Received: 14/06/2023 Revised: 06/09/2023 Accepted: 21/11/2023 Published: 08/02/2024

ORIGINAL ARTICLE

DOI 10.58430/jib.v130i1.43

INSTITUTE OF BREWING & DISTILLING

Barley variety interacts positively with floor malting to produce different malts and beers

- Campbell P. Morrissy[1,2]
- Curtis Davenport[3]
- Scott P. Fisk[1]
- Vern Johnson[4]
- Darrin Culp[5]
- Hayley Sutton[2]
- Harmonie M. Bettenhausen[6]
- Ron Silberstein[3]
- Patrick M. Hayes[1]

[1] Department of Crop and Soil Science, Oregon State University, Corvallis, Oregon, USA.
[2] pFriem Family Brewers, Hood River, Oregon, USA.
[3] Admiral Maltings, Alameda, California, USA.
[4] Deschutes Brewery, Bend, Oregon, USA.
[5] Intermountain Research and Extension Center, University of California, Tulelake, California, USA.
[6] Center for Craft Food and Beverage, Hartwick College, Oneonta, New York, USA.

Campbell@pfriembeer.com

Abstract

Why was the work done: Floor malting maintains a small but notable market share due to its reputed contributions to beer flavour. These malts are viewed as premium products and are produced in both historic and contemporary floor maltings. Despite this, little work has been performed on floor malting to evaluate its effect on malt and subsequent beer quality and flavour. Accordingly, this work investigated whether floor malting produces distinct malts and beers relative to pneumatic maltings.

How was the work done: A mini-floor malting protocol was developed to malt small quantities of grain in a repeatable system that produces malt comparable to the production scale. Two winter barley varieties (Lontra and Thunder) were used to understand whether there was a malting type by variety interaction effect on beer flavour.

What are the main findings: Both floor and pneumatic malts produced similar malts and beers based on quality metrics and the differences found between malts were more attributable to variety and the respective rate of proteolysis. Sensory results showed that there was a significant malting type by variety interaction driving hedonic and descriptive sensory results.

Why is the work important: These results suggest that while the different malting types produce analytically similar malt, selection of barley variety can be used to optimise the floor malting process to produce distinct beer flavour profiles.

Keywords:

barley variety, winter barley, floor malting, malt quality

Introduction

Floor malting dates back as far as malting itself and is the simplest method where steeped barley is spread on a floor and allowed to germinate prior to drying. Floor malting grew to a refined, industrial process in the 19th century so as to keep pace with growing beer demand (Dornbusch, 2010). While the first patents for pneumatic malting systems date back to the mid-1800s, floor malting continued to be the dominant industry practice throughout the first half of the 20th century, declining to a minority of malt production by the 1970s (Hudson 1986). However, even as the malting industry shifted from floor to pneumatic, it was considered that floor maltings produced superior malt and provided the level of modification best suited for the all-malt, infusion mashed beers common in the United Kingdom (Marshall 1952). Further, floor malting is thought to contribute distinctive flavours in Scotch malt whisky that are not replicated by pneumatic maltings (Bathgate 2019). Floor malting is inherently at a smaller scale, rarely exceeding 30 metric tonne batch sizes and, even in its most automated form, is still a relatively manual process (Briggs 1998). Technically, there are higher moisture losses with germination during floor malting and the possibility of anaerobic conditions due to the lower rate of removal of CO_2 in the less dynamic germination bed (Whitmore and Spahrow 1957). Anaerobiosis during floor malting can result in starch reserves being utilised at a greater rate than in pneumatic malting resulting in greater malting loss. Despite these considerations, floor maltings have been retained in the production of some premium products and new facilities have opened with the advent of craft malting in the United States.

Despite the historical importance of floor malting to the brewing and distilling industries, research on the contribution to flavour is limited. Although many publications in the past consider floor malting as the industrial practice of the time there are no comparisons with pneumatic malting. That said, there have been recent studies investigating the topic. Griggs (2018) compared malts made with the heritage variety Maris Otter® produced by a floor and pneumatic maltings and found they could be differentiated by their volatile chemical profile, including compounds with known contributions to malt and beer flavour. Another study evaluated malts and beers made with CDC Copeland in a commercial floor maltings and a laboratory pneumatic maltings and found significant differences in malt quality specifications, but a sensory panel was unable to differentiate between beers made with the malts (Kilfoil et al. 2019).

More recently, Morrissy et al (2022b) used a novel mini-scale floor malting protocol to investigate the contribution of barley genotype to beer flavour. This work also evaluated a new barley variety using floor malting which exhibited nuanced differences compared to the floor malted control. However, this study did not compare beers produced from floor malt and pneumatic malt made with the same varieties.

In the work reported here, the role of floor malting in beer flavour is investigated with barley grown in the Klamath Basin which runs through Oregon and California. While malting barley in California only makes up a small portion of acreage planted nationally, it was once a famed region with malt being exported to British breweries in the early 1900s (Beaven 1936). Today the Klamath Basin is one of only a few remaining regions in the state growing malting barley at measurable scale. The Klamath Basin encompasses a large watershed and is managed for agriculture, fisheries, recreation, and ecological purposes (NOAA 2022), with the majority of agricultural land in the upper basin, relying primarily on irrigation water from Upper Klamath Lake. The region is in a multi-year drought and water rights are tied to the demands from users and are subject to strict management (Snyder 2018; Vandermolen and Horangic 2018). Given the current pressure on water resources, winter barley is of interest due to its reduced requirement for water, lower disease pressure, and overall ecosystem services, although additional work is warranted to evaluate the suitability of winter barley to the region.

The unique qualities of the heritage variety Maris Otter have been touted by brewers and it is claimed that its true potential was best unlocked in a floor maltings (Robin Appel, personal communication). This begs the question of whether the converse is true and if floor malt is at its best when using appropriate varieties. This research used a workflow of mini-malting, brewing, and sensory analysis to evaluate the effects of floor and pneumatic malting on beer flavour. It builds on previous work evaluating the effect of barley genotype on beer flavour (Herb et al. 2017a; Bettenhausen et al. 2020; Windes et al. 2021; Morrissy et al. 2022a, b; Sayre-Chavez et al. 2022; Morrissy et al. 2023).

The aims of the work reported here are (i) does floor malting produce significantly different malts and beers compared to pneumatic malts; and (ii) is there a malting type by barley variety interaction in which some varieties perform better in a floor malting? In addition, this work considers the potential for winter malting barley in the Klamath Basin together with further refinement of the novel mini-floor malting protocol (Morrissy et al. 2022b).

Materials and methods

Barley and grain quality

The genotypes of the barley, their pedigrees, and growth habits are reported in Table 1. Thiunder and Lontra are two-row, winter malting barley varieties developed by Oregon State University (OSU) and released in 2019 and 2023 (Hayes et al. 2019; Morrissy et al. 2024). Thunder is on the American Malting Barley Association's (AMBA) list of recommended malting varieties, whereas Lontra has not been evaluated (https://ambainc.org/recommended-varieties.php). CDC Copeland is a two-row, spring malting variety released in 1999 by the Canadian Crop Development Centre and carries an AMBA recommendation (CMBTC, 2022).

Lontra and Thunder were grown under conventional conditions at the University of California - Intermountain Research and Extension Center (UC-IREC) in Tulelake, CA, USA; planted in the fall of 2021 and harvested in the summer of 2022. CDC Copeland was grown under organic conditions by Cascade Farms in Tulelake; it was planted in spring of 2021 and harvested in the summer of 2021. CDC Copeland was contracted by Admiral Maltings and achieved malt quality specification. Barley grain analysis was performed using American Society of Brewing Chemists (ASBC) Methods of Analysis. (Barley-2, Physical Tests; Barley-3, Germination). Protein and moisture were measured using a FOSS Infratec-NOVA near-infrared grain analyser (Hillerød, Denmark).

