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Evaluating Barley for the Emerging Craft Malting Industry in Western Washington

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ABSTRACT

Craft malting companies are emerging in response to demand from the rapidly growing North American craft brewing industry, and creating a market for malting barley (*Hordeum vulgare* L.) in production regions considered to be of minor importance for this crop. Growing malting barley in these under-represented areas, such as western Washington, requires identification of cultivars with suitable agronomic and quality characteristics. Twelve two-row spring barley cultivars were evaluated for 2 yr at four western Washington locations to assess suitability for craft malt production in the region. Standard North American malting cultivars had lower yield stability than locally adapted feed cultivars. Pre-harvest sprouting reduced falling number and germination capacity resulting in a high proportion of samples unsuitable for malt quality evaluation. Cultivars with the highest levels of resistance to pre-harvest sprouting did not meet malt quality standards when malted according to standard micro-malting methods. However, craft maltsters have more flexibility to alter processing conditions to produce malt from cultivars previously deemed unacceptable for large-scale malting and brewing. Craft brewer specifications for malt are also different from large-scale industry. The current work suggests the need to adjust the malting process to work with locally adapted cultivars while expanding regional testing and breeding programs.

Core Ideas

- Demand for barley for craft malt production outside of major production regions is increasing.
- Standard North American malting barley cultivars are susceptible to preharvest sprouting and foliar pathogens common in nontraditional growing regions such as western Washington.
- To meet demand for craft breweries the emerging craft malting industry will need to find ways to work with locally adapted cultivars while expanding regional testing and breeding programs.

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In North America, major malting and brewing companies have defined malting barley quality parameters to meet the needs of adjunct brewing, in which unmalted sources of starch are commonly used (Briggs, 1998). On a global basis the top 10 malting companies produce more than 50% of malt (Punda and Prikhodko, 2009; Huvet, 2014), and four brewing companies control more than 40% of beer sales (Howard, 2013). To meet the needs of these companies, malting barley cultivars have been bred for high levels of malt extract, diastatic power, a-amylase, and free amino nitrogen (FAN) according to guidelines set by the American Malting Barley Association (AMBA, 2014). Recent increase in demand from the craft brewing industry has stimulated the development of new barley cultivars with malting quality parameters specific to all-malt brewing.

The volume of beer produced by craft breweries grew 18% in 2014 representing 11% of the U.S. beer market (Brewers Association, 2015a). It is estimated that all-malt brewing methods use three to seven times more barley per unit of beer produced (Bond et al., 2015). The ideal malt for this style of brewing has lower levels of diastatic power, α-amylase, FAN, and total protein than malt for adjunct brewing (Brewers Association, 2014). These quality parameters are similar to those of the United Kingdom and European base malts (Briggs, 1998), which are commonly imported by U.S. craft breweries.

Market research conducted in the mid-1990s indicated that the craft brewing industry could offer a niche market for malt, and that meeting this demand would be difficult with established malting infrastructure (Bastian et al., 1999). A survey of 52 craft breweries in 2001 found that 59% of breweries were interested in using malt that was produced locally (Processing Center, 2001). In the past 15 yr, 30 craft malthouses have opened with the goal of producing unique malts from regionally grown grains (Thomas, 2013; Frank and Meltzer, 2014;

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Abbreviations: AMBA, American Malting Barley Association; ASBC, American Society of Brewing Chemist; DU, dextrinizing units; FAN, free amino nitrogen; FN, falling number; G, genotype; GC, germination capacity; GE, germination energy; ISLAND, Island County; L, location; MVCON, conventionally managed field in Mount Vernon, WA; MVORG, certified organic field in Mount Vernon, WA; NIR, near infrared reflectance; QTL, quantitative trait loci; R, replicate within location–year; WHATCOM, Whatcom County; WS, water sensitivity; Y, year.

Stayton, 2014; Rowe, 2015), including Skagit Valley Malting in western Washington. The Craft Maltsters Guild, which represents members located across North America, defines craft malt as being produced with greater than 50% grains "grown in the region of the craft malthouse" (www.craftmalting.com). This interest is helping create demand for malting barley in minor growing areas.

Barley grain and malting quality are influenced by growing conditions as well as genotype × environment interaction (Eagles et al., 1995). Genotype and environment have been found to have an influence on malt quality traits including grain protein and b-glucan content (Zhang et al., 2001). Available N and planting date can have a significant effect on barley grain protein (Weston et al., 1993) as can moisture stress (Coles et al., 1991) and seeding rate (O'Donovan et al., 2011). Genetic differences between barley cultivars can influence stability of grain protein content over environments (Bertholdsson, 1999). Given the importance of these environmental influences and interactions, evaluating barley cultivars within a target environment to select genotypes with stable malting quality is critical.

Pre-harvest sprouting is a challenge for malting barley production in some regions, as its occurrence can reduce the ability of the grain to germinate in the malting process (Schwarz et al., 2004). Quantitative trait loci (QTL) controlling malting quality and dormancy, which confers resistance to pre-harvest sprouting, are tightly linked (Ullrich et al., 2009; Castro et al., 2010; Jin et al., 2011). This association has complicated the development of malting barley cultivars resistant to pre-harvest sprouting and breeding for high levels of a-amylase may have inadvertently reduced resistance to pre-harvest sprouting (Lin et al., 2009; Edney et al., 2013). Testing in areas with consistent patterns of precipitation near the end of the growing season may assist in the identification of cultivars with resistance to pre-harvest sprouting.

There are more than 250 licensed breweries in Washington, primarily concentrated in the coastal region west of the Cascade Mountains (Washington State Liquor Control Board, 2014). Washington craft breweries produced 405,000 barrels (117 L barrel^{-1}) of beer in 2014 (Brewers Association, 2015b). Additionally, the craft distilling industry is growing rapidly, and Washington state law requires that craft distillers purchase more than 51% of their raw ingredients from within the state (Vinh, 2015). These factors are contributing to an increase in demand for local malting barley production.

In western Washington, barley is grown on approximately 2470 hectares as an important rotational component of the diverse cropping systems found in the region (USDA NASS, 2012). The region has an Oceanic climate conducive to the development of foliar pathogens, and precipitation in late August and early September increases the risk of pre-harvest sprouting. To improve understanding of traits necessary for production of barley for craft malting the present study aims to: (i) compare agronomic and grain quality of standard North American malting cultivars and locally adapted feed cultivars and (ii) investigate stability and genotype × environment interactions of key agronomic and grain quality traits. Results are discussed in the context of meeting the needs of the emerging craft malting industry, locally and nationally.

