

L. N. Rubottom, S. R. Lafontaine and T. H. Shellhammer

Evaluating the impact of kilning temperature on hop quality in American deep bed dryers

Kilning represents a substantial energy input for processing hops and has the potential to significantly impact hop quality. As part of a multi-year project to understand how different kilning parameters influence the brewing quality of popular American hop varieties, this study examined how kilning temperature impacts chemical and sensory changes of Amarillo® and Simcoe® hops. Kiln temperature was manipulated on pilot and commercial scales and the resulting hops were assessed for their chemical, sensory, and brewing qualities. Static drying temperatures ranging from 49 – 82 °C (120 – 180 °F) on pilot scale kilns and 49 – 71 °C (120 – 160 °F) on commercial scale kilns were examined. In general, hop chemistry and sensory were only modestly impacted by higher temperatures, while drying time was substantially reduced at higher temperatures. Given that significant differences in chemistry or sensory were not observed for hops kilned over a broad temperature range, these results offer hop growers potential flexibility in hop drying temperature while minimally impacting Amarillo® and Simcoe® aroma quality.

Descriptors: hops, kilning temperature, hop quality, hop chemistry, beer sensory

1 Introduction

Historically hops were grown as a commodity crop for bittering purposes in beer, but in the last two decades American bred aroma hops have become a significant contributor to hop aroma and flavor in the United States and elsewhere [4]. American aroma hops started making their appearance in the beer market in the late 1980s and only made up 11,000 acres of the U.S. hop crop by 2005. However, in 2019 U.S. aroma hop acreage was 40,000 – 45,000 acres (or approximately 80 % of hops grown in the U.S.) [27]. Most growing and processing-related research has primarily investigated the quality drivers of alpha hops [7, 29]. With the increased demand for aroma hops, there is an inherent need to understand the critical drivers of hop quality and how processing steps influence quality and consistency.

Currently, hop quality is evaluated using various chemical analyses and tactile methods. For chemical analysis, brewers and hop growers rely on a combination of total oil content, hop storage index (HSI), oil composition, and alpha and beta acid concentrations to determine hop quality [9, 26]. Previous studies have shown that on-farm harvest timing and processing factors can significantly impact overall hop quality, for example, investigations on harvest

maturity, kilning conditions, pelletizing, CO₂ extraction, and other on-farm practices [7, 12, 13].

The purpose of drying hops is to preserve them for brewing without sacrificing hop quality. Prior to drying, hops typically have 65–80 % moisture content and the goal of kilning is to reduce them to a moisture content of 8–12 %. The final moisture content can have a considerable impact on hop storability. If the moisture content is too high, there is the potential of mold/mildew and/or in some cases hot spots in hop bales can develop leading to possible combustion, whereas overdried hops are prone to shattering and may suffer from browning [24, 25]. Overall, under-dried and over-dried hops are considered low quality, which may devalue the hops.

There are differences in how hops are dried in different geographical regions. For example, in Germany indirectly heated, multitier kilns with three to four layers ranging from 20 – 30 cm (8 – 12 inches) deep are used for drying hops or belt conveyors are used for hop drying in other parts of Europe [16, 30]. In the United States, the primary focus of this study, hops are dried using a direct fired kiln with deep beds ranging from 60 – 80 cm (24 – 32 inches) [21]. Hot air is produced from natural gas or propane burners and is fed to a plenum under the hop bed and forced up and through the hop bed, driving off moisture from the hops. Once hops have reached the target moisture content, the kilning step is ceased, the hops are cooled, and the kiln is emptied by moving the hops to the baling room [16, 21]. During drying, the hops at the bottom of the bed are exposed to high airflow and higher temperatures for a more extended period when compared to the hops at the top of the bed. This results in inhomogeneous drying throughout the bed, whereby the hops at the bottom of the bed have a lower moisture content than hops at the top of the bed. An important step in the process is to allow the moisture content to equilibrate within the dried hop mixture by placing them in large piles in an open warehouse for 24 hours before baling. Baled hops may be sold as whole-cone

<https://doi.org/10.23763/BrSc22-15rubottom>

Authors

Lindsey N. Rubottom, Scott R. Lafontaine, Thomas H. Shellhammer, Department of Food Science & Technology, Oregon State University, Corvallis, USA; corresponding author: tom.shellhammer@oregonstate.edu

hops, but more often they are further processed into pellets and potentially extracted with supercritical CO₂ or ethanol.