Malting and malt analysis

All malts were processed to meet the brand specifications of Maiden Voyage pale ale malt, a commercial malt from Admiral Maltings (https://admiralmaltings.com/malt/maiden-voyage-certified-organic). Malts are differentiated as 'mini-scale' (<150kg) and 'plant-scale' (production size batch, 8-10 metric tonnes) and by malting equipment – 'floor' and 'pneumatic'. Floor malts were produced at Admiral Maltings and pneumatic malts were produced using the Barley Project (https://barleyworld.org) single vessel mini-malter (a custom unit fabricated at Oregon State University). All experimental malts were mini-scale and differentiated on variety and malt type: 'Lontra-Floor', 'Lontra-Pneumatic', 'Thunder-Floor', and 'Thunder-Pneumatic'. Maiden Voyage was included as a floor malted, plant-scale reference. Malting conditions for the malts are detailed in Table 2.

Malt quality was analysed by the Hartwick College Center for Craft Food & Beverage (Oneonta, New York, USA), using ASBC Methods of Analysis (Malt-4, Extract; Malt-6, Diastatic Power; Malt-7, Alpha-Amylase; Malt-8, Protein; Malt-12, Friability, Beer-31, Free Amino Nitrogen). Standard malt quality parameters were benchmarked against the AMBA guidelines for all-malt brewing (AMBA, 2023).

Skinned malt was measured using the ASBC Method of Analysis Barley-2, Physical Tests. Dimethyl sulphide precursor (DMSp) was measured at the Rahr© Technical Center (Shakopee, MN, USA).

Table 1.

Barley varieties.

Description	Pedigree	Growth Habit	Developer
Lontra	04-028-36/Maris Otter	Winter	Oregon State University
Thunder	Wintmalt/Charles	Winter	Oregon State University
CDC Copeland	WM861-5/TR118	Spring	Crop Development Centre, University of Saskatchewan

Table 2.

Malting conditions.

Malt	Steep Out Moisture %	Target Moisture %	Sprays #	Post-Spray Moisture %	Pre-Kiln Moisture %	GC
Lontra - Pneumatic	45.4	49.0	2	50.1	48.0	98
Lontra - Floor	47.1	47.0	0	-	46.6	93
Thunder - Pneumatic	45.8	45.0	0	-	44.2	99
Thunder - Floor	45.4	44.0	0	-	46.6	102
Copeland - Mini Floor	45.1	45.0	0	-	44.5	99
Maiden Voyage	45.8	45.0	0	-	45.6	103

GC = growth count index (max = 125). Sprays – supplemental moisture applied by spraying grain during the first day of germination; duration of each spray was 2.5 minutes.

using the ASBC Method of Analysis Malt-14, DMSp by headspace Gas Chromatography. β-Glucanase activity in malt was measured at the University of California-Davis (Davis, CA, USA.) using the method of Held and Fox (2023).

Floor malting

Floor malts were produced in batches (27 kg) at Admiral Maltings in February 2023 using the mini-malting protocol described by Morrissy et al (2022b). The mini-scale steeping system is shown in Figure 1. The malting conditions were designed to match those of Maiden Voyage brand pale ale malt.CDC Copeland was included in the mini-malting trials to benchmark the mini-malting protocol against the plant-scale batch. The malt used for brewing was a composite of three malting replicates to generate sufficient malt for brewing. Malt quality was reported on the composite sample for each malt, individual replicate data is available upon request.

The mini-floor malting protocol was as follows.

Steeping: Each barley variety was steeped in 121 L polyethylene bins modified to allow aeration during wet steeps and CO_2 exhaust during dry steeps. Steeping cycles varied between varieties to achieve optimal modification. Thunder had a shorter wet steep duration than Copeland and Lontra, and the third wet steep duration was adjusted to 45-47% moisture content at end of steeping.

Germination: Steeped grain was spread onto a temperature-controlled germination floor at a depth of 9 cm and turned twice per day using a shovel. Bed area remained constant throughout germination and the green malt expanded to a depth of approximately 14 cm. Top of the bed temperatures were maintained at approximately 18°C with bottom of bed temperatures at approximately 15°C. Germination lasted 120 hours.

Figure 1.

Steeping equipment for the mini-floor malting

Kilning: The mini-scale malts were kilned using perforated stainless steel cylinders for isolation within a plant-scale batch of Maiden Voyage. The kilning programme was as follows (time and applied air temperatures): 12 h free dry (8h ramp from 49 to 60°C, 5 h hold at 60°C); 7 h force dry (5 h ramp from 71° to 91°C, 2 h hold at 91°C); 5 h curing (1h ramp from 91° to 96°C, 4 h hold at 96°C). Kilned malt was cleaned with a de-culming device and screen cleaner using a 5/64" sift screen (Cimbria, Denmark).

The plant-scale batch of Maiden Voyage pale ale malt was produced at Admiral Maltings in February 2023 using 7250 kg of CDC Copeland barley. The plant-scale malting protocol was as follows.

Steeping: Barley was hydrated in conical bottom steep tanks as follows: 10 h wet, 18 h dry, 10 h wet, 9 h dry, 1h spray. Aeration was provided during wet steeps, 5 minutes on/5 minutes off. CO_2 exhaust was provided during dry steeps, 5 minutes on/7 minutes off.

Germination: Steeped grain was spread onto a temperature-controlled germination floor at a depth of 9 cm and turned twice per day using a mechanical turner. Bed area remained constant throughout germination and the green malt expanded to a depth of approximately 14 cm. Top of bed germination temperatures were maintained at approximately 18°C with bottom of bed temperatures at approximately 16°C. Germination lasted 120 hours.

Kilning: The programme was identical to that described above for mini malting. Kilned malt was cleaned with a de-culming device and screen cleaner using a 5/64” sift screen (Cimbria, Denmark).

Pneumatic malting

Malting at OSU was performed using the mini-malter in 68 kg batches in January and February (2023). Standard steeping parameters were used, with the exception of an additional hour in the third steep for Lontra, due to its higher protein level. Both varieties were germinated for four days at 17°C. Supplementary moisture was applied to Lontra during the first day of germination to increase modification due to protein level. Both malts were kilned using the same parameters as pale ale malt. The complete mini-pneumatic protocol was as follows.

Steeping: 8 h wet, 14 h dry, at 15°C; 8 h wet, 12 h dry, at 15°C; 2 h wet (Thunder), 3 h wet (Lontra) at 15°C. Steep 3 was increased by one hour for Lontra to achieve a higher steep out moisture (due to its higher protein level).

Germination: 96 h at 17°C. Supplementary moisture was applied to Lontra during the first day of germination to further increase moisture content.

Kilning: (time and applied air temperatures): 10 h at 50°C, 3 h at 60°C, 3 h at 65°C, 2 h at 70°C, 2 h at 90°C, 4 h at 115°C. Conditions (grain bed temperature) 10 h at 44°C, 3 h at 57°C, 3 h at 62°C, 2 h at 66°C, 2 h at 77°C, 4 h at 93°C.

Brewing and beer analysis

Ales were prepared at Deschutes Brewery (Bend, Oregon, USA.) using an Esau and Hueber four-vessel, 2.5hL brewery. Each of the malts was brewed with separately in March 2023. The brewing recipe and protocol was designed with to produce a commercial-type English-style Ale that emphasised malt characteristics. A detailed brewing protocol is available upon request.

Mashing: 37.2 kg of each malt was mashed with 95L of water at 70°C with 25 g of calcium sulphate and 30 mL of lactic acid added to achieve a mash pH of 5.3. Once mash-in was complete, the mash was held at 66.7°C for 30 min, the mash was then ramped, held for 5 min at 76.7°C and agitated for 5 min at 85% rotation speed prior to transfer to the lauter tun.

Lauter: Wort was recirculated for 15 min prior to separation. Wort separation proceeded until 227 L were collected and grains were sparged with 114 L of water at 76.7°C.

