Malting barley for North American distillers: Novel GN0 winter barley varieties meet and exceed contemporary expectations

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The use of barley varieties that are non-producers of glycosidic nitrile (GN0) to produce distilling malt is commonplace in countries where the compound is tightly regulated. However, in the US, where only voluntary limits are in place, the trait has only recently been demanded by distillers. The GN0 allele was identified in the 1990's, and was found to be inherited in a simple Mendelian fashion and recently North American breeders have been able to introgress it into their varieties. Further, winter malting barley has been of interest to the entire supply chain due to inherent ecosystem advantages over spring barley and all the entries evaluated here are winter growth habit. This work evaluated whether two novel GN0 winter barley genotypes (Top Shelf and DH170472) would meet the end-use expectations of the malting variety Thunder, a GN producer. The three lines were assessed in a pipeline of malting, distilling, and sensory and this manuscript is one of only a few to focus on the direct effects of barley genotype on spirit sensory. It was found that both novel lines produced suitable malt and distillate, but sensory evaluation did not find strong differences among the three. Further, Top Shelf proved to have positive attributes for both all-malt and grain distilling and has potential to be used as a dual-purpose variety depending on field management and growing environment. This work shows the potential for North American GN0 winter barley varieties for the domestic distilling industry.

1. INTRODUCTION

The breeding and assessment of barley varieties for distilling malt quality has been a focus in countries where distilling plays a major role in the overall barley supply chain [1]. However, despite the long history of bourbon and rye whiskey production in the United States, there has been limited work on developing and evaluating domestic barley varieties specifically suited for grain distilling and nearly none for all-malt distilling. Similarly, due to limited demand, there have been few varieties developed by domestic breeders that are non-producers of glycosidic nitrile (GN) [2]. Recently there has been increasing interest from both the domestic grain distillers and the nascent American single-malt whiskey distilling industry to source quality malting barley varieties that meets their respective needs and are non-producers of glycosidic nitrile (GN0).

Malting barley for grain distilling is normally characterized by higher protein, amylolytic enzyme activity (diastatic power and α-amylase), and free amino nitrogen (FAN) than what is required for adjunct brewing [3,4]. These differing requirements are due to the low inclusion rate of malt in the overall mash bill of grain whiskey (≤20%) compared to adjunct brewing (40-70%). Conversely, barley for all-malt distilling, where the mash bill is 100% malted barley, aligns more closely with all-malt brewing. The exception to this similarity is the need to maximize fermentability as measured by predicted spirit yield (PSY). An additional requirement for either type of distilling malt is no production of GN. The particular glycosidic nitrile found in barley, epiheterodendrin (EPH), is converted via a multi-stage pathway throughout fermentation and distillation into a compound called ethyl

carbamate (EC), which is regulated in many countries as a carcinogen [5]. In Scotland, where Scotch whisky production is a dominant industry, the use of GN0 barley varieties is essentially the norm for both all-malt and grain distilling, and breeders have adjusted to include that trait in their varieties. Generally, barley varieties for distilling are characterized as non-producers (<0.5 g/tonne), low-producers (0.5-1.5 g/tonne), and high-producers (>1.5 g/tonne) of GN. The GN0/non-producers lack a functional transcription factor related to the synthesis of GN and are incapable of producing EPH [6]. Producers (GN+) on the other hand show quantitative expression of GN between low- and high-producers, and production can be modulated by growing environment and malting conditions, and even known low-producers can be subject to conditions that would produce levels considered problematic [7]. The lack-of-function allele of GN0 lines has been found to be inherited in a simple Mendelian fashion and has been used in breeding programs to develop suitable distilling varieties [6,8]; however, only recently have North American breeders focused on the trait [2]. The two novel barley lines used in this work – Top Shelf and DH170472 – are both GN0, while the control variety – Thunder – is a known producer.

