are quality parameters associated with potential processing issues or problems with final beer quality. High levels of wort β-glucans and high wort viscosity have been associated with slow wort and beer filtration, development of beer haze, and formation of gels and precipitates in beer (Bamforth and Martin 1981, 1983; Wang et al. 2004). Malt friability, when used in conjunction with other parameters that indicate malt modification, may be used by the brewer to predict lautering performance. In our study, wort β-glucans were significantly affected by variety, nitrogen, and seeding rates and interactions among these factors. Cerveza had significantly higher concentrations of wort β-glucan than Newdale (151.8 vs. 109.8 mg L^{-1}). Lower seeding rates resulted in higher

Fig. 5. Malt quality variable response to the tested factors of variety, seeding rate, and nitrogen application rate. Points represent mean values and error bars represent standard error values from the mixed model analysis of site-year averages. Units of analysis were fine extract (F. extract; %), malt protein (M. protein; %), Kolbach index (%), β-glucan (B. glucan; mg kg^{-1}), diastatic power (DP; °L), α-amylase (A. amylase; DU), colour (°L), free amino nitrogen (FAN; mg kg^{-1}), and friability (mg g^{-1}).



wort β-glucan concentration compared with higher seeding rates (139.3 vs. 122.4 mg L^{-1} for 200 vs. 400 seeds m^{-2}). Increased nitrogen application rates from 0 to 120 kg ha^{-1} increased wort β-glucan concentration from 77.6 to 208.1 mg L^{-1}, respectively. Genotypic variation in β-glucan content in grain were previously shown to be extensive and contribute to the subsequent concentration of these polysaccharides in wort (Molina-Cano et al. 1989; Zhang et al. 2001; Krstanović et al. 2016); however, the concentration of β-glucans in wort is also affected by the degree of their degradation during malting and brewing. One of the main purposes of the malting and mashing stages of beer production is to promote the hydrolysis of β-glucans enabled by the action of β-glucanases that are synthesized during germination (Bamforth and Martin 1981, 1983). Any factors that impede β-glucan hydrolysis may affect their concentration in wort. For example, lower grain hydration during steeping was shown to be responsible for incomplete cell wall degradation during malting and to detrimentally affect the overall malt quality (Palmer 2006; Shaluk et al. 2019). In our study, barley seeded at 200 seeds m^{-2} hydrated to a lower level (462 g kg^{-1}) during steeping compared with barley seeded at 400 seed m^{-2} (464 g kg^{-1}). This higher hydration level of barley produced at higher seeding rates can be related to better water absorption of smaller kernels and consequently to better cell wall modification and lower levels of β-glucans in wort. Higher concentration of proteins in grain, however, can impede water absorption during steeping and lead to higher levels of β-glucans in wort. As observed in this study, increasing nitrogen application from 0 to 120 kg ha^{-1} significantly decreased the steep-out moisture of grain from 467 to 460 g kg^{-1}. The viscosity of wort is closely related to the concentration of β-glucans in wort. Wort viscosity was, therefore, affected by variety, nitrogen, and seeding rates in a similar way as observed for wort β-glucans. On average, Cerveza produced wort with significantly higher viscosity than Newdale (1.48 vs. 1.44 cP, respectively).

Fig. 6. Principle component analysis biplot as a summary of the correlation between cultural practices and malt quality for specific sites. Data are comprised of malt quality from all sites in 2014; only Ithaca and Princeville for 2015; and Charlottetown, Ithaca, and Princeville for 2016. The first and second axes (scores 1 and 2) explain 48% and 42% of the variability in the data. [Colour online.]



Overall, lower seeding rates produced barley that resulted in higher wort viscosity compared with higher seeding rates (1.46 vs. 1.45 cP for 200 vs. 400 seeds m^{-2}, respectively), and wort viscosity tended to increase with increasing nitrogen application rate (1.45–1.47 cP for 0–120 kg N ha^{-1}, respectively). Malt friability was not significantly affected by variety and seeding rates but significantly decreased with increasing nitrogen fertilization rates (78.8%–65.9% for 0–120 kg N ha^{-1}, respectively). The results of this study emphasize the importance of moderation of fertilizer use to achieve acceptable malt quality in eastern North America.