Wort Boiling: Nugget T-90 hop pellets (23 g) (Barth-Haas, Yakima, WA, USA.) were added at the beginning of boil. Sonnet T-90 hop pellets (294 g) (Hopsteiner, Yakima, WA, USA.) were added at 55 min into boil. The hopping schedule was designed to achieve 20 bitterness units (IBU) in the final beer. The boil finished after 60 min.

Whirlpool and cooling: After transfer from the kettle, the wort rested in the whirlpool for 15 min.

Fermentation and maturation: Wort was cooled to 18.8°C and pitched with 1.2-1.8 kg of English Ale Yeast (A09, Imperial Yeast, Oregon, USA.) to achieve 1×10^6 cells/mL/°P. The wort was oxygenated with beverage grade oxygen via a 2-micron carbonation stone at the bottom of the tank for 10 min with the oxygen regulator set at 3g/L. Beers were held at 20°C for 34 h after which the temperature setpoint was raised to 22.2°C until achieving the diacetyl specification of ≤20 µg/L. The beers were crash cooled to 1°C for 48 h and then transferred to a bright tank for conditioning and fined with BioFine® (Kerry Group PLC, Ireland) at a rate of 1mL/L and allowed to clarify.

Packaging: Beer was packaged in 20 L kegs at 2.5 v/v of carbonation, dissolved oxygen was ≤ 30µg/L for all beers.

Brewing quality analysis was performed at Deschutes Brewery using ASBC Methods of Analysis (Beer-2, Specific Gravity; Beer-4, Alcohol; Beer-9, pH; Beer-10, Colour; Beer-23a, Beer Bitterness; Beer-25b, Diacetyl). Mash efficiency was calculated by dividing the recovered extract at the end of lauter by the potential total extract provided by malt.

Sensory

An initial sensory evaluation was performed to determine if there were perceptable differences between samples that warranted further evaluation and to aid in the development of the sensory lexicon. A consumer sensory panel was hosted at the Master Brewers Association of the Americas (MBAA) District Northwest Spring Technical Meeting (Hood River, Oregon) in April 2023. The sensory activity was open to all attendees and of the 53 participants, 90% were male identifying and 10% were female identifying with an age distribution of 21-30, 10%; 31-40, 60%; 41-50, 20% and 51+, 10%. Samples were presented blind, and tasters used a check-all-that-apply (CATA) analysis (Ares et al. 2014) using a simplified lexicon within the SampleOx© sensory app developed by DraughtLab© (https://www.draughtlab.com). As brewing industry professionals, tasters were experienced beer sensory evaluators and familiar with the attributes in the simplified lexicon.

The CATA analysis was followed by a hedonic assessment using a liking scale, rating each sample on a scale of 1-9, with 1 corresponding to 'extreme dislike' and 9 to 'extreme like'. Panellists were presented with one blind-coded sample at a time and had to complete the evaluation before moving to the next.

Further sensory evaluation was performed using the sensory panel at pFriem Family Brewers – referred to as the 'brewery panel'. The panel consisted of 13 panellists (ten male, three female, ages 25-37) using the methodology and training reported by Morrissy et al (2022b). Sensory evaluation was performed over three sessions to generate sufficient replicates for analysis (n = 26); panellists were presented samples in a randomised order for each session. Samples were presented blind, and panellists were asked to assess each sample using Quantitative Descriptive Analysis® (QDA) (Stone, 1992) followed by a hedonic assessment. An eleven-attribute lexicon was developed from the results of the consumer sensory analysis, with the top five CATA selections for each sample included. Based on previous results using similar beers (Morrissy et al. 2022b), *butter* and *vegetal* were also added. The attributes were: *bitter*, *bread*, *butter*, *caramel/honey*, *cereal*, *citrus*, *grassy/herbal*, *floral*, *nutty*, *sweet*, and *vegetal*. Panellists were first presented with the QDA and were asked to rate each attribute on a scale of 0-5, where 0 is 'not present' and 5 is 'extremely present'. Finally, panellists were asked to perform a hedonic assessment on a 1-5 scale, with 1, 'strongly dislike'; 2, 'dislike'; 3, 'neither like nor dislike'; 4, 'like'; 5, 'strongly like'. Data were collected with the DraughtLab© app.

Statistics

Data aggregation and graphical demonstration of data was performed using Microsoft Excel (version 16.16.27). Statistical analysis was performed using the R environment for statistical computing (https://www.r-project.org/). Analysis of variance (ANOVA) was performed on sensory data with malting type (floor or pneumatic) and variety (genotype) as main effects and individual malts treated as the interaction term (malting type x variety).

Results and discussion

Grain quality

Both winter barley varieties used in this work showed acceptable grain quality. Thunder had moderate grain protein within the AMBA recommended range for all-malt brewing (≤12.0%), while Lontra was above (12.2%) (Table 3). Lontra had a lower percentage of plump kernels but also a smaller percentage of thin kernels (sift screen <5/64”), which may indicate a smaller mean kernel size but better homogeneity. At the time of malting, both varieties showed no dormancy and little to no water sensitivity which is in accordance with previous findings from Tulelake (Halstead et al. 2022; Morrissy et al. 2023). Test weights were near the same and both yielded well, showing comparable results to previous winter barley trials using the same varieties and to irrigated spring barley yield trials (Wilson 2021; Morrissy et al. 2024). Thunder out-yielded Lontra by over 1,000 kg/ha, and while a substantial difference, this was not a replicated agronomic trial and plots differed in size by an order of magnitude. Previous work (Morrissy et al. 2024) found that yield differences between the two varieties varied between years and environments with each outyielding the other depending on conditions.

Malting

Mini malting was successful in producing acceptable malt for brewing. The pneumatic malting protocol has been used in previous studies in malting and brewing (Windes et al. 2021; Morrissy et al. 2022a, 2023), while the floor malting protocol was developed more recently (Morrissy et al. 2022b). Each process used bespoke steeping regimes to target grain moisture based on previous experience and levels of modification. Thunder takes up water quickly and is prone to over modification. Accordingly, this variety had shorter wet steeps and a lower target cast moisture than Lontra (Table 2).

The novel mini-floor malting protocol was benchmarked using CDC Copeland and produced malt of similar quality to the plant-scale (Table 4). The exceptions were β-glucan and friability which were respectively higher (214 v 77 mg/L) and lower (86.4 v 93.3%) in the mini-floor malt. It was noted by the maltster that during the first two rounds of floor malting, all samples experienced colder than usual steep temperatures during the second immersion (11.3-13.3°C) than was typical (14.0-15.0°C). This observation was of interest as colder steeping temperatures can retard cytolytic modification (Müller et al. 2013) and this manifested in the CDC Copeland mini-floor malts, whereas the plant-scale malt - under normal steep temperatures - hydrated to a similar level with no issues with modification (Table 4).

This effect was not seen with Lontra and Thunder. Both varieties had high levels of β-glucanase activity, which was significantly higher than other winter barley varieties from multiple locations including Tulelake (Table 5). This may lead to stable cytolytic modification in the malthouse despite deviations in malting process. Generally, the updated mini-floor malting protocol showed significant improvement with the addition of adequate aeration and CO_2 removal during steeping. Further refinement of the bespoke malting protocol (as in a commercial malt house) may mediate these effects but the results reported here show the effectiveness of this tool for the evaluation of floor malting of barley genotypes.

Table 3.

Grain quality data for the two winter barley varieties harvested in 2022 at UC-IREC and malted for this work. Thunder was planted in a 0.04 ha plot and Lontra in a 0.40 ha plot.

Variety	Protein %	Plump >6/64”	Thin <5/64”	TW g/L	Yield kg/ha	GE % 4mL	WS % 8mL
Lontra	12.2*	89.5*	0.6	639.7	6904.4	100	90
Thunder	10.9	92.0	4.0*	646.2	8002.9	99	95

*Outside of AMBA guidelines for all-malt brewing. TW = test weight; GE = germination energy - percentage of kernels germinated in 4mL of water; WS = water sensitivity – percentage of kernels germinated in 8 mL of water.