Historically winter barley has not been a major grain source for distilling malt either in the United States or internationally. As of 2022 over 85% of malting barley purchases in the United Kingdom, where distilling is a major industry, were spring growth habit varieties, and the majority of that was GN0 [9]. The smaller percentage of winter barley was primarily geared towards the brewing industry. Additionally, it was only in 2021 that the first known GN0 winter barley variety was released – SY Vessel [10]. Despite the lower percentage of acreage globally, winter barley offers ecosystem service advantages over spring barley such as increased yields, lower irrigation requirements, and reduced weed pressure. In growing regions where winter cereals can thrive, these varieties offer a more resilient cropping strategy as climate change poses a hotter and drier landscape. All lines used here are winter growth habit and Top Shelf is now the first winter GN0 variety to be released in North America [11].

The effect of barley variety on beer flavor has now been well documented [12-15] and it is a natural extension of this work to question the role grain variety plays in the overall whiskey sensory profile. However, the effects of the respective grain genotypes on spirit flavor has received little focus with only a few recent works investigating the topic. One study found corn/maize variety had an effect on the sensory profile of bourbon-style whiskey [16]. Another found that a barley variety by environment interaction had an effect on Irish-style all-malt whiskey, but not barley variety alone [17]. Most recently, work evaluated the effect on new-make spirit sensory of a naked (huskless) barley genotype compared to a standard (husk-adhering) malting variety [18]. It was found that barley genotype was a significant driver of spirit flavor, but it was not clear whether this could be attributed primarily to the naked phenotype. That work also discussed GN levels as naked varieties are inherently low GN as acrospires are lost during malting. The genetic control of barley varieties contribution to beer flavor has only been recently investigated [19]. It was shown that 'flavorful genes' may be inherited via association with other traits of interest for malting quality, and thus it is critical to assess the possibility of the GN0 allele carrying over positive or negative attributes that may impact the sensory profile of whiskey.

This work aims to assess the broad hypothesis that new, GN0, winter barley varieties will produce acceptable malts for use in whiskey production. Within this framework, we assess malt quality, distilling parameters, and new-make spirit sensory to understand how barley variety contributes to each. Unlike previous work, this is one of the first projects to assess novel GN0 North American barley varieties for their contributions to distilling malt quality, distillation, and contribution to new-make spirit flavor. A secondary aim is to provide the framework of an evaluation pipeline for future evaluation of novel GN0 germplasm as breeders continue to release new varieties.

2. MATERIALS & METHODS

BARLEY & GRAIN QUALITY

The barley genotypes used in this study, their pedigrees, GN status, and growth habits are shown in Table 1. GN status is abbreviated as non-producer (GN0) and producer (GN+) based on genotype, and quantitative expression is defined as low-producer (0.5-1.5 g/tonne) and high-producer (>1.5 g/tonne). Thunder is on the recommended variety list published by the American Malting Barley

TABLE 1 Barley selections used for the malting, distilling, and sensory research described in this report.

LINE	PEDIGREE	GN STATUS	GROWTH HABIT	DEVELOPER
DH170472	DH130939*/Calypso	GN0	Winter	OSU
Top Shelf	DH130939*/Calypso	GN0	Winter	OSU
Thunder	Wintmalt/Charles	GN+/high	Winter	OSU

*GN0 parent.

Association (AMBA) [20]. It is a two-row, GN+, winter malting barley with broad industry acceptance for adjunct brewing and grain distilling malt due to its robust enzyme package and FAN [21]. Top Shelf is a recently released winter malting variety that is GN0 and currently undergoing evaluation via the AMBA pipeline [11]. DH170472 is an elite selection and a sister of Top Shelf, and is also a GN0 genotype and is currently undergoing evaluation for variety release for the craft malting industry. For the purpose of this work and ease of labelling, released varieties and experimental genotypes will be herein all be referred to as lines.

Barley used in this work was grown at the OSU Hyslop Crop Science Field Research Laboratory (Corvallis, OR, U.S.A.). It was planted in Fall 2020 and harvested in Summer 2021 and was managed as is typical for malting barley at the field site. 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 analyzer (Hillerød, Denmark).