The colour of wort and beer is very important to craft brewers. Craft maltsters and brewers are generally striving to create products with distinctive flavors and aromas, and colour invariably raises expectations of the unique flavor experience. In our study, wort colour values were not significantly affected by variety, however both nitrogen and seeding rate had significant effects. A lower seeding rate resulted in lower colour values (3.28° vs. 3.51°, for 200 vs. 400 seeds m^{-2}, respectively) and conversely, lower fertility levels resulted in higher colour values ranging from 3.62° at 0 kg ha^{-1} vs. 3.21° at 120 kg ha^{-1}. The interaction between variety and seeding rate was significant ($P = 0.025$) with values ranging from 3.12° to 3.76° for Newdale seeded at the low vs. high seeding rate and from 3.48° to 3.24° for Cerveza under similar conditions. Wort colour is measured using spectrophotometric analysis at a single wavelength (430 nm). Wort colour is affected by chemical reactions (including Maillard reactions) occurring during malting and mashing and tends to increase with increasing degree of modification, usually indicated by higher friability, Kolbach index, and FAN and lower wort β-glucan values (Schwarz and Li 2011). Although wort colour is an attribute that is not normally reported in the cultivar descriptions when a variety is being released, it may affect the potential uptake of craft malt.

PCA showed correlations between cultural practices and malt qualitative parameters (Fig. 6). Overall, score 1 loaded heavily (eigenvectors ≥0.2 in length) on the positive side with Kolbach index, friability, colour, and steep-out moisture and was negatively loaded by malt protein and β-glucan. Score 2 loaded heavily on the positive side with soluble protein, DP, FAN, and α-amylase, and negative loading occurred primarily with fine extract, malt yield, and viscosity. There were clear effects of nitrogen fertility on malt qualitative parameters. Cerveza with nitrogen applied at 60 kg ha^{-1} correlated with higher values for β-glucan, malt yield, and viscosity and at similar levels of fertility. Newdale correlated with higher values of both soluble and malt protein, α-amylase, and DP. Control treatments (0 kg ha^{-1}) resulted in increased levels of fine extract colour and friability for Cerveza and increased values for steep-out moisture and Kolbach index for Newdale. Higher levels of fertility (120 kg ha^{-1}) correlated with marginally greater values for soluble protein, malt protein, and FAN in Newdale; Cerveza at higher fertility levels showed slight correlations with malt yield and viscosity.

Cerveza seeded at 400 seeds m^{-2} correlated with increased colour values and friability at the zero nitrogen application rate and increased β-glucan and plump seed (%) when nitrogen was applied at 60 kg ha^{-1}. At the lower seeding rate (200 seeds m^{-2}), fine extract was positively correlated with the zero nitrogen treatment, increased TKW with 60 kg N ha^{-1}, and increased malt yield and viscosity at a nitrogen application rate of 120 kg ha^{-1} (Fig. 6). Overall, Newdale and Cerveza separate along the vertical axis (score 2), that is associated with soluble protein, DP, α-amylase, malt yield, viscosity, and fine extract; whereas, nitrogen rate separates along the horizontal axis (score 1) that is associated with malt protein, β-glucan, Kolbach index, colour, friability, and steep-out moisture.

Recommendations from this research with regards to both the craft and industrial brewing sectors would be to seek out varieties that were acceptable to other entities along the value chain that would include both maltsters and brewers. As craft malting is a relatively new endeavor, there is considerably more flexibility with choosing varieties. As discussed above, 90 kg N ha^{-1} would provide the optimal yield response for producers, and compromise of yield for quality would be achieved at 60 kg N ha^{-1} with a seeding rate of 400 seeds m^{-2}.

Conclusions

Growing malt barley in the northeast is a highly technical undertaking. There is a necessity of balance between implementing factors specifically to enhance yield to mostly benefit the farmer versus factors that will achieve acceptable quality suitable for premium malt and beer to benefit the maltster and the brewer. This study highlights the importance of this balance, whereby in most cases management for yield and management for quality were inversely related. This also underlines the importance of connectivity along the craft malt value chain where the needs of farmers, maltsters and brewers are integrated. The challenge for successful production of quality malt barley lies in the need for farmers to receive compensation when management decisions to improve quality will negatively affect yield. This study clearly shows that although there is an optimum rate of nitrogen application for yield, the highest malt quality is realized with little or no nitrogen application. Mechanisms such as a shortened value chain combined with forward contracting that will guarantee adequate returns on investment to the farmer will serve to subsidize a lower yielding crop and to cover the costs of the associated inputs required to achieve quality malt suitable for the craft sector in the Northeast.

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References

ASBC. 2004. Methods of analysis. 9th ed. American Society of Brewing Chemists (ASBC), St. Paul, MN, USA.

Bamforth, C.W., and Martin, H. 1981. β-Glucans and β-glucan solubililase in malting and mashing. J. Inst. Brew. **87**: 365–371. doi:10.1002/j.2050-0416.1981.tb04052.x.

Bamforth, C.W., and Martin, H. 1983. The degradation of β-glucans during malting and mashing: the role of β-glucanase. J. Inst. Brew. **89**: 303–307. doi:10.1002/j.2050-0416.1983.tb04190.x.