Table 4.

Comparison between CDC Copeland floor malts produced at mini- and plant-scale.

Entry	Moisture %	Friability %	Extract FGDB %	Colour SRM	β-glucan mg/L	Protein %	S/T %	FAN mg/L	DP °L	AA DU
CDC Copeland – Mini Floor*	2.9	86.4	81.2	2.81	214	11.6	45.1	206	94	59.6
Maiden Voyage (CDC Copeland)	2.8	93.3	80.1	2.96	77	11.8	43.1	205	97	55.3

*Malt quality is the mean of the three malting replicates.
FGDB = fine grind dry basis; S/T = soluble to total protein ratio; FAN = free amino nitrogen; DP = diastatic power; AA = α-amylase; DU = dextrinizing units.

Table 5.

β-Glucanase activity of five barley lines from a multi-location trial in 2021.

Line	β-Glucanase U/mg
DH140963	0.31^{c}
DH141132	0.39^{b}
Lightning	0.33^{bc}
Lontra	0.51^{a}
Thunder	0.54^{a}

Letters in superscript annotates mean separation at the ≤0.05 level. The same letter indicates no significant difference between entries.

Malt Quality

None of the malts including those at plant scale, met all the American Malting Barley Association's (AMBA) recommended guidelines (Table 6). Overall, despite higher than desired total protein, the malts produced with Lontra were better suited for all-malt brewing than Thunder malt with quality more associated with variety than malting type. Compared to Thunder, Lontra malts had moderate enzymatic activity (DP and α-amylase) and lower FAN (free amino nitrogen). This was unexpected given the higher grain protein and lower soluble to total protein (S/T) ratio. Overall, Lontra malts had a lower extract than Thunder, which typically correlates with higher grain and malt protein. Both pneumatic malts had a lower dry basis extract than the floor malt which suggests additional malting loss associated with that process (Piendl 1976). Maiden Voyage malt also had low extract, which was noted in previous work with CDC Copeland (crop year 2021) from the Klamath Basin, which is likely to be related to the challenges of spring barley grown under drought conditions (Morrissy et al. 2022b).

In agreement with previous observations (Halstead et al. 2022; Morrissy et al. 2023), the malts exceeded the AMBA guidelines for FAN (140-190 mg/L) with Thunder well above specification at both malthouses with 248 mg/L for Thunder-Pneumatic and 282 mg/L for Thunder-Floor (Table 6). It appears that modification in these two lines can be attributed to variety rather than malting type. While both Lontra malts exceeded the FAN guideline and had higher grain protein than Thunder, they appear to have moderate modification. The S/T ratios of Lontra indicate that further reduction in steep out moisture, lower germination temperatures, or other process manipulations may help to manage proteolytic modification. Malt is the primary source of the FAN used by yeast with most strains requiring 100-150mg/L for fermentation of a standard gravity beer (Meilgaard 1976; Hill and Stewart 2019). However, excess FAN can contribute to off-flavours in package and negatively affect shelf stability (Ferreira and Guido 2018). Accordingly, as Thunder malts have approximately twice the wort FAN required for a standard gravity fermentation, this may be problematic in the production of flavour stable all-malt beers.

Previous observations (Morrissy et al. 2022b) have shown that Lontra may be prone to husk damage and skinning (≥33% lost husk) during malting and cleaning. Results from this work support this, with Lontra malts having 27.3% skinned malt kernels with Thunder at 18%. There was no malt or malting type effect on malt skinning, but variety had a significant impact (*p*-value = $1.13e^{-4}$). Despite the differences in skinned kernels, wort filtration time and clarity were not affected with all malts behaving as normal (data not shown).

Table 6.

Quality analysis for mini-floor and plant-scale floor malts.

Entry	Moisture %	Friability %	Extract FGDB %	Extract FG As Is %	Colour SRM	β-glucan mg/L	Protein %	S/T %	FAN mg/L	DP °L	AA DU	pH
Lontra - Pneumatic	3.1	91.2	80.5#	78.0	2.35	87	12.4*	44.6	206*	124	48.8	5.75
Lontra - Floor	4.1	90.0	81.3	78.0	2.35	120*	12.8*	43.3	204*	124	48.9	5.80
Thunder - Pneumatic	3.1	90.8	82.4	79.9	4.38	113*	11.3	52.0*	248*	121	78.0*	5.69
Thunder - Floor	4.0	90.9	82.8	79.5	4.13	97	11.4	57.1*	282*	149	83.7*	5.76
Maiden Voyage (CDC Copeland)	2.8	93.3	80.1#	77.9	2.96	77	11.8	43.1	205*	97#	55.3	5.76

*Exceeds AMBA guidelines for all-malt brewing. #Below AMBA guidelines for all-malt brewing. Colour (SRM) was not benchmarked against AMBA guidelines due to the malt-type used.
FGDB = fine grind dry basis; S/T = soluble to total protein ratio; FAN = free amino nitrogen; DP = diastatic power; AA = α-amylase; DU = dextrinising units.

There was not a substantial pH difference among the malts (Table 6). Griggs (2018) found wort pH to be 0.49 lower in malt made in a floor maltings compared to a pneumatic system. Here, although the difference between the malts was marginal (at 0.11), the floor malts were (slightly) higher than the pneumatic malts. However, Kilfoil et al (2019) also found no difference in wort pH between malting styles. Floor maltings can promote a higher rate of lactic acid bacteria activity during germination and associated increased acidity (O'Sullivan et al. 1999). Additionally, the type of fuel used to fire kilns can impact malt pH. Historically maltings (of both types) were fired with anthracite coal or fuel oil that naturally contained sulphur compounds which have been found to lower malt pH (Macey 1958; Bathgate 2019). These sulphur compounds limited the production of nitrosodimethylamine (NDMA) and as malt kilns were retrofitted to burn natural gas, sulphur dioxide was added in order to control NDMA (and maintaining the pH effect (Hudson 1986)). With modern kilns employing heated air with indirect fuel contact, sulphur dioxide is not required. Given that the work reported here and that by Kilfoil et al (2019) was performed in recently commissioned floor maltings, whereas that of Griggs (2018) was in a floor maltings from the mid-19th century, the malt pH may relate less to floor malting and more to the infrastructure and sanitation protocols used in the malt house.

All malts used in this study were analysed for the di-methyl sulphide precursor (DMSp). Previous research suggested that floor malting may be more prone to producing DMSp due to the difficulty in tightly controlling bed temperature (Kavanagh et al. 1976). However, the temperatures (19-25°C) used by Kavanagh et al (1976) exceeded the temperatures during germination of either of the malts reported here. Indeed, this suggestion may reflect the use of older facilities with poorly controlled air tempering and gradients across the grain bed resulting in hot spots (Hertrich 2013). Further, previous work found that beers made with Lontra malt scored high for the vegetal sensory attribute, begging the question whether DMS was a contributor to the sensory profile (Morrissy et al. 2022b). The level of DMSp (Table 7) was below the accepted normal value of 5 mg/L (Yin 2021). While this analysis was performed as a single replicate, it is noteworthy that there was greater separation between genotype than malting type, which aligns with work showing genotype is a major driver of DMS production (Pitz 1987; Yang et al. 1998). These results refute the suggestion that floor malting is more prone to DMSp development (Kishnani et al. 2022), and that genotype, growing environment, or other factors outside of the malthouse are bigger contributors.

Table 7.

Content of di-methyl sulphide precursor (DMSp).