METHODS

Trial Locations and Management

Cultivars were evaluated at four field sites chosen to represent a range of regional microclimates and production systems during the 2013 and 2014 growing seasons. Two trials were grown at Washington State University Northwestern Washington Research and Extension Center, near Mount Vernon, WA (48.4200° N, 122.3261° W); one in certified organic fields (MVORG), and one in conventionally managed fields (MVCON). Conventionally managed on-farm trials were grown in Whatcom County (WHATCOM) near Lynden, WA (48.9467° N, 122.4569° W) and Island County (ISLAND) near Coupeville, WA (48.2183° N, 122.6836° W). For each location, daily weather data were obtained from the nearest Washington State University AgWeatherNet automated weather station (http://weather.wsu.edu/awn.php).

Twelve spring barley cultivars were selected to represent standard North American two-row malting barley cultivars and locally adapted feed cultivars (Supplemental Table S1). At each location, three replicate plots were planted in a randomized complete block design. Seed was planted in plots with a 3.34 m^2 harvest area in seven rows on 15.24 cm centers at a rate of 135 kg ha^{-1} using a modified Allis-Chalmers tractor equipped with a cone-planter (Briggs and Stratton, Wauwatosa, WI). Plots were harvested with a Wintersteiger plot combine (Wintersteiger Ag, Ried im Innkreis, Austria), and excess chaff was removed using an airblast seed cleaner (Almaco, Nevada, IA) before conducting yield and quality assessments.

Trial management was adjusted according to local practice, production system, and growing conditions. The MVCON was planted in Field silt loam soil (medial over sandy or sandy-skeletal, mixed, nonacid, mesic Aquic Xerofluvent) in 2013 and Skagit silt loam soil (fine-silty, mixed, superactive, nonacid, mesic Fluvaquentic Endoaquept) in 2014 (Soil Survey Staff, National Resource Conservation Service, USDA, 2015). Custom fertilizer blend (27–7–8; Wilbur-Ellis, Aurora, CO) was applied using a broadcast spreader (EarthWay Products INC, Bristol, IN) at 90 kg N ha^{-1}. The following herbicides were applied to control weeds: Axial XL {[8-(2,6-diethyl-4-methylphenyl)-7-oxo-1,2,4,5-tetrahydropyrazolo[1,2-d][1,4,5]oxadiazepin-9-yl] 2,2-dimethylpropanoate; Syngenta, Greensboro, NC} at 1.2 L ha^{-1}; Maestro 2EC (3,5-dibromo-4-hydroxybenzonitrile; Nufarm Americas Inc, Burr Ridge, IL) at 1.17 L ha^{-1}; Harmony Extra SG {thifensulfuron: Methyl 3-[[[[(4-methoxy-6-methyl-1,3,5-triazin-2-yl) amino] carbonyl]amino]sulfonyl]-2-thiophenecarboxylate and tribenuron: Methyl 2-[[[[N-(4-methoxy-6-methyl-1,3,5-triazin-2-yl)methylamino]carbonyl]amino]sulfonyl]benzoate; DuPont, Wilmington, DL} at 35 g ha^{-1} total product. In 2014 Quadris (methyl (E)-2-{2-[6-(2-cyanophenoxy) pyrimidin-4-yloxy]phenyl}-3-methoxyacrylate; Syngenta, Greensboro, NC) was applied at 0.88 L ha^{-1} to control severe powdery mildew at the seedling stage.

The MVORG was planted in Field silt loam soil (Soil Survey Staff, National Resource Conservation Service, USDA, 2015). Before planting, Proganic fertilizer (8–2–4; Wilbur-Ellis, Aurora, CO) was applied at a rate of 90 kg N ha^{-1} in 2013 and 80 kg N ha^{-1} in 2014 with a 1.8 m wide drop spreader (Gandy, Owatonna, MN). In 2014, this trial was cultivated using a tine-weeder (Lely Southwest Inc, Temple, TX) when barley reached the two-leaf stage.

WHATCOM was planted in the Everett complex gravelly, ashy, sandy loam soil (Soil Survey Staff, National Resource Conservation Service, USDA, 2015). After planting, the field was fertilized with urea (46–0–0) at 90 kg N ha^{-1} and the following herbicides were applied: Maestro 2EC at 1.75 L ha^{-1}; Harmony Extra SG at 35 g ha^{-1} total product.

ISLAND was planted in the Ebeys-Coupeville complex loam soil (Soil Survey Staff, National Resource Conservation Service, USDA, 2015). No in-season fertilizer was applied, and weeds were controlled using Base Camp MCP Ester (2-ethylhexyl ester of 2-methyl-4-chlorophenoxyacetic acid; Wilbur-Ellis Company, Fresno, CA) according to local grower practices.

Agronomic and Disease Assessments

Yield (kg ha^{-1}) was calculated based on clean grain weight and harvested plot area. Days to heading (from 1 January) were recorded at MVCON and MVORG in 2013 and 2014. Plant height (cm) and lodging (percentage of plot area) were recorded at MVCON, MVORG, and WHATCOM in 2013 and 2014 and all locations in 2014. In 2013, severity of barley leaf rust (*Puccinia hordei* Otth) and powdery mildew [*Blumeria graminis* (DC.) E.O. Speer f. sp. *hordei* Em. Marchal] were recorded as percentage infected leaf area at MVCON and MVORG. In 2014, disease severity was evaluated at all locations.

Grain Quality Assessments

Test weight (kg hL^{-1}) was measured after grain was passed through an airblast cleaner (Almaco, Nevada, IA) to remove chaff. Percent plump kernels (% > 0.24 by 1.9 cm) was determined by weight of kernels that remained on a slotted screen after shaking 100 g for 30 s on a Seedburo 98-SS Screen Shaker (Seedburo, Des Plaines, IL). Grain protein (g kg^{-1}) was determined by near infrared reflectance (NIR) on a Perten Inframatic 9200 grain analyzer (Perten Instruments, Hagersten, Sweden). Samples were tested for pre-harvest sprouting damage by measuring falling number (FN) on a Perten 1500 Falling Number instrument (Perten Instruments, Hagersten, Sweden) according to AACC International method: 56-81.03 (AACC International, 2009). Samples (300 g) were ground using a Perten Laboratory Mill 3100 (Perten Instruments, Hagersten, Sweden), and flour moisture was measured by Perten Inframatic 8600 flour analyzer (Perten Instruments, Hagersten, Sweden).Values of <220 s were considered indicative of pre-harvest sprouting (Tordenmalm et al., 2004; Schwarz et al., 2004). Germination energy (GE), germination capacity (GC), and water sensitivity (WS) were determined according to American Society of Brewing Chemist (ASBC) Method Barley-3,C (ASBC, 2009).