MALTING & MALT QUALITY

Malting was performed using the OSU single-vessel (steep/germination/kiln) mini-malter in 68kg batches in January and February of 2022. All lines underwent the same protocol, except for the final steep time and supplemental moisture during germination, as they were adjusted based on previous experience with the lines to promote modification. Due to the limitations of seed availability and the resources required for mini-malting, each line was only malted as a single replicate and thus statistical analysis was not performed.

The complete mini-malting protocol is shown here. Steeping cycles time were as follows, with vessel temperature shown in parentheses: 10h wet, 12h dry (15°C); 10h wet, 10h dry (15°C); 6h wet for Top Shelf and DH170472 and 4h wet for Thunder (15°C). Germination proceeded for 96h at 16°C for all lines. During germination, supplemental moisture was applied to Top Shelf and DH170472 via overhead sprayers for 2.5min per spray. Kilning conditions were the same for all lines and shown as time and applied air temperature: 10h at 50°C; 3h at 60°C; 3h at 65°C; 2h at 70°C; 2h at 80°C; 4h at 90°C. The kilning cycle was followed by a final cool down for 20m at 20°C.

Growth count index is a measurement of acrospire growth at the end of germination and is an in-malting assessment of vigor and indicator of modification. The acrospires of 100 kernels were measured as a percentage of the kernel length. Acrospires <25% the length of the kernel were weighted at a coefficient of 0.25; 25-50% at 0.50; 51-75% at 0.75; 76-100% at 1.0; and acrospires longer than the kernel (>100%) at 1.25. The counts were multiplied by their weight coefficient and summed for a cumulative growth count. In-malting assessments of moisture and growth count are shown in Table 2.

Malt quality parameters were analyzed at 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). Predicted spirit yield (PSY) was analyzed following the method developed by Bringhurst et al [22]. Glycosidic nitrile was quantified using EBC Analytica 4.21, Glycosidic Nitrile in Ale, Lager, and Distilling Malts.

DISTILLING

Double-distilled, all-malt whiskeys were produced in February and March 2023 at the James B. Beam Institute at the University of Kentucky (Lexington, KY, U.S.A.). Mashes, fermentations, and distillations were performed in triplicate and bottled separately. The distillation protocol was adapted from the method for laboratory-scale bourbon-style whiskey production developed by Verges et al [23].

Each malt was sub-sampled into 3.1kg batches for each replicate and was milled in a roller mill to a target sieve distribution of approximately 70% husk/broken kernels (sieve #14), 20% coarse grit (sieve #16), 10% fine grit (sieve #100), and ≤1% flour (pan) as measured using a modification of the ASBC Method of Analysis (Malt-15, Grist). Milled malt was mashed with

TABLE 2 In-malting assessments of all three lines used in this study.

LINE	STEEP OUT MOISTURE %	TARGET MOISTURE %	SPRAYS #	POST-SPRAY MOISTURE %	PRE-KILN MOISTURE %	GC
DH170472	43.9	48.0	3	50.0	47.3	100
Top Shelf	44.7	48.0	1	46.7	43.9	105
Thunder	45.2	45.0	0	—	42.5	100

Abbreviations: 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.

7.5L of 71.6°C water and held at 63.5°C for one hour. Wort was separated in a batch process with first worts drained and collected followed by a sparge with 72°C water to achieve a final collection volume of 7.6L. Sugar content (°Brix) was measured and the wort volume was diluted to a target of 16.5-17.0° Brix, with all final volumes approximately 9.5L. Wort was then cooled to 30°C in a water bath prior to yeast pitch. To prepare yeast for fermentation, 9.4g DistillaMax MW distiller's yeast (Lallemand, Montreal, QC, Canada) was hydrated with warm tap water along with DistillaVite yeast nutrient (Lallemand, Montreal, QC, Canada) and 50mL of liquid malt extract. The yeast mixture was held for five minutes and then added to the cooled wort. The vessel was sealed with an airlock and held in an incubator at 30°C. Fermentation continued until the gravity of the beer fell to ≤1.0° Brix. Distillation followed the methods outlined by Verges et al [23], with the first distillation collecting 1900mL of 30-35% ABV low wines and the second distillation collecting 400mL of 70-75% ABV high wines. New-make spirit was diluted to approximately 40% ABV for bottling. A composite of each distillation replicate was made prior to sensory evaluation to form a representative sample and then diluted with dechlorinated brewing water to 20% ABV as recommended for sensory evaluation [24]. The sensory samples were re-packaged in sealed sample bottles for storage between sessions.