Malt/Entry	DMSp mg/L
Lontra - Pneumatic	3.77
Lontra - Floor	3.89
Thunder - Pneumatic	2.54
Thunder - Floor	3.00
Maiden Voyage (CDC Copeland)	1.35

Malts were kilned to match the malt colour of Maiden Voyage pale ale malt with the mini-floor malts malted within a Maiden Voyage batch whereas the pneumatic malts used a protocol to produce the same outcome. Despite the same germination and kilning protocols, the colour was noticeably higher in both Thunder malts than Lontra (Table 6). The Lontra malts were similar in colour to the Maiden Voyage and at 2.35 were just outside the brand specification (2.5-3.5 SRM). This implies a variety-based correlation to colour, vis-à-vis proteolysis, as the malts produced with Lontra and Thunder developed almost the same colour regardless of malt house. Colour had a positive relationship with indicators of proteolytic modification (S/T, FAN, and α-amylase) (Coghe et al. 2006; Herb et al. 2017b). However, although Lontra had higher grain and malt protein, yet resulted in lower colour malt; a further indication of tempered modification. The mild colour development of Lontra may offer advantages in allowing a more aggressive kilning regime so as to develop flavour compounds and remove DMSp, whilst not producing malt that is out of specification for colour (Mackie and Slaughter 2000).

Brewing

All malts performed satisfactorily in the brewhouse with beers - except for apparent extract (AE) and colour – analytically consistent (Table 8). There may be a correlation between barley variety as both Lontra malts resulted in the highest AE (and lowest ABV). Mash efficiency was consistent at about 93%, except for Lontra-Floor at 89.9%. Mash efficiency was not significantly correlated with any other malting or brewing parameters (data not shown), and this may reflect inherent batch variation within the brewhouse not mitigated by multiple replicates. While Lontra malts had greater husk damage, brewhouse yield was normal for Lontra-Pneumatic. Fermentation was within the normal cycle time with the beers having a similar pH (range of 0.11). Prior to cooling, all beers were below the specification for diacetyl (≤20 µg/L). Finally, bitterness was broadly consistent between the beers with a range of 4 mg/L. However, sensory assessment of bitterness did not correlate significantly with IBU (Table 9).

Sensory

Consumer sensory testing showed separation between the different malts. The significant differences in the hedonic sensory evaluation (Figure 2) were explored with further sensory analysis by the brewery panel. Lontra-Floor was the most preferred and differed significantly from Lontra-Pneumatic and Maiden Voyage. However, separation was minor with a 0.46-point differential (1-9 scale) between the most liked and the least liked. Nonetheless, it is interesting that Lontra separated between groups whereas Thunder did not, showing a malting type by variety interaction. The CATA analysis was also successful in developing a lexicon for further sensory evaluation as there were eight unique attributes within the top five selections for each line.

Sensory analysis by the brewery panel showed some significant differences in hedonic assessment as (Figure 3). In this evaluation, Thunder-Pneumatic was the most preferred with Lontra-Floor second most preferred, but they were not significantly different from each other, and both differed significantly from Thunder-Floor. There was again a significant malting type by variety effect in preference as Thunder malts separated between groupings, but Lontra did not. Correlation analysis (Table 9) identified only one sensory attribute to significantly correlate with preference – *cereal* (Pearson's r = 0.97, significant at the 0.01 level).

One attribute was found to differ significantly between the five malts – *butter* (Figure 4). This is of interest as *butter* did correlate positively with

Table 8.

Analysis of beers.

Entry	Mash Efficiency %	OG °P	AE °P	ABV %	pH	Colour SRM	IBU mg/L	Diacetyl µg/L
Lontra - Pneumatic	93.3	12.0	2.8	4.89	4.10	4.56	20.0	8
Lontra - Floor	89.9	12.0	2.9	4.89	4.10	4.92	22.0	2
Thunder - Pneumatic	93.6	12.0	2.6	5.03	4.07	7.26	22.5	10
Thunder - Floor	93.2	11.8	2.2	5.06	4.14	7.07	22.0	19
Maiden Voyage (CDC Copeland)	92.6	12.0	2.5	5.02	4.03	5.12	24.0	5

OG = original gravity; AE = apparent extract; ABV = alcohol by volume; IBU = international bitterness units.

Table 9.

Pearson's correlation coefficients between sensory outcomes and process parameters.
Correlations between sensory attributes and malting/brewing parameters are not shown.

		Bitter	Bread	Butter	Caramel/Honey	Cereal	Citrus	Floral	Grassy/Herbal	Nutty	Sweet	Vegetal	Preference
Preference		0.01	0.28	-0.80	-0.29	**0.97****	0.45	0.30	0.28	-0.10	0.04	-0.74	1.00
Efficiency	**%**	-0.54	0.13	-0.64	-0.73	0.67	0.65	0.37	0.38	-0.62	-0.46	-0.43	0.80
OG	**°P**	-0.49	0.04	-0.78	-0.71	0.78	0.51	0.41	0.43	-0.57	-0.44	-0.63	0.87
AE	**°P**	-0.54	-0.01	-0.57	-0.56	0.54	**0.90***	0.60	0.58	-0.65	-0.33	-0.21	0.65
ABV	**%**	0.70	0.24	0.32	0.54	-0.17	-0.88	-0.65	-0.64	0.79	0.46	-0.09	-0.27
Beer pH		0.19	0.14	0.77	0.48	-0.72	0.18	-0.20	-0.24	0.23	0.33	**0.91***	-0.69
Beer Colour	**SRM**	0.86	0.68	0.51	0.68	-0.16	-0.49	-0.77	-0.81	**0.93***	0.71	0.22	-0.17
IBU	**mg/L**	0.50	-0.20	-0.53	0.34	0.52	-0.49	0.12	0.12	0.46	0.37	-0.80	0.32
Diacetyl	**µg/L**	0.45	0.32	**0.92***	0.50	-0.78	-0.63	-0.79	-0.79	0.58	0.31	0.68	-0.77
Moisture	**%**	0.42	-0.08	0.29	0.73	-0.27	0.38	0.26	0.20	0.36	0.65	0.48	-0.36
Friability	**%**	-0.29	-0.47	-0.30	-0.39	0.07	-0.68	-0.01	0.07	-0.24	-0.50	-0.55	-0.01
Extract	**FGDB**	0.83	0.65	0.62	0.80	-0.28	-0.16	-0.59	-0.66	0.87	0.81	0.50	-0.28
Wort Colour	**SRM**	0.81	0.66	0.48	0.59	-0.14	-0.61	-0.82	-0.85	**0.89***	0.61	0.14	-0.15
β-glucan	**mg/L**	0.54	0.54	-0.07	0.50	0.37	0.64	0.10	0.01	0.44	0.72	0.10	0.39
Protein	**%**	-0.62	-0.49	-0.44	-0.38	0.20	0.83	0.85	0.84	-0.73	-0.34	-0.04	0.21
S/T	**%**	0.71	0.53	0.80	0.68	-0.54	-0.50	-0.79	-0.82	0.81	0.59	0.57	-0.54
FAN	**mg/L**	0.74	0.47	0.78	0.73	-0.54	-0.54	-0.74	-0.78	0.83	0.62	0.53	-0.56
DP	**°L**	0.38	0.30	0.84	0.59	-0.71	0.03	-0.39	-0.43	0.43	0.46	**0.89***	-0.68
AA	**D.U.**	0.81	0.57	0.63	0.68	-0.33	-0.60	-0.80	-0.83	**0.90***	0.64	0.32	-0.35
Wort pH		-0.26	-0.83	-0.26	0.13	-0.10	0.37	0.84	0.84	-0.35	-0.03	0.00	-0.25

*Significant at the 0.05 level; **significant at the 0.01 level

Figure 2.

Hedonic sensory results from the consumer panel (MBAA District NW meeting in April 2023)**.** Letters above each bar annotate mean separation between entries; those with the same letter are not significantly different. The vertical axis is scaled to emphasise separation.