Malting Quality Assessments

Grain harvested from plots with FN > 220 s, GE > 90% and, WS < 10% was considered suitable for malting. If a cultivar met these criteria in a minimum of two out of three replicates within a trial, grain was sized to remove kernels that passed a 0.24 by 1.9 cm sieve. Grain protein and moisture were determined by NIR and 80-g samples were micro-malted according to methods described by Karababa et al. (1993). Samples were germinated for 4 d. Fine ground malt was prepared for the Congress Mash using a Buhler-Miag disc mill (model no. DLFUW-11060, Uzwil, Switzerland) calibrated according to ASBC Method Malt-4, and samples for determination of malt enzyme activity were prepared with a Udy Cyclone mill (Udy Corp., Fort Collins, CO) fitted with a 0.5-mm screen. The levels of a-amylase activity and diastatic power were determined using a Technicon Instrument Corporation (Tarrytown, NY) flow auto-analyzer according to a modification of ASBC Method Malt-6 (ASBC, 2009) as previously described (Karababa et al., 1993). Wort samples were produced from the fine grind malt using a Congress Mash according to ASBC Malt Method-4 (ASBC, 2009). Malt extract in the wort was determined using an Anton-Parr DMA 5000 density meter (Anton Parr GMBH. Graz, Austria) and wort samples were analyzed for soluble protein, FAN, wort viscosity, and, wort β-glucan according to ASBC Methods Wort-17, Wort-12, Wort-13, and Wort-18, respectively (ASBC, 2009).

Statistical Analysis

Statistical analysis was conducted using SAS University (Version 9.4, SAS Institute, Cary, NC). To investigate genotype means across years and locations an ANOVA was conducted with location, year, and block treated as random effects; pairwise comparisons were made using Fisher's protected least significant difference. To investigate interactions and main effects, a second ANOVA was conducted using PROC MIXED with genotype, location, and year considered fixed effects, and block considered a random effect. PROC UNIVARIATE was used to verify assumptions of normality; if residuals were not normal data were log, square root, arc sine, or rank transformed. Non-parametric Friedman's test was conducted using PROC MIXED on rank transformed data (Ipe, 1987). Untransformed means are presented and the transformation used in each analysis is noted. Pearson's correlations were determined using PROC CORR. Stability of agronomic and quality traits were evaluated using consistency plots of mean ranks vs. standard deviation of rank (Francis and Kannenberg, 1978; Meints et al., 2015).

RESULTS AND DISCUSSION

Weather

In 2014, MVCON had the highest mean temperature due to a delayed planting caused by heavy spring rain (Supplemental Table S2). ISLAND had the lowest mean temperature and cumulative precipitation in 2013 (14.1°C, 99.6 mm) and 2014 (14.0°C, 130.3 mm). Despite low precipitation during the growing season, ISLAND had the highest cumulative precipitation during the 2 wk before harvest in 2013 and the second highest in 2014. At MVCON in 2014, a major rain event occurred 2 September, resulting in a cumulative precipitation of 42.9 mm in the 2 wk before harvest.

Agronomic Traits

Across years and locations, Bentley had the lowest mean grain yield (4435 kg ha^{-1}) and Richard had the highest mean grain yield (6407 kg ha^{-1}; Table 1). In the ANOVA, all the main effects genotype (G), location (L), and year (Y) and two- and three-way interactions were significant (Table 2). A combination of change in rank and magnitude contributed to the significant L × Y interaction. All locations had lower yield in

Table 1. Means across years and locations for grain yield, heading date, plant height, lodging, leaf rust, and powdery mildew of 12 barley cultivars grown in conventionally managed field (MVCON), organic field (MVORG), Island County (ISLAND), and Whatcom County (WHATCOM) trials during the 2013 and 2014 growing seasons. Letter groupings indicated significant differences between means (Fishers protected LSD $P \leq 0.05$); $P > F$ indicates significance of genotype as a fixed effect with location and year as random effects.

Genotype	Yield†	Heading‡	Height§	Lodging§	Leaf rust¶	Powdery mildew¶
	kg ha^{-1}	Days from Jan 1	cm		%	
Richard	6407a	172	66cd	5	13d	0e
2004NZ170	5528ab	173	60d	12	29bcd	12 d
AC Metcalfe	4959bcd	170	81ab	14	45ab	24bcd
Baronesse	5466b	170	73bc	16	22bcd	22cd
Bentley	4435 d	172	81ab	17	40ab	30bc
Bob	5408bc	171	75bc	26	18cd	30bc
CDC Copeland	4602bcd	173	86a	30	57a	28abc
CDC Meredith	4672bcd	172	75b	28	40abc	26bc
Full Pint	4957bcd	171	61d	2	1e	42
Harrington	4516cd	171	77ab	29	59a	4ae
Hockett	4527cd	169	75b	28	59a	32b
Newdale	4744bcd	170	75b	19	37abc	28abc
Mean	5018	171	74	19	35	23
$P > F$	0.0188	0.0511	0.0018	0.0818	0.0002	<0.0001

† Mean of all locations in 2013 and 2014.

‡ Mean of MVCON and MVORG in 2013 and 2014.

§ Mean of MVCON, MVORG, and WHATCOM in 2013 and all locations in 2014.

¶ Mean of MVCON and MVORG in 2013 and all locations in 2014.

2014 except MVORG, which exceeded MVCON in 2014, but not 2013 (Fig. 1). Similarly, changes in rank and magnitude of genotypes contributed to the significant three-way interactions. Richard, CDC Meredith, and Bentley had a low standard deviation of rank indicating relative yield was stable over years and locations, whereas cultivars Full Pint and Newdale had a high standard deviation of rank (Fig. 2). The highest yielding cultivars (Richard, 2004NZ170, Baronesse, and Bob) are locally adapted feed cultivars which have been widely grown and/or were selected in this region.