SENSORY

Sensory evaluation took place in September 2023 at pFriem Family Brewers (Hood River, OR, U.S.A.) using their existing sensory panel (23 panelists; 17 male-identifying, 6 female-identifying; age range 24 to 44 years old). Panelists performed the evaluation from one to four times but assessed samples no more than one time per day. In total there were 36 unique evaluations. Sensory was performed using a difference from control discrimination assessment [25]. Panelists were presented with four samples, the control (Thunder), and three single-blinded samples, which included a second sample of the control nested within the blinded samples (blinded-Thunder). Each panelist received the blind samples in a randomized order and were provided a unique randomization for each session. Panelists were asked to evaluate samples first on aroma only and then flavor/mouthfeel. Scores were given on a 1-10 scale in reference to the control, with 1 being not different and 10 being extremely different. Panelists received their instructions from and entered responses into a Google Form.

STATISTICS

Data aggregation and graphical demonstration of data were performed using Microsoft Excel (version 16.16.27) and Google Sheets. Statistical analysis was performed using the R environment for statistical computing (https://www.r-project.org/). Analysis of variance (ANOVA) was performed on distilling and sensory data. Fisher's LSD was used for mean separation on the distilling data while Dunnett's multiple comparison was used to compare sensory results of the experimental lines from the control (Thunder).

3. RESULTS & DISCUSSION

BARLEY, MALTING, & MALT QUALITY

The three lines evaluated in this study met most of the guidelines for grain quality for either all-malt or grain distilling or both (Table 3). Thunder had the lowest grain protein and was considered best suited for all-malt distilling whereas the two GN0 lines only met the guideline for grain distilling. Top Shelf had the highest percentage of plump kernels, but all were similar and well above the threshold for either type of malt and neither line had any thin kernels, an indication of good homogeneity and malting quality potential. Top Shelf did fall just outside of the specification for germination energy, but at only 1% below threshold it was not considered concerning. No line was considered water sensitive and no adaptations to malting protocol were required.

In order to produce malt suitable for distilling, the research group's standard malting protocol for brewing malt was adapted in two ways. First, the time of each wet immersion during the steeping process was extended for all lines to promote proteolysis while taking considerations to minimize extract degradation and mitigate overall malting loss. Secondly, a gentler kilning cycle was employed in order to preserve

TABLE 3 Grain quality of the three lines used in this study.

LINE	PROTEIN %	PLUMP % ≥6/64"	THIN % <5/64"	GE 4ML	WS 8ML
DH170472	12.3#	98.6*#	0.0*#	100*#	96
Top Shelf	12.2#	99.5*#	0.0*#	97	93
Thunder	10.6*#	99.1*#	0.0*#	98*#	91

Abbreviations: GE, germination energy - percentage of kernels germinated in 4mL of water; WS, water sensitivity – percentage of kernels germinated in 8mL of water.

*meets AMBA guidelines for all-malt brewing and distilling; #meets AMBA guidelines for grain distilling. There is no guideline for water sensitivity, but all three entries are considered to have no water sensitivity.

enzymatic activity, while maintaining final malt moisture ≤6.5%. Generally, the protocol remained the same for each line, apart for two less hours in the third steep for Thunder due to previous results from malting this variety as it is prone to overmodify, even outside of the acceptable limits for this type of malt [26]. Conversely, to promote proteolytic modification in both Top Shelf and DH170472, supplemental moisture was applied during germination to further increase grain moisture content. Only Thunder met the target grain moisture after the steep cycle, partially due to the maltster's experience with the variety, but both the GN0 lines got within a similar range of target after spraying during germination (Table 2). Even with the varying malt moistures, all three lines showed similar vigor as shown by growth count.