Bathgate, G.N. 1973. The biochemistry of malt kilning. Brew. Dig. **48**: 60–65.

Beer Canada. 2019. National overview. Beer Canada, Ottawa, ON, Canada. [Online]. Available from https://industry.beercanada.com/national-overview [18 July 2019].

Brewers Association. 2019*a*. Malting barley characteristics. Brewers Association, Boulder, CO, USA. [Online]. Available from https://www.brewersassociation.org/best-practices/malt/malting-barley-characteristics [2 July 2019].

Brewers Association. 2019*b*. National beers sales & production data. Brewers Association, Boulder, CO, USA. [Online]. Available from https://www.brewersassociation.org/statistics-and-data/national-beer-stats/ [2 July 2019].

Choo, T.M., Martin, R.A., Savard, M.E., and Blackwell, B. 2014. Effects of planting date and earliness on deoxynivalenol contamination in barley under natural epidemic conditions. Can. J. Plant Sci. **94**: 1363–1371. doi:10.4141/cjps2013-369.

Edney, M.J., O'Donovan, J.T., Turkington, T.K., Clayton, G.W., McKenzie, R., Juskiw, P., et al. 2012. Effects of seeding rate, nitrogen rate and cultivar on barley malt quality. J. Sci. Food Agric. **92**: 2672–2678. doi:10.1002/jsfa.5687. PMID:22523006.

Garstang, J.R., Spink, J.H., Suleimenov, M., Shillinger, W.F., McKenzie, R.H., Tanaka, D.L., et al. 2011. Cultural practices: focus on major barley-producing regions. Pages 221–281 in S.E. Ullrich, ed. Barley: production, improvement, and uses. Blackwell Publishing Ltd., Chichester, UK.

Gordon, A.G. 1970. Pre-germination in barley. J. Inst. Brew. **76**: 140–143. doi:10.1002/j.2050-0416.1970.tb03273.x.

Henson, C.A., Duke, S.H., and Bockelman, H.E. 2018. Comparisons of modern U.S. and Canadian malting barley cultivars with those from pre-prohibition: II. Amylolytic enzyme activities and thermostabilities. J. Am. Soc. Brew. Chem. **76**: 38–49. doi:10.1080/03610470.2017.1396843.

Hmielowski, T. 2017. From Field to Pint: malting barley in the eastern U.S. CSA News, **62**: 4–7.

Izydorczyk, M.S. 2010. Using RVA to measure pre-germination in barley and predict germination energy after storage. Canadian Grain Commission, Winnipeg, MB, Canada. [Online]. Available from https://www.grainscanada.gc.ca/en/grain-research/scientific-reports/rva/.

Kahle, D., and Wickham, H. 2013. ggmap: spatial visualization with ggplot2. R J. **5**: 144–161. doi:10.32614/RJ-2013-014.

Krstanović, V., Lalić, A., Kosović, I., Velić, N., Mastanjević, K., and Mastanjević, K. 2016. A survey of total β-glucan content in Croatian barley varieties. Cereal Res. Comm. **44**: 650–657. doi:10.1556/0806.44.2016.032.

Laidig, F., Piepho, H.P., Drobek, T., and Meyer, U. 2014. Genetic and non-genetic long-term trends of 12 different crops in German official variety performance trials and on-farm yield trends. Theor. Appl. Genet. **127**: 2599–2617. doi:10.1007/s00122-014-2402-z. PMID:25307935.

Laidig, F., Piepho, H.P., Rentel, D., Drobek, T., and Meyer, U. 2017*a*. Breeding progress, genotypic and environmental variation and correlation of quality traits in malting barley in German official variety trials between 1983 and 2015.

Theor. Appl. Genet. **130**: 2411–2429. doi:10.1007/s00122-017-2967-4. PMID:28821914.

Laidig, F., Piepho, H.P., Rentel, D., Drobek, T., Meyer, U., and Huesken, A. 2017*b*. Breeding progress, environmental variation and correlation of winter wheat yield and quality traits in German official variety trials and on-farm during 1983–2014. Theor. Appl. Genet. **130**: 223–245. doi:10.1007/s00122-016-2810-3. PMID:27796431.

Legge, W.G., Haber, S., Harder, D.E., Menzies, J.G., Noll, J.S., Tekauz, A., et al. 2008. Newdale barley. Can. J. Plant Sci. **88**: 717–723. doi:10.4141/CJPS07194.

Legge, W.G., Tucker, J.R., Bizimungu, B., Fetch, T.G., Haber, S., Menzies, J.G., et al. 2013. Cerveza barley. Can. J. Plant Sci. **93**: 557–564. doi:10.4141/cjps2012-299.