Heading date ranged from 169 d (Hockett) to 173 d (CDC Copeland) from 1 January, and plant height ranged from 60 cm (Full Pint) to 86 cm (CDC Copeland; Table 1). In the ANOVA, G, L, Y, G × L, G × Y, and L × Y, all had a significant effect on heading date and plant height (Table 2). The significant L × Y interaction is expected given the wide range of planting dates from year to year (Supplemental Table S2). This may have also contributed to variation in plant height, as photoperiod genes have been found to influence height (Laurie et al., 1994).

Percent lodging ranged from 2% (Full Pint) to 30% (CDC Copeland; Table 1). In the overall ANOVA, G, L, and G × L were significant for percent lodging (Table 2). There was a significant positive correlation between lodging and height (r = 0.33, $P \leq 0.01$; Table 3) though the low r value indicates a large portion of variance in lodging is explained by factors other than height. Given the potential for lodging in high yield growing environments (Robertson and Stark, 2003), the selection of semi-dwarf varieties may be an important selection criteria for increasing regional production (Kuczyńska et al., 2013). For the

Table 2 Analysis of variance of fixed effects genotype (G), location (L), year (Y), and interactions for grain yield, heading date, plant height, lodging, leaf rust, and powdery mildew for 12 barley cultivars grown in conventionally managed field (MVCON), organic field (MVORG), Island County (ISLAND), and Whatcom County (WHATCOM) trials during the 2013 and 2014 growing seasons.

Effect	Grain yield†		Heading (Days from Jan 1)‡		Height§		Lodging§		Leaf rust¶		Powdery mildew¶	
	kg ha^{-1}				cm		%		%		%	
	df	$P > F$	df	$P > F$	df	$P > F$	df	$P > F$	df	$P > F$	df	$P > F$
G	11	<0.0001	11	<0.0001	11	<0.0001	11	<0.0001	11	<0.0001	11	<0.0001
L	3	0.0001	1	<0.0001	3	<0.0001	3	<0.0001	3	<0.0001	3	<0.0001
Y	1	0.0013	1	<0.0001	1	<0.0001	1	0.5383	1	<0.0001	1	0.0003
G x L	33	<0.0001	11	<0.0001	33	0.0005	33	0.0093	33	<0.0001	33	<0.0001
G x Y	11	<0.0001	11	0.0002	11	0.0002	11	0.5936	11	0.0158	11	0.012
L x Y	3	0.0027	1	<0.0001	2	<0.0001	2	0.4716	2	<0.0001	2	<0.0001
G x L x Y	33	0.0002	11	0.114	22	0.2895	22	0.3132	22	0.0002	22	<0.0001
Transformation		None		None		Rank		Rank		Rank		Rank

† Mean of all locations in 2013 and 2014.

‡ Mean of MVCON and MVORG in 2013 and 2014.

§ Mean of MVCON, MVORG, and WHATCOM in 2013 and all locations in 2014.

¶ Mean of MVCON and MVORG in 2013 and all locations in 2014.

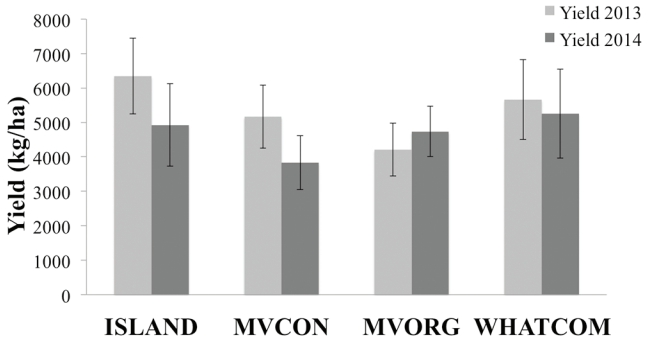

Fig. 1. Mean grain yield (kg ha^{-1}) of 12 cultivars grown in conventionally managed field (MVCON), organic field (MVORG), Island County (ISLAND), and Whatcom County (WHATCOM) trials during the 2013 and 2014 growing season. Error bars indicate standard deviation from the mean.

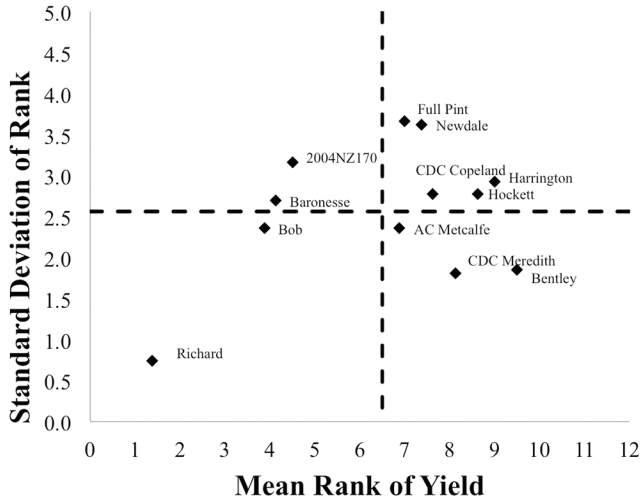

Fig. 2. Consistency plot of mean rank of grain yield (kg ha^{-1}) vs. standard deviation of rank for cultivars grown in conventionally managed field (MVCON), organic field (MVORG), Island County (ISLAND), and Whatcom County (WHATCOM) trials during the 2013 and 2014 growing seasons. Dashed lines indicate mean values. The lower the rank number, the higher the grain yield.

short growing season in western Washington, earlier maturing genotypes can be an advantage. Cultivars such as Full Pint with a semi-dwarf growth habit did not have longer days to heading as has been observed in other studies (Kuczyńska et al., 2013).