Overall the three lines produced malt well suited for distillation (Table 4). All three lines exceeded the guidelines for PSY (≥400 LAA/tonne), a critical designation for all-malt distilling malt relative to brewing malt, and often a hurdle for certain varieties developed initially with brewing malt parameters in mind. Thunder performed adequately, meeting the guidelines for all-malt and/or grain distilling for each parameter except diastatic power, setting a suitable benchmark as the control. DH170472 met the most guidelines for all-malt distilling (six), but did not exceed the other lines for any metric. It also interestingly had the lowest friability and fell below the accepted guideline, which may indicate issues not reported in a standard malt analysis. Top Shelf met the most guidelines for grain distilling (seven), including having the highest DP, α-amylase, and FAN of the three lines. It also had the highest extract and PSY, key requirements for all-malt distilling. Often these parameters can run in opposition of each other, but this indicates Top Shelf's potential as a dual-purpose distilling variety that provides broad applications.

Glycosidic nitrile was quantified for the three malts and the results are shown in Table 4. Both Top Shelf (0.3 g/tonne) and DH170472 (0.2 g/tonne) fell below the threshold for a non-producer (<0.5 g/tonne). While they are both known to be non-producers of EPH, the trace measurable cyanide found in the laboratory mash and distillation is primarily due to the hydrolysis of other minor cyanogenic glycosides. Results below the 0.5 g/tonne threshold are considered artifacts of the assay and not likely to lead to quantifiable EC in a production process. Thunder is a known producer and quantified at 1.1 g/tonne, and while this is within the range for a low-producer, previous quantification of different malts made with Thunder ranged from 1.7-4.2 g/tonne (unpublished data, Bettenhausen, HM). Turner et al. showed that among GN+ varieties, GN production correlates positively with certain malting conditions –increased steep out moisture, germination time, and germination temperature – and that there is a significant variety by malting condition interaction [7], but the specific effects of malting protocol on Thunder is unclear.

DISTILLATION

The lab-scale distillation protocol was designed to produce spirit best suited for sensory analysis and not necessarily to directly replicate an industrial process. For example, the first distillation is cut based on volume (1.9L) as opposed to the standard practice of running the wash still until the outlet ABV reaches ≤1% [27]. The laboratory method results in low wines at 30% ABV as opposed to approximately 20% ABV, leaving more ethanol behind in the stillage than is standard, but preventing the accumulation of long-chain alcohols (fusel oils) and other undesirable congeners in the low wines. Thus, some of the results may not necessarily indicate one barley variety's suitability for distillation over the others. However, within the distillation process itself, it is important to evaluate the results (Table 5) for possible outliers that may confound the sensory results.

TABLE 4 Malt quality of the mini-malts used for this study. Parameters were benchmarked against AMBA guidelines for all-malt and grain distilling respectively.

LINE	EXTRACT % FGDB	COLOR SRM	PROTEIN %	β-GLUCAN MG/L	FRIABILITY %	S/T %	FAN MG/L	DP °ASBC	α-AMYLASE DU	PSY LAA/TONNE	GN G/TONNE
DH170472	82.3*#	2.17*#	12.2#	76*	75.2	44.8*	240#	174	69.7*	401*	0.2*#
Top Shelf	84.4*#	2.44*#	12.1#	70*	82.0^	50.5#	284#	200#	80.9#	409*	0.3*#
Thunder	83.4*#	2.21*#	10.7*	83*	91.3^	52.6#	267#	162	84.3#	405*	1.1

Abbreviations: FGDB, fine grind, dry basis; SRM, standard reference method; S/T, soluble to total protein ration; DP, diastatic power; DU, dextrinizing units; FAN, free amino nitrogen; PSY, predicted spirit yield; LAA, liters of absolute alcohol.