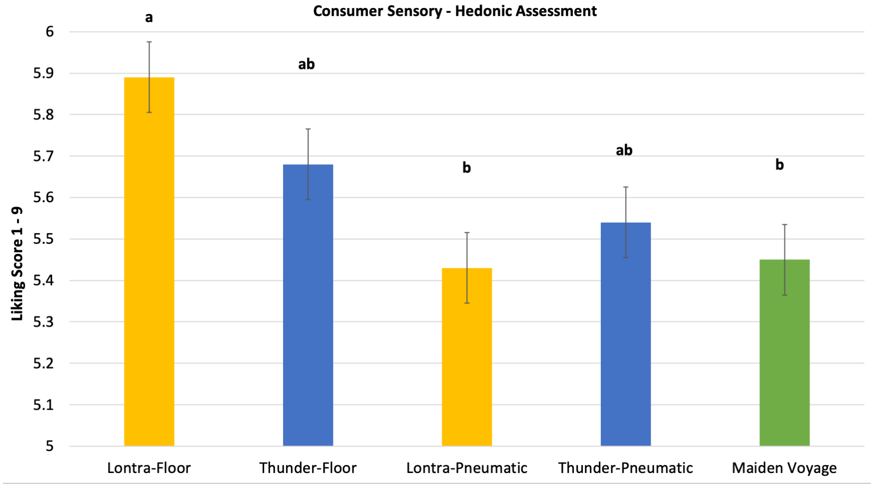
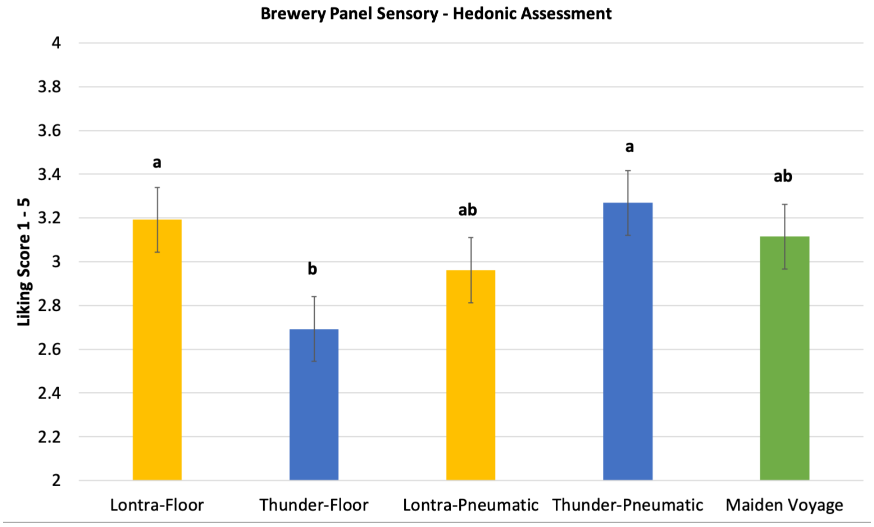


Figure 3.

Hedonic sensory results from the brewery panel. Letters above each bar annotate mean separation between entries; those with the same letter are not significantly different. The vertical axis is scaled to emphasise separation.



diacetyl (2,3-butanedione) (Table 9). Indeed, the highest diacetyl level (19 µg/L) was close to the lowest sensory threshold reported at 17 µg/L (Saison et al. 2009). While the correlation between the sensory attribute *butter* and diacetyl is not surprising given the low concentration. This implies that the beer matrix is acting synergistically and may emphasise butter-associated flavours (Morrissy et al. 2022b). Notably, *cereal* did not significantly differ (p-value = 0.0774) despite having a strong positive correlation with preference (Table 9) but was the only other attribute with a p-value ≤0.10. *Vegetal* was included in the lexicon due to previous work where the floor malted Lontra beer scored highly for this attribute. However, *vegetal* did not differ significantly between malts and had the lowest score of any attribute (Table 10). Interestingly, *vegetal* had a positive relationship with beer pH (Table 9), which may suggest some conversion of DMSO during fermentation (Anness and Bamforth 1982). However, given that DMSp values were low for all malts, it is unclear if DMS plays a role in the sensory profile of these beers.

As only one attribute varied significantly due to the malting type by variety interaction (malt entry), main effects were analysed for the remaining ten (Figure 5). Although malting type (floor vs. pneumatic) was not a significant source of variation for any attribute, there was a significant variety (genotype) effect for three attributes: *caramel/honey*, *citrus*, and *nutty*. These results (Figure 5) showed greater separation between barley variety than previous work on the role of barley genotype in beer flavour (Herb et al. 2017a; Windes et al. 2021; Li et al. 2022; Morrissy et al. 2022a, 2023). However, this is the first report to evaluate varieties across multiple malting types.

Thunder malts scored higher for *caramel/honey* and *nutty*, which may be reflect Maillard reaction products associated with higher colour formation (Blenkinsop 1991; Coghe et al. 2004). Of these, *nutty* correlated positively with colour (wort and beer), but *caramel/honey* did not. *Nutty* also correlated positively with α-amylase, a further indication of a relationship with proteolysis and the greater modification of the Thunder malts. On the other hand, Lontra malts scored higher for *citrus*. Apparent extract was the only quality parameter to correlate with *citrus*, but this is likely to be an underlying varietal effect rather than a link between sensory outcome and final gravity. Given the significant differences in proteolytic modification between the two varieties (regardless of malting type) these differences in sensory descriptors are

Figure 4.

Radar plot showing descriptive sensory results for all five malts used in this assessment. 'Butter' was the only significantly different attribute (p<0.05).

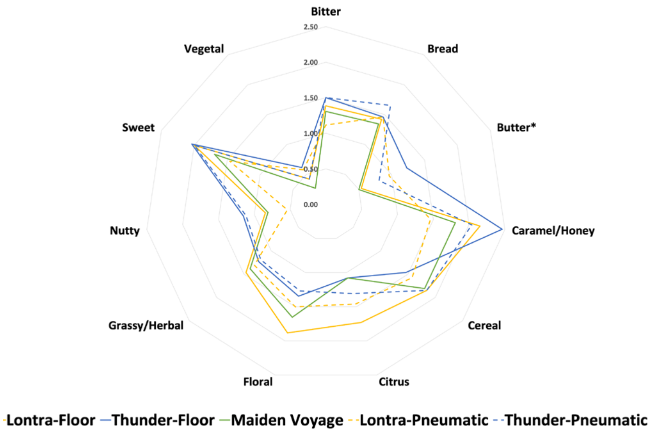


Figure 5.

Radar plot - descriptive sensory results against barley variety. 'Caramel/honey', 'citrus', and 'nutty' were all significant at the 0.05 level. Maiden Voyage (CDC Copeland) was not included in this comparison as there was no pneumatic component.

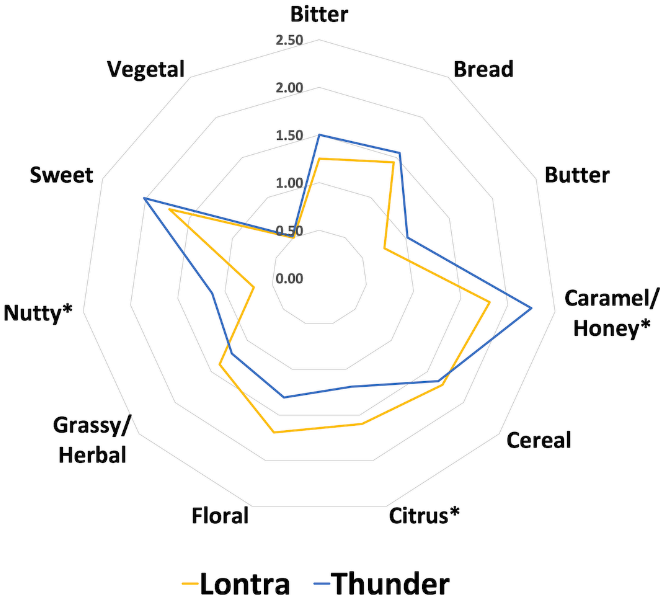


Table 10.