Disease Severity

Leaf rust severity ranged from 2% (Full Pint) to 69% (Harrington) and powdery mildew severity ranged from 0% (Richard) to 42% (Full Pint; Table 1). In the ANOVA, all the main effects as well as two- and three-way interactions were significant for leaf rust and powdery mildew (Table 2). Variability in disease severity between locations and years contributed to significant interaction terms, but cultivars with known major resistance genes had a low mean severity and standard deviation across environments indicating stability. An adult plant leaf rust resistance gene, *Rph20,* has been identified in Baronesse (Hickey et al., 2012). Bob and Richard both have Baronesse in their pedigree and have a similar level of resistance to leaf rust. Full Pint carries a single major leaf rust resistance gene, allelic to *Rph3* (Castro et al., 2012). Harrington was rated as resistant to powdery mildew when it was released (Harvey and Rossnagel, 1984) and Richard was found to be resistant in the present study. Yield was negatively correlated with both leaf rust ($r = -0.44$, $P \leq 0.01$) and powdery mildew ($r = -0.29$, $P \leq 0.01$), suggesting the importance of controlling these foliar pathogens (Table 3).

Grain Quality

Grain protein ranged from 105 g kg^{-1} (Bob) to 120 g kg^{-1} (CDC Copeland and Newdale); test weight ranged from 56 g hL^{-1} (CDC Meredith) to 63 g hL^{-1} (Bob); and plump kernels ranged from 75% (Harrington) to 86% (Richard; Table 4). The AMBA guidelines for all malt two-row specify grain protein levels below 120 g kg^{-1} (12%). In this sense all cultivars showed that they could meet protein requirements under western Washington growing conditions. Plump kernels in excess of 90% are generally desired (AMBA, 2014) as large kernel size is indicative of higher extract yield, which is

Table 3. Pearson's correlation coefficients for agronomic and grain quality traits of 12 barley cultivars grown in conventionally managed field (MVCON), organic field (MVORG), Island County (ISLAND), and Whatcom County (WHATCOM) trials during the 2013 and 2014 growing seasons.

Trait	Height	Lodging	Mildew	Leaf rust	Yield	Grain protein	Test weight	Plump kernels	Falling number	Germination energy	Water sensitivity	Germination capacity
	cm		– % –		kg ha^{-1}	g kg^{-1}	kg hL^{-1}	%	s		%	
Heading	–0.76**	–0.32*	0.31*	–0.2	–0.45**	–0.01	–0.21	0.18	0.36**	0.11	–0.15	0.32*
Height		0.33**	0.08	0.40**	0.09	–0.11	0.11	–0.05	–0.31**	–0.06	0.04	–0.19
Lodging			0.30**	–0.13	–0.03	–0.01	0.18	0.05	–0.25*	0.06	–0.12	0.16
Mildew				–0.09	–0.29**	0.14	0.06	0.04	–0.34**	0.04	0.15	–0.02
Leaf rust					–0.44**	–0.12	–0.27**	–0.12	0.04	–0.02	0.1	–0.15
Yield						–0.34**	0.62**	0.50**	0.18	0.13	–0.27**	0.08
Protein							–0.73**	–0.78**	–0.57**	–0.34**	0.49**	–0.49**
TW								0.79**	0.42**	0.29**	–0.56**	0.40**
Plump									0.42**	0.16	–0.42**	0.30**
Falling number										0.49**	–0.59**	0.59**
Germination energy											–0.41**	0.77**
Water sensitivity												–0.54**

* Significant at $P \leq 0.05$.
** Significant at $P \leq 0.01$.

Table 4. Means across years and locations for grain protein, test weight, plump kernels, falling number, germination energy (GE), germination capacity (GC) and water sensitivity (WS) of 12 barley cultivars grown in conventionally managed field (MVCON), organic field (MVORG), Island County (ISLAND), and Whatcom County (WHATCOM) trials during the 2013 and 2014 growing seasons. Letter groupings indicated significant differences between means (Fishers protected LSD $P \leq 0.05$); $P > F$ indicates significance of genotype as fixed effect with location and year as random effects.

Genotype	Grain protein	Test weight	Plump kernels	Falling number	GE	GC	WS
	g protein kg^{-1}	kg hL^{-1}	%	s	%		
Richard	105	61abc	86a	287ab	97a	98	6de
2004NZ170	116	61bcd	79cd	269bc	96ab	98	9cde
AC Metcalfe	115	60cde	81bcd	164 def	87d	91	20ab
Baronesse	114	62ab	85ab	363a	97a	99	4e
Bentley	114	57fg	81abcd	173 def	95abc	96	14abc
Bob	105	63a	84abc	262bc	96abc	97	11bcd
CDC Copeland	120	58efg	78d	202de	93bcd	94	8cde
CDC Meredith	116	56g	77d	174def	91d	93	24a
Full Pint	119	60bcd	84abc	131 f	85d	88	16abc
Harrington	119	57fg	75d	136 ef	91cd	90	20ab
Hockett	115	59def	77d	215cd	97a	98	9cde
Newdale	120	59def	75d	206cd	98a	98	5de
Mean	115	60	80	215	94	95	12
$P > F$	0.0919	0.0003	0.0124	0.0002	0.0027	0.2255	0.0041

Table 5. Analysis of variance of fixed effects genotype (G), location (L), year (Y), and interactions for grain protein, test weight, plump kernels, falling number, germination energy, germination capacity, and water sensitivity for 12 barley cultivars grown in conventionally managed field (MVCON), organic field (MVORG), Island County (ISLAND), and Whatcom County (WHATCOM) trials during the 2013 and 2014 growing seasons.

Effect	Grain protein		Test weight		Plump kernels		Falling number		GE		GC		WS	
	g protein kg^{-1}		kg hL^{-1}		%		s		%		%		%	
	df	$P > F$	df	$P > F$	df	$P > F$	df	$P > F$	df	$P > F$	df	$P > F$	df	$P > F$
G	11	<0.0001	11	<0.0001	11	<0.0001	11	<0.0001	11	<0.0001	11	<0.0001	11	<0.0001
L	3	0.0729	3	<0.0001	3	<0.0001	3	<0.0001	3	0.4825	3	0.1039	3	<0.0001
Y	1	0.0094	1	0.1374	1	0.0383	1	<0.0001	1	0.0084	1	0.0113	1	<0.0001
G x L	33	<0.0001	33	<0.0001	33	0.001	33	<0.0001	33	<0.0001	33	0.155	33	0.0017
G x Y	11	0.0028	11	0.0004	11	0.0362	11	<0.0001	11	0.0083	11	0.0009	11	<0.0001
L x Y	3	<0.0001	3	<0.0001	3	<0.0001	3	<0.0001	3	0.0543	3	0.0003	3	<0.0001
G x L x Y	33	0.0063	33	0.0002	33	0.0021	33	<0.0001	33	<0.0001	33	0.009	33	0.1154
Transformation		Rank		Rank		Rank		Rank		Rank		Rank		Rank