*meets AMBA guidelines for all-malt brewing and distilling; #meets AMBA guidelines for grain distilling. Due to the nature of the process, there is no β-glucan or PSY specification for grain distilling. ^Meets accepted industry guideline [29]; there is no AMBA recommendation for friability.

TABLE 5 Mashing, fermentation, and distillation results for the three lines. Each analysis reported is a mean of three replicates.

LINE	MASH OG °BRIX	MASH PH	BEER PH	LOW WINES* % ABV	HIGH WINES % ABV	COLLECTION VOL ML	ABSOLUTE ALCOHOL ML	BOTTLING STRENGTH % ABV
DH170472	18.7	5.6	4.3	33.3[a]	74.3	403.7	300.1	38.9
Top Shelf	19.5	5.3	4.3	29.5[b]	73.7	407.0	299.8	37.5
Thunder	17.8	5.7	4.1	29.7[b]	73.2	410.0	300.0	37.5

Abbreviations: OG, original gravity; ABV, alcohol by volume.

*significant at the ≤0.05 level. Letters in superscript indicate differences in mean separation, entries with the same letter are not significantly different at the ≤0.05 level.

The exception is recovered extract in the mash (Mash OG) due to the nature of this step and separation from the distilling process per se. Mash OG was not significantly different between the lines, which is indicative that all lines performed suitably for distillery mashes. Within the distilling process, only one metric showed significant differences between the lines – low wines %ABV – with DH170472 having a higher ABV than Top Shelf and Thunder. Ultimately, all spirits finished similarly with the final mean absolute alcohol (LAA) collected in the high wines nearly the same for all lines (300.0mL +/- 0.2mL). It was noted that there was excessive foaming during all replicates of the wash distillation runs of Top Shelf and DH170472, but not with Thunder, and this may have caused the higher variation across low wines proof (σ = 2.1% ABV). The foaming may be a result of the higher protein in both of those lines

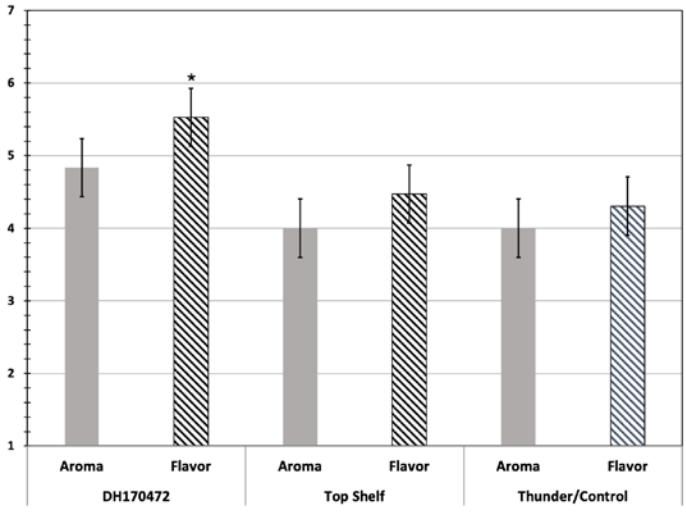

FIGURE 1 Results of the difference from control sensory evaluation (n=36). Samples were scored based on relative difference from the control (1-10). Thunder was the experimental control and replicated within the blinded samples. Data shown here is the raw scoring from the panel. *Indicates significant difference at the p ≤0.05 level. Standard error was calculated using the overall standard deviations for aroma (σ=2.38) and flavor (σ=2.35) respectively.

[28], but unlike an industrial setting, no antifoam was added to the lab distillations. Given the lack of significance for all parameters other than low wines, and the very similar final LAA, these lines were deemed very suitable for sensory analysis. Further investigation and optimization of a lab-scale malt whiskey protocol is warranted to incorporate enhanced processing evaluation of barley variety with sensory evaluation. Inclusion of fermenter antibiotics and antifoams in the stills to mimic industrial protocols will help mitigate between replicate variation and more closely resemble the industry process.