Leiper, K.A. and Miedel, M. 2009. Colloidal stability of beer. Pages 111–161 in C. Bamforth, I. Russell, and G. Stewart, eds. Beer: A Quality Perspective. Academic Press, Burlington, US.

Marshall, I.B., Schut, P.H., and Ballard, M. 1999. A national ecological framework. Agriculture and Agri-Food Canada, Research Branch, Centre for Land and Biological Resources Research, and Environment Canada, State of the Environment Directorate, Ecozone Analysis Branch, Ottawa, ON/Hull, QC, Canada. [Online]. Available from http://sis.agr.gc.ca/cansis/nsdb/ecostrat/1999report/index.html [15 June 2020].

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.

Molina-Cano, J.L., de Togores, F.R., Royo, C., and Pérez, A. 1989. Fast-germinating low β-glucan mutants induced in barley with improved malting quality and yield. Theor. Appl. Genet. **78**: 748–754. doi:10.1007/BF00262573. PMID:24225838.

O'Donovan, J.T., Clayton, G.W., Harker, K.N., Turkington, T.K., and Lupwayi, N.Z. 2009. Relationship between seeding rate and plant density of hulled and hull-less barley as influenced by seeding depth in a no-tillage system. Can. J. Plant Sci. **89**: 645–647. doi:10.4141/CJPS08203.

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.

O'Donovan, J.T., Anbessa, Y., Grant, C.A., Macleod, A.L., Edney, M.J., Izydorczyk, M.S., et al. 2015. Relative responses of new malting barley cultivars to increasing nitrogen rates in western Canada. Can. J. Plant Sci. **95**: 831–839. doi:10.4141/cjps-2014-415.

O'Donovan, J.T., Edney, M.J., Izydorczyk, M.S., Turkington, T.K., Juskiw, P.E., McKenzie, R.H., et al. 2017*a*. Effect of seeding date and rate on malting barley (*Hordeum vulgare* L.) quality. Can. J. Plant Sci. **97**: 10–13. doi:10.1139/cjps-2016-0137.

O'Donovan, J.T., Izydorczyk, M.S., Tidemann, B., Edney, M.J., Turkington, T.K., Grant, C.A., et al. 2017*b*. Effect of preceding crop and nitrogen application on malting barley quality. Can. J. Plant Sci. **97**: 1014–1023. doi:10.1139/cjps-2016-0411.

OMAFRA. 2017. Agronomy guide for field crops. Publication 811. C. Brown, ed. Ministry of Agriculture, Food and Rural Affairs, Toronto, ON, Canada.

Palmer, G.H. 2006. Barley and malt. Pages 139–159 in F.G. Priest, and G.G. Stewart, eds. Handbook of brewing 2nd ed. CRC Press, Boca Raton, US.

Pierce, J.S. 1982. The Margaret Jones Memorial Lecutre: amino acids in malting and brewing. J. Inst. Brew. **88**: 228–233. doi:10.1002/j.2050-0416.1982.tb04099.x.

Riis, P., and Bang-Olsen, K.B. 1991. Germination profile — a new term in barley analysis. Proc. European Brewery Convention, Lisbon, Portugal. IRL Press, Oxford, UK. pp. 100–108.

Schwarz, P., and Li, Y. 2011. Malting and brewing uses of barley. Pages 478–521 in S.E. Ullrich, ed. Barley: production, improvement, and uses. Blackwell Publishing Ltd., Chichester, UK.

Shaluk, D., Bazin, S., Chepurna, A., and Izydorczyk, M.S. 2019. Effects of variable grain hydration during steeping on the content and physicochemical properties of non-starch polysaccharides in malt and wort. Food Res. Int. **116**: 430–440. doi:10.1016/j.foodres.2018.08.058. PMID:30716965.

Shrestha, R.K., and Lindsey, L.E. 2019. Agronomic management of malting barley and research needs to meet demand by the craft brew industry. Agron. J. **111**: 1570–1580. doi:10.2134/agronj2018.12.0787.

Spaner, D., Todd, A.G., and McKenzie, D.B. 2001. The effect of seeding rate and nitrogen fertilization on barley yield and yield components in a cool maritime climate. J. Agron. Crop Sci. **187**: 105–110. doi:10.1046/j.1439-037X.2001.00507.x.

Wang, J., Zhang, G., Chen, J., and Wu, F. 2004. The changes of β-glucan content and β-glucanase activity in barley before and after malting and their relationships to malt qualities. Food Chem. **86**: 223–228. doi:10.1016/j.foodchem.2003.08.020.

Zhang, G., Chen, J., Wang, J., and Ding, S. 2001. Cultivar and Environmental Effects on (1→3,1→4)-β-D-Glucan and Protein Content in Malting Barley. J. Cereal Sci. **34**: 295–301. doi:10.1006/jcrs.2001.0414.