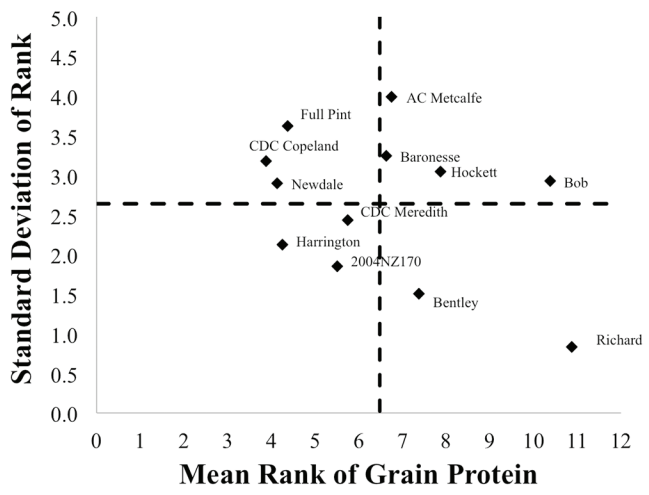

Fig. 3. Consistency plot of mean rank of grain protein (g kg^{-1}) vs. standard deviation of rank for cultivars grown in conventionally managed field (MVCON), organic field (MVORG), Island County (ISLAND), and Whatcom County (WHATCOM) trials during the 2013 and 2014 growing seasons. Dashed lines indicate mean values. The lower the rank number, the higher the grain protein.

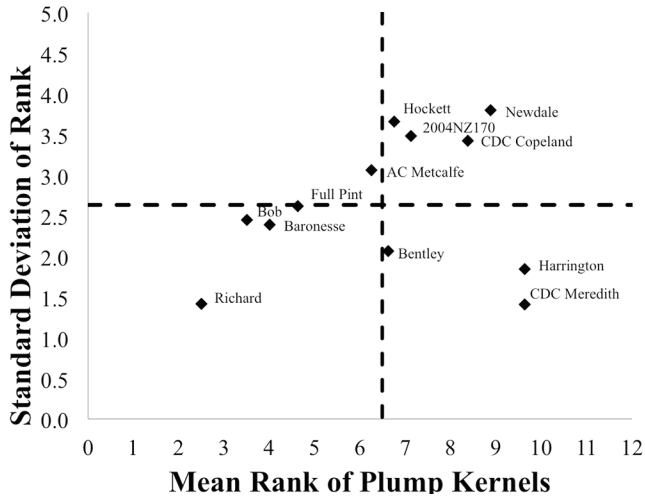

Fig. 4. Consistency plot of mean rank of plump kernels (%) vs. standard deviation of rank for cultivars grown in conventionally managed field (MVCON), organic field (MVORG), Island County (ISLAND), and Whatcom County (WHATCOM) trials during the 2013 and 2014 growing seasons. Dashed lines indicate mean values. The lower the rank number, the higher the % plump kernels.

a critical economic factor to brewers. However, barley with plump kernels in excess of 75% is frequently used to produce high quality malt. Thin and plump grains will absorb water at different rates, and a high percentage of thins can cause problems with malt homogeneity. As such the thinner fractions are generally removed before malting.

In the ANOVA, all the main effects as well as two- and three-way interactions were significant for plump kernels. For protein L was not significant and for test weight Y was not significant, all other main effects and interactions were significant for these traits (Table 5). Consistency plots for grain protein (Fig. 3) and kernel plumpness (Fig. 4) show that Richard had below average standard deviation of rank for protein and kernel plumpness, indicating that this cultivar is stable for these grain quality parameters. Cultivars with a high standard deviation of rank were more likely to change rank in response to environmental conditions. Grain protein can be influenced by environmental factors such as N availability, temperature, and drought stress (Birch and Long, 1990; Coles et al., 1991; Weston et al., 1993; Eagles et al., 1995). Significant two- and three-way interactions for grain quality will limit the ability of maltsters to select grain with consistent quality from year to year as well as from place to place. While this may be a challenge, craft maltsters are also working to market malt as unique based on location and growing season.

Falling Number and Germination

The FN ranged from 131 sec (Full Pint) to 363 sec (Baronesse; Table 4). In the ANOVA, all the main effects as well as two- and three-way interactions were significant for FN (Table 5). A FN below 220 s indicates that sprouting has occurred which will reduce the malting quality, particularly the ability of grain to re-germinate during malting (Tordenmalm et al., 2004). The feed cultivars Baronesse, Bob, and 2004NZ170 all had below average standard deviation of rank and a high mean rank, indicating that their resistance to pre-harvest sprouting is stable across environments (Fig. 5). Factors contributing to pre-harvest sprouting include temperature, and timing and duration of precipitation following anthesis (Rodríguez et al., 2001). Variation in these factors likely contributed to significant interactions observed in the present study.

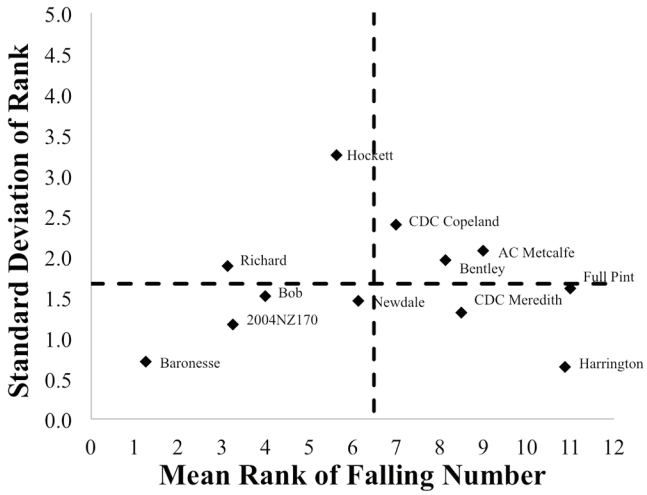

Fig. 5. Consistency plot of mean rank of falling number (s) vs. standard deviation of rank for cultivars grown in conventionally managed field (MVCON), organic field (MVORG), Island County (ISLAND), and Whatcom County (WHATCOM) trials during the 2013 and 2014 growing seasons. Dashed lines indicate mean values. The lower the rank number the higher the falling number value.