SENSORY

The sensory methodology for this work was chosen for two reasons. First, by including a rating system in the response it ensured that minor malting or distillation variation not related to barley variety would not limit the detection of differences. Second, by including the control within the blinded samples, the analysis allowed for the calibration of the panel. That is, the relative differences could be benchmarked against the ratings for the blinded control. The difference from control scores for both flavor and aroma for each line (DH170472, Top Shelf, and the blinded-Thunder) are shown in Fig 1.

Sensory evaluation found that the barley genotypes investigated here did not play a major role in determining new-make spirit aroma and flavor profile. There were no significant differences among the lines for aroma, and only one line (DH170472) was found to be significantly different in the flavor assessment. The panel successfully rated the blinded-Thunder sample as the least different from the control but it was still rated an average of 4.00 for aroma and 4.31 for flavor. This scoring indicates that, while overall differences from control were scored moderately (overall aroma mean = 4.28; overall flavor mean = 4.77), in actuality they were much smaller as referenced to the blinded-Thunder scores. DH170472 was rated as the most different for both aroma and flavor but was only found to be significantly different from Thunder for flavor. Its difference rating

was 1.22 points greater than blinded-Thunder, and despite the significance, the relative magnitude of distance between the two is considered small. Top Shelf was rated the same as Thunder for aroma and only 0.17 points higher for flavor, a non-significant difference. With only minor differences between lines, it can be concluded that all barley used in this study performed suitably in that they did not cause variation in spirit sensory profile relative to a standard malting variety. Currently the only AMBA guideline related to sensory is that "malted barley must provide desired beer and spirit flavor," and these lines meet the mark [4]. While this work evaluated all-malt whiskey, it can be assumed that given the small portion of malted barley in a typical grain-whiskey mash bill, the sensory profile of grain spirit would be impacted even less so by the respective barley variety.

4. CONCLUSION

As demand for domestically bred and grown GN0 barley becomes a priority for the distilling industry it is crucial to understand how these new lines will perform in their respective processes and this was the first work to evaluate these barley lines in a pipeline of malting, distilling, and sensory. The results show that novel, North American bred, GN0 malting barley lines performed as well and, in some instances, better than the control. Additionally, as winter barley lines, they all provide opportunities for diversifying the malting barley supply chain, building resiliency in an unsure climate future. Both Top Shelf and DH170472 met malting expectations, meeting most of the AMBA guidelines and performing similar to or exceeding Thunder. Top Shelf in particular showed promise with high extract and PSY even with high grain protein and further, soluble extract did not seem to be affected when modification was pushed up in the malt house. It may prove to be an apt dual-purpose variety that can be used for either all-malt or grain distilling dependent on environment, field management, and their respective effects on grain protein. Increased selection pressure for distillation specific malt quality phenotypes can benefit the industry by providing lines that are suited for those users rather than adapting malting or distilling protocols to varieties bred for brewing. Lab scale distillations found each line performed adequately, but was not a true assessment of their potential in an industrial distillery and further work Is required to develop a protocol that adequately measures performance, not only producing quality spirit for sensory. From a sensory perspective, all lines performed similarly with only a small difference in flavor for DH170472. These nuanced differences were even more muted than the findings in previous work on beer. Given the lack of significance for Top Shelf and no difference for aroma in DH170472, this indicates that these lines are likely to produce spirit that meets the existing brand expectations of distillers. Thunder barley is currently being used by grain distillers based on its propensity towards high DP, α-amylase, and FAN, but as it is a GN+ variety, is not a long-term solution and both of the novel lines offer suitable alternatives for all types of distilling. Additionally, this pipeline can be refined to offer a practical assessment of the malt and spirit produced from future GN0 lines as breeders continue to develop new germplasm for the distilling industry.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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