Mean attribute scores from the brewery sensory panel (n=26).

Malt	Bitter	Bread	Butter[#]	Caramel/Honey*	Cereal	Citrus*	Floral	Grassy/Herbal	Nutty*	Sweet	Vegetal	Entry Mean
Lontra - Pneumatic	1.12	1.46	0.96	1.46	1.58	1.46	1.50	1.31	0.54	1.46	0.58	1.22
Lontra - Floor	1.38	1.42	0.54	2.15	1.85	1.73	1.88	1.46	0.85	2.00	0.42	1.43
Thunder - Pneumatic	1.50	1.65	0.81	2.04	1.85	1.31	1.27	1.19	1.12	2.00	0.42	1.38
Thunder - Floor	1.50	1.46	1.23	2.46	1.46	1.08	1.35	1.23	1.15	2.04	0.62	1.42
Maiden Voyage	1.31	1.35	0.50	1.81	1.81	1.08	1.65	1.38	0.81	1.69	0.27	1.24
Attribute Mean	1.36	1.47	0.81	1.98	1.71	1.33	1.53	1.32	0.89	1.84	0.46	

*Significant at the 0.05 level; **significant at the 0.01 level

not profound. Although outside the scope of this work, sensory analysis of the flavour stability of aged beers would be of interest given the high FAN of all malts and possible mitigation of malting type.

Conclusions

This work considered whether floor malted barley produced distinct beers compared to pneumatic malt and whether certain varieties are more influenced by floor malting than others. Although there was no significant descriptive sensory differences between floor and pneumatic malting, there was a significant interaction between variety and floor malting that had a positive impact on beer preference. Barley variety played a significant role in driving beer flavour and had a more pronounced effect than reported in previous work, although this appeared to be driven by the propensity for proteolytic modification. Lontra - a new malting barley variety - was suited to floor malting, producing a malt with quality and sensory attributes that were more closely aligned to the plant-scale Maiden Voyage rather than Thunder. The Lontra-Floor was well-liked by both consumer and brewery panels falling in the upper quartile for both. Both barley varieties performed well agronomically in the Klamath Basin and produced suitable malts and beers providing further evidence for the potential of winter malting barley in the region. Additionally, the improved mini-floor malting protocol was successful in producing quality malts and can be confidently used in further studies of malting quality in a floor malthouse. Ultimately this work found that distinct malts and beers can be produced from different varieties using different malting technologies. It provides further evidence that varieties can be deployed with appropriate malting equipment and with protocols to optimise malt quality and beer flavour.

Author Contributions

Campbell Morrissy: Conceptualisation, methodology, formal analysis, investigation, data curation, writing (original draft, reviewing and editing), project administration.
Curtis Davenport: Methodology, investigation, resources, data curation, writing (reviewing and editing).
Scott Fisk: Methodology, investigation, resources, data curation, writing (reviewing and editing).
Vern Johnson: Investigation, resources, data curation.
Darrin Culp: Resources, data curation.
Hayley Sutton: Resources, data curation.
Harmonie Bettenhausen: Writing (reviewing and editing).
Ron Silberstein: Resources.
Patrick Hayes: Conceptualisation, investigation, writing (reviewing and editing), supervision, project administration, funding acquisition.

Acknowledgements

We would like to thank the following for support throughout this project: The teams at Admiral Maltings, Deschutes Brewery, and pFriem Family Brewers for their contributions to the malting, brewing, and sensory trials. Specific thanks to Simon Traeger and Chris Allen at pFriem Family Brewers for preparing beers for sensory evaluation. Lindsay Barr and Victoria Chaplin at DraughtLab© for assistance in setting up the sensory panels and interpretation of the results. Christina LaRue of MBAA District Northwest for accommodating the consumer sensory panel at the district meeting. Theresa Kukar and the team at the Rahr© Technical Centre for providing malt DMSp analysis. Dr. Glen Fox at UC-Davis for providing the β-Glucanase assay.

References

AMBA. 2023. Guidelines for malting barley breeders. https://ambainc.org/news-details.php?id=63d2780a0c948

Anness BJ, Bamforth C. 1982. Dimethyl sulphide - a review. *J Inst Brew* 88:244-252. https://doi-org/10.1002/j.2050-0416.1982.tb04101.x

Ares G, Antúnez L, Giménez A, Roigard C, Pineau B, Hunter DC, Jaeger SR. 2014. Further investigations into the reproducibility of check-all-that-apply (CATA) questions for sensory product characterization elicited by consumers. *Food Qual Prefer* 36:111-121. https://doi.org/0.1016/j.foodqual.2014.03.010

Bathgate GN. 2019. The influence of malt and wort processing on spirit character: the lost styles of Scotch malt whisky. *J Inst Brew* 125:200-213. https://doi.org/10.1002/jib.556

Beaven E. 1936. Barley for brewing since 1886. *J Inst Brew* 42:487-495. https://doi.org/10.1515/9783112615584

Bettenhausen HM, Benson A, Fisk S, Herb D, Hernandez J, Lim J, Queisser SH, Shellhammer TH, Vega V, Xao L, Heuberger AL, Hayes PM. 2020. Variation in sensory attributes and volatile vompounds in beers brewed from genetically distinct malts: an integrated sensory and non-targeted metabolomics approach. *J Am Soc Brew Chem* 78:136-152. https://doi.org/10.1080/03610470.2019.1706037

Blenkinsop P. 1991. The manufacture, characteristics, and uses of speciality malts. T*ech Q Master Brew Assoc Am* 28:145-149.

Briggs DE. 1998. *Malts and Malting*. Blackie Academic, London, England.

CMBTC. 2022. CDC Copeland. http://cmbtc.com/wp-content/uploads/2015/11/CMBTC_fact_cdc_copeland.pdf

Coghe S, Martens E, D'Hollander H, Dirinck PJ, Delvaux FR. 2004. Sensory and instrumental flavour analysis of wort brewed with dark specialty malts. *J Inst Brew* 110:94-103. https://doi.org/10.1002/j.2050-0416.2004.tb00188.x

Coghe S, Gheeraert B, Michiels A, Delvaux FR. 2006. Development of Maillard reaction related characteristics during malt roasting. *J Inst Brew* 112:148-156. https://doi.org/10.1002/j.2050-0416.2006.tb00244.x

Dornbusch H. 2010. Brewing with the living past: floor-malted heirloom barleys for ales and lagers. *The New Brewer* 27:52-56.

Ferreira IM, Guido LF. 2018. Impact of wort amino acids on beer flavour: a review. *Fermentation* 4:1-13. https://doi.org/10.3390/fermentation4020023

Griggs D. 2018. Does the technology of malting have an impact on the taste and aroma of base malt? *Am Soc Brew Chemists - Malt Flavor and Aroma Symposium*. Minneapolis, MN, USA.