Malting is a germination process and values of GE in excess of 95% are desired (AMBA, 2014). Mean germination energy (GE) ranged from 85% (Full Pint) to 98% (Newdale; Table 4). In the ANOVA, G, Y, G × L, G × Y, and G × L × Y were significant for GE (Table 5). Mean germination capacity (GC) ranged from 88% (Full Pint) to 99% (Baronesse; Table 4). In the ANOVA, G, Y, G × Y, L × Y, and G × L × Y interactions were significant for GC (Table 5). The difference between GC and GE is typically viewed as an indicator of dormancy, which will break with time (Briggs, 1998). However, in the current study, lower values for GE and GC were likely due to pre-harvest sprouting. Water sensitivity is a specialized case of dormancy, where the germination of grain in excess water is reduced. Differences of 25% or more between the 4 and 8 mL germination tests are indicative of severe water sensitivity. In the present study values for water sensitivity (WS) ranged from 4% (Baronesse) to 24% (CDC Meredith), suggesting most cultivars tested were not water sensitive (Table 4). In the ANOVA, G, L, Y, G × L, G × Y, and L × Y were significant for WS (Table 5).

Falling number was used as a measure of pre-harvest sprouting, and was positively correlated with GE ($r = 0.49$, $P \leq 0.01$) and GC ($r = 0.59$, P £ 0.01) and negatively correlated with WS ($r = -0.59$, $P \leq 0.01$; Table 3). The relationship between FN and germination indices confirms previous reports that FN can be used to predict the germination of barley in storage (Woods et al., 1994; Tordenmalm et al., 2004). The GE of severely sprouted barley rapidly decreases with storage time. Falling number was also negatively correlated with lodging ($r = -0.25$, $P \leq 0.05$; Table 3), which may be related to higher levels of lodging at sites with more rainfall before harvest, as well as increased susceptibility to pre-harvest sprouting of lodged grain. None of the standard malting cultivars evaluated in this trial had a mean FN over 220 s and only Newdale had a GE more than 98% (Table 4).

The results presented here confirm previous reports that Full Pint and Harrington have low dormancy and are susceptible to pre-harvest sprouting (Li et al., 2003; Castro et al., 2010; Darby et al., 2014) whereas Baronesse is known to have high levels of dormancy (Castro et al., 2010). Given the tight association between major malt quality and dormancy QTL, identification of cultivars which combine malt quality suitable for North American adjunct style brewing and resistance to pre-harvest sprouting has been a challenge for barley breeders (Ullrich et al., 2009; Castro et al., 2010; Jin et al., 2011; Edney et al., 2013). Malting cultivars developed in the United Kingdom commonly have a moderate degree of dormancy (Briggs et al., 1994) suggesting that combining resistance to pre-harvest sprouting with quality suitable for all-malt styles of brewing is an avenue that could be pursued by North American barley breeders selecting for high rainfall regions. Given linkage between malt quality QTL and dormancy, it is likely dormant varieties will have lower a-amylase, requiring increased malting time in addition to storage before malting.

Table 6. Number of location years that genotypes met criteria of germination energy >90%, water sensitivity <10% and falling number >220 s). Means across years and locations for α-amylase, malt extract, free amino nitrogen (FAN), and β-glucan of barley cultivars that met criteria, grown in conventionally managed field (MVCON), organic field (MVORG), Island County (ISLAND), and Whatcom County (WHATCOM) trials during the 2013 and 2014 growing seasons. Letter groupings indicated significant differences between means (Fishers protected LSD $P \leq 0.05$); $P > F$ indicates significance of genotype as fixed effect with location and year as random effects.

Genotype	Number of location years	Alpha-amylase	Extract	FAN	β-glucan
		DU†	g extract kg^{-1}	mg L^{-1}	
Richard	6	59bc	810	164b	319
2004NZ170	6	53c	798	159b	319
AC Metcalfe	0	na	na	na	na
Baronesse	7	52c	797	137cc	277
Bentley	1	67a	843	168a	48
Bob	4	56c	805	157b	333
CDC Copeland	2	67ab	827	194a	57
CDC Meredith	0	na	na	na	na
Full Pint	0	na	na	na	na
Harrington	0	na	na	na	na
Hockett	2	77a	829	190a	163
Newdale	2	71a	819	163a	151
Mean		63	816	166	208
$P > F$		0.037	0.0635	0.016	0.1513

† DU, dextrinizing units; na, not applicable.

Table 7. Analysis of variance of fixed effects genotype (G), location (L), year (Y), and interactions for α-amylase, extract, free amino nitrogen (FAN), and β-glucan for barley cultivars with >90% germination energy, <10% water sensitivity, and falling number >220 s grown in conventionally managed field (MVCON), organic field (MVORG), Island County (ISLAND), and Whatcom County (WHATCOM) trials during the 2013 and 2014 growing seasons.

Effect	Alpha-amylase		Extract		FAN		β-glucan	
		DU†		g extract kg^{-1}		mg L^{-1}		mg L^{-1}
	df	$P > F$	df	$P > F$	df	$P > F$	df	$P > F$
G	7	<0.0001	7	<0.0001	7	<0.0001	7	<0.0001
L	3	<0.0001	3	<0.0001	3	<0.0001	3	0.7903
Y	1	0.0476	1	0.0004	1	0.0004	1	0.9775
G × L	9	<0.0001	9	0.102	9	0.102	9	<0.0001
G × Y	3	0.0006	3	0.0877	3	0.0877	3	0.0084
L × Y	2	0.0003	2	0.3872	2	0.3872	2	0.0023
G × L × Y	2	0.1652	2	0.1004	2	0.1004	2	0.009
Transformation		None		None		None		Rank

† DU, dextrinizing units.

Table 8. Pearson's correlation coefficients for malt quality traits of 12 barley cultivars grown in conventionally managed field (MVCON), organic field (MVORG), Island County (ISLAND), and Whatcom County (WHATCOM) trials during the 2013 and 2014 growing seasons.

Trait	Malt protein	Malt loss	α-amylase	Diastatic power	Extract	Viscosity	Soluble protein	Soluble protein/ Total	Color	Free amino N	β-glucan
Falling number	–0.29	–0.57**	–0.6	–0.44**	–0.16	0.25	–0.62**	–0.27	–0.31	–0.73**	0.18
Malt protein		0.75**	0.21	0.62**	–0.6**	–0.18	0.3	–0.54**	–0.32	0.26	0.05
Malt loss			0.44**	0.78**	–0.36*	–0.24	0.52**	–0.17	–0.2	0.56**	–0.05
α-amylase				0.55**	0.33	–0.62**	0.88**	0.6**	0.47**	0.82**	–0.5**
Diastatic Power					–0.45**	–0.2	0.64**	0.05	–0.33	0.58**	0.03
Extract						–0.34	0.06	0.55**	0.65**	0.2	-0.58**
Viscosity							–0.5**	–0.31	–0.41*	–0.54**	0.83**
Soluble protein								0.63**	0.42*	0.91**	–0.32
Soluble protein/ Total									0.64**	0.58**	–0.33
Color										0.41*	-0.47**
Free amino N											–0.39*

* Significant at $P \leq 0.05$.

** Significant at $P \leq 0.01$.

Malt Quality

None of the cultivars met all three basic germination criteria (GE > 90%, WS < 10% and FN > 220 s) criteria in all of the trials. Baronesse met these criteria in seven out of eight trials whereas AC Metcalfe, CDC Meredith, Full Pint, and Harrington did not meet them in any of the trials (Table 6). Only samples that met basic germination criteria were selected for micro-malting. In this selected subset of samples a-amylase ranged from 52 dextrinizing units (DU) (Baronesse) to 77 DU (Hockett; Table 6). While the lower values are undesirable for adjunct brewing, they are in the range desired by craft brewers (Brewers Association, 2014). Genotype was significant for α-amylase, extract, FAN, and β-glucan (Table 7). Location and Y were significant for α-amylase, extract, FAN. The interactions G × L, G × Y, and L × Y were significant for α-amylase and b-glucan and G × L × Y was also significant for β-glucan. Craft brewers desire malt with FAN below 200 mg L^{-1}. In the present study FAN ranged from 137 mg L^{-1} (Baronesse) to 194 mg L^{-1} (CDC Copeland; Table 6). Extract ranged from 797 g kg^{-1} (Baronesse and 2004NZ170) to 843 g kg^{-1} (Bentley; Table 6). High extract is desirable in both all-malt and adjunct brewing as it relates positively to brewhouse yield though it tends to be of greater concern to large-scale brewers. High levels of wort β-glucan (>100 mg L^{-1}) are undesirable as they can slow both lautering and beer filtration rates. In the current study, wort β-glucan ranged from 48 mg L^{-1} (Bentley) to 333 mg L^{-1} (Bob; Table 6). The largest number of cultivars met basic germination requirements in MVORG 2014. When this trial was analyzed separately, genotype was significant for α-amylase, extract, FAN, and, β-glucan (Supplemental Table S3).

Within the subset of samples micro-malted, FN was negatively correlated with major malt quality parameters including malt loss, α-amylase, diastatic power, soluble protein, and FAN (Table 8). Grain protein was positively correlated with diastatic power, and negatively correlated with extract (Table 8), similar to previous reports (Weston et al., 1993). When malted according to standard micro-malting procedures, all locally adapted feed cultivars had high β-glucan levels; Baronesse and 2004NZ170 had below standard extract levels. However, α-amylase and FAN levels observed for feed cultivars were acceptable for all-malt brewing (Table 6). Additional trials to identify cultivars with resistance to pre-harvest sprouting, lower levels of β-glucan and higher levels of extract may be necessary.

Adjusting malting methods to accommodate differences in barley parameters is another method that could be utilized to produce malt from barley grown in minor production areas. Steeping at a lower temperature has been found to reduce β-glucan content in malt (Rimsten et al., 2002), which could help overcome one of the major quality impairments of the locally adapted feed varieties. Skagit Valley Malting, recently established in western Washington, has successfully produced malt from Richard with low levels of wort β-glucan, demonstrating the potential for cultivar specific malting (Supplemental Table S4). While it is not uncommon to see elevated β-glucan levels in micro-malting, the cultivar Richard was deemed unsatisfactory in AMBA pilot malt trials, targeted toward adjunct brewing. Other craft malt houses across North America are malting cultivars previously classified as feed barleys (Thomas 2013; Frank and Meltzer, 2014). Developing methods of malting locally adapted cultivars is creating new opportunities for craft brewers and barley producers in minor growing regions.

CONCLUSION

Demand from the craft brewing industry has created opportunity for the development of a craft malting industry (Bastian et al., 1999; Processing Center, 2001; Thomas, 2013; Frank and Meltzer, 2014). Given the challenges of producing high quality malting barley, careful selection of locally adapted cultivars will be important for the continued growth of the craft malting industry. In under-represented regions across North America, barley cultivars will need to be identified with resistance to locally important pathogens and abiotic pressures, such as pre-harvest sprouting, to consistently produce high yields and meet basic quality standards. The development of custom malting regimes may allow for the production of malt from cultivars not previously considered to be suitable for malting.

Developing funding models to support new, and strengthen existing, barley testing and breeding programs will be needed to continue selection and development of locally adapted cultivars for craft malt production in diverse growing regions. Meeting 100% of the malt needs of craft breweries in Washington state would require approximately 13,000 t of malt at a rate of 32 kg of barley per barrel of beer (Bond et al., 2015; Brewers Association, 2015b). Meeting this demand would require a minimum of 2600 ha of barley production, assuming a mean yield of 5000 kg ha^{-1} and no loss during growing or malting. Revenue derived from a traditional royalty model of US$0.04 per kg of seed planted (at 135 kg ha^{-1}) could provide much needed support for regional variety testing programs, though it is unlikely that this would be sufficient to sustain a dedicated breeding program.

Participatory approaches that leverage funding from end-users may help facilitate breeding for regional barley production in western Washington and elsewhere (Brouwer et al., 2015). A combination of traditional seed sale royalty (paid by grower) and end-use royalty (paid by maltster and/or brewer) could be divided between local testing programs and regional breeders. Until this or a similar model of revenue sharing can be achieved, the continued growth of the craft malting industry will depend on the current capacity of public sector programs to identify the best locally adapted cultivars.

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