Halstead M, Morrissy CP, Fisk S, Fox G, Hayes PM, Carrijo D. 2022. Barley grain protein is influenced by genotype, environment, and nitrogen management and is the major driver of malting quality. *Crop Science* 63:115-127. https://doi.org/10.1002/csc2.20842

Hayes PM, Filichkin T, Fisk S, Helgerson L, Meints B. 2019. Release of Thunder two-row winter barley. Oregon Agricultural Experiment Station. https://barleyworld.org/sites/barleyworld.org/files/thunder_release_web.pdf

Held S, Fox G. 2023. Simultaneous evaluation of β-glucan and β-glucanase relationship during different mash temperature profiles. *J Am Soc Brew Chem* 81:544-553. https://doi.org/10.1080/03610470.2022.2145841

Herb D, Filichkin T, Fisk S, Helgerson L, Hayes PM, Meints B, Jennings R, Monsour R, Tynan S, Vinkemeir K, Romagosa I, Moscou M, Carey D, Thiel R, Cistue L, Martens C, Thomas W. 2017. Effects of barley (*Hordeum vulgare* L.) variety and growing environment on beer flavour. *J Am Soc Brew Chem* 75:345-353. https://doi.org/10.1094/ASBCJ-2017-4860-01

Herb D, Filichkin T, Fisk S, Helgerson L, Hayes PM, Benson A, Vega V, Carey D, Thiel R, Cistue L, Jennings R, Monsour R, Tynan S, Vinkemeier K, Li Y, Nguygen A, Onio A, Meints B, Moscou M, Romagosa I, Thomas W. 2017. Malt modification and its effects on the contributions of barley genotype to beer flavour. *J Am Soc Brew Chem* 75:354-362. https://doi.org/10.1094/ASBCJ-2017-4976-01

Hertrich J. 2013. Topics in brewing: malting barley. *Tech Q Master Brew Assoc Am* 50:29-41. https://doi.org/10.1094/tq-50-1-0331-01

Hill AE, Stewart GG. 2019. Free amino nitrogen in brewing. *Fermentation* 5:1-11. https://doi.org/10.3390/fermentation5010022

Hudson OP. 1986. Malting technology - Centenary review. *J Inst Brew* 92:115-122. https://doi.org/10.1002/j.2050-0416.1986.tb04384.x

Kavanagh TE, Derbyshire RC, Hildebrand RP, Clark BJ, Meeker FJ. 1976. Dimethyl sulphide formation in malt - effect of malting conditions. *J Inst Brew 82*:270-272. https://doi.org/10.1002/j.2050-0416.1976.tb03768.x

Kilfoil G, Kishnani MP, Speers RA. 2019. Comparing floor and pneumatic malting: effects on malt and beer quality. *Mast Brew Assoc Am conference*. Calgary, Alberta, Canada.

Kishnani P, Barr L, Speers RA. 2022. Evaluation of dimethyl sulfide thresholds. *J Am Soc Brew Chem* 80:109-111. https://doi.org/10.1080/03610470.2021.1945852

Li Y, Nguyen A, Lodge B, Onio A, Santiano S, Watts P, Beattie A, Badea A, Capettini F. 2022. Examination of influence of barley variety and growing location on beer sensory attributes. *Tech Q Master Brew Assoc Am* 59:91-101.

Macey, A. 1958. Oil firing in the malting industry II. Effects of oil firing. *J Inst Brew* 64:222-226. https://doi.org/10.1002/j.2050-0416.1958.tb01662.x

Mackie AE, Slaughter JC. 2000. Key steps during barley malting that influence the concentration of flavor compounds. *J Am Soc Brew Chem* 58:69-72. https://doi.org/10.1094/ASBCJ-58-0069

Marshall FG. 1952. Recent developments in the malting industry. *J Inst Brew* 59:10-15. https://doi.org/10.1002/j.2050-0416.1953.tb02706.x

Meilgaard MC. 1976. Wort composition: with special reference to the use of adjuncts. *Tech Q Master Brew Assoc Am* 13:78-90.

Morrissy CP, Féchir M, Bettenhausen HM, Van Simaeys KR, Fisk S, Hernandez J, Mathias K, Benson A, Shellhammer TH, Hayes PM. 2022a. Continued exploration of barley genotype contribution to base malt and beer flavor through the evaluation of lines sharing Maris Otter parentage. *J Am Soc Brew Chem* 80:201-214. https://doi.org/10.1080/03610470.2021.1952509

Morrissy CP, Davenport C, Hooper A, Fisk S, Bettenhausen HM, Hayes PM. 2022b. The effect of floor-malting on novel barley germplasm derived from a cross with Maris Otter®. *Tech Q Master Brew Assoc Am* 59:63-73.

Morrissy CP, Halstead M, Féchir M, Carrijo D, Fisk S, Johnson V, Bettenhausen HM, Shellhammer TH, Hayes PM. 2023. Barley variety and growing location provide nuanced contributions to beer flavor using elite germplasm in commercial-type malts and beers. *J Am Soc Brew Chem* 81:404-415. https://doi.org/10.1080/03610470.2022.2110819

Morrissy CP, Filichkin T, Fisk S, Helgerson L, Davenport C, Silberstein R, Culp D, Hayes PM. 2024. Registration of 'Lontra' malting barley: a two-row, winter-habit cultivar of interest to the craft malting and brewing industries. *J Plant Regist* 18:1-10. https://doi.org/10.1002/plr2.20316

Müller C, Kleinwaechter M, Selmar D, Methner FJ. 2013. The influence of elevated steeping temperatures on the resulting malt homogeneity and malt quality. *BrewSci* 66: 114–122.

NOAA. 2022. Klamath River Basin, NOAA Fisheries. https://www.fisheries.noaa.gov/west-coast/habitat-conservation/klamath-river-basin

O'Sullivan TF, Walsh Y, O'Mahony A, Fitzgerald GF, Van Sinderen D. 1999. A comparative study of malthouse and brewhouse microflora. *J Inst Brew* 105:55-61.https://doi.org/10.1002/j.2050-0416.1999.tb00006.x

Piendl A. 1976. Barley variety and malting technology as influencing factors on the properties of malt - an evaluation by means of the analysis of variance. *Tech Q Master Brew Assoc Am* 13:131-141.

Pitz WJ. 1987. Factors affecting S-Methylmethionine levels in malt. *J Am Soc Brew Chem* 45:53–60. https://doi.org/10.1094/ASBCJ-45-0053

Saison D, De Schutter D, Uyttenhove B, Delvaux FR. 2009. Contribution of staling compounds to the aged flavour of lager beer by studying their flavour thresholds. *Food Chem* 114:1206-1215. https://doi.org/10.1016/j.foodchem.2008.10.078

Sayre-Chavez B, Bettenhausen HM, Windes S, Aron P, Cistué L, Fisk S, Helgerson L, Heuberger AL, Tynan S, Muñoz-Amatraín M. 2022. Genetic basis of barley contributions to beer flavour. *J Cereal Sci* 104:103430. http://doi.org/10.1016/j.jcs.2022.103430

Snyder P. 2018. *Water demand, adaptive capacity, and drought: an analysis of the Upper Klamath basin, Oregon and California*. MS thesis, Central Washington University, Ellensburg, WA, USA. https://digitalcommons.cwu.edu/etd/1100/

Stone H. 1992. Quantitative Descriptive Analysis (QDA), in Hootman, C. (ed.) *Manual on Descriptive Analysis Testing for Sensory Evaluation*. American Society for Testing and Materials, 15-21.

Vandermolen K, Horangic A. 2018. Implications of regulatory drought for farmer use of climate information in the Klamath basin. *Weather Clim Soc* 10:269–274. http://doi.org/10.1175/WCAS-D-17-0078.1

Whitmore ET, Spahrow DHB. 1957. Laboratory micro-malting technique. *J Inst Brew* 63:397-398. https://doi.org/10.1002/j.2050-0416.1957.tb06277.x

Wilson R. 2021. University of California Intermountain Research and Extension Center: 2021 Spring research update. https://ucanr.edu/sites/irecBETA/files/355679.pdf

Windes S, Bettenhausen HM, Van Simaeys KR, Clawson J, Fisk S, Heuberger AL, Lim J, Queisser S, Shellhammer TH, Hayes PM. 2021. Comprehensive analysis of different contemporary barley genotypes enhances and expands the scope of barley contributions to beer flavor. *J Am Soc Brew Chem* 79:281-305. http://doi.org/10.1080/03610470.2020.1843964

Yang B, Schwarz P, Horsley R. 1998. Factors involved in the formation of two precursors of dimethylsulfide during malting. *J Am Soc Brew Chem* 56:85–92. http://doi.org/10.1094/asbcj-56-0085

Yin XS. 2021. *Malt.* American Society of Brewing Chemists, St. Paul, MN, USA.