There are three primary operational considerations when kilning hops: air speed, hop bed depth, and the air-on temperature [15, 16]. Airspeed is used to push moisture out of the hop bed; when the airspeed is increased, hot air moves through the bed faster and drives more moisture off the hops. One consequence of increased fan speed is “blowouts” in the hop bed, which can lead to uneven drying and other quality issues. Typically, air speed is kept high at the beginning of drying to rapidly drive off moisture and is turned down throughout drying to prevent blowouts as the hops’ bulk density is reduced. American hop growers lay the hop bed in the kiln to depths ranging from 60 – 80 cm (24 – 32 inches). As one would expect, a thinner bed of hops dries faster than a thicker bed, but the thinner bed may reduce the overall drying capacity of a hop grower [16]. Finally, the temperature of the air being used also impacts drying times. Historically, hops have been dried at temperatures ranging from 63 – 66 °C (145 – 150 °F) [23, 25, 30]. In recent years American growers have been drying their hops at lower temperatures, from 51 – 63 °C (125 – 145 °F), because of evidence indicating greater preservation of the essential oil in hops and a lower hop storage index [15, 29]. When drying hops at lower temperatures, hops spend a much longer time in the kiln (typically 8 – 13 hours to dry hops at 51 – 53 °C (125 – 128 °F) depending on the hop variety). The increased drying time at lower temperatures can create a bottleneck for the hop grower thereby reducing overall drying capacity which, in turn, may result in some hops not being harvested at peak harvest maturity. This ultimately limits the amount of hops a grower can optimally process during a given harvest year. These three factors, air speed, hop bed depth, and the air-on temperature, combined can directly impact hop quality.

There is limited information available in the public domain investigating how different hop kilning parameters impact aroma hops’ brewing quality. Most hop growing and processing-related research has investigated the quality drivers of alpha hops (hops used in brewing for bittering purposes) [3, 6, 29]. In the last two decades, the rise of interest in aroma hops has been fast, with a vast amount of research needing to be done to understand the key drivers of aroma hop quality [27]. Early work investigating the impact of kiln temperature on alpha hop quality found that high-temperature treatments (70 °C (158 °F)) were preferred in hop evaluations and brewing trials over lower temperature kilned hops. [3, 5]

More recently, in 2013, Nielsen et al. performed a technical evaluation assessing the impact of kiln temperature and bed depth on hop quality [15] and found that higher kilning temperatures impacted hop chemistry for Citra® hops, with increased hop storage index and caryophyllene oxide and decreased total oil content of the hops. While the 2013 study evaluated hop chemistry, there were no sensory or brewing evaluations to determine how changes in kilning parameters would ultimately impact the brewing quality of aroma hops.

A recent study published in 2020 found drying at temperatures at 60 and 65 °C (140 and 150 °F) resulted in no significant changes to measured hop chemistry analytes such as total oil, linalool, myrcene, and β-caryophyllene [17]. Another study published in

2021 [19], investigated the impact of kiln temperature at 40 and 60 °C (104 and 140 °F) on total essential oil for multiple varieties and found that the average loss of total oil over the 20 °C range was 13.9 %, though some varieties experienced more substantial losses (33 % for the variety Saaz). The variability in research findings may also be attributable to differences in hop varieties and/or different kilning equipment. However, one must also recognize the inherent inhomogeneity in hop sampling for example along the length of individual bines, location of the hop plants within a field, harvesting during the day vs at night, and other factors.

The objective of this work was to evaluate how in-process drying metrics (hop temperature, moisture content, and drying time), hop chemistry, and sensory (hops and brewing) are impacted by kilning temperature over two harvest years. Prior work [18] by this research group has shown that elevated kiln temperature can reduce the dextrin-reducing enzymes in hops that are responsible for hop creep, which may be a benefit for drying hops at elevated kilning temperatures. However, ensuring that these elevated temperatures do not have a significant impact on the factors influencing aroma hop quality is critical.

2 Methods and Materials

2.1 Experimental Design

The impact kiln temperature has on hop quality was evaluated over two harvest years (2018 and 2019) by looking evaluating the static air-on temperature on the aroma quality of two popular hop varieties, Simcoe® and Amarillo®, using both chemical and sensory evaluations. The details of the project design are described in a 2021 publication by Rubottom et al. [18]. In brief, Amarillo® and Simcoe® hops were dried in commercial and pilot scale kilns at multiple static temperatures (49, 60, 71, and 82 °C (120, 140, 160, and 180 °F)) until they reached a 10 % target moisture content. During both harvest years, each variety was dried at two farms and duplicate drying runs were performed at each condition. Each duplicate came from a different field within the farm in an attempt to account for variability driven by processing and/or agriculture differences (i.e. maturity, etc.). For example, one replicate consisted of a 49, 60, and 71 °C (120, 140, and 160 °F) treatment from a single field, and the second replicate was dried at the same three temperatures but on a different day and with hops coming from a different field. At each farm, a “control” sample was collected and dried using the farm’s standard drying regime for that variety, and this standard drying regime varied farm to farm. For example, Farm D used an initially high temperature of 68 °C (155 °F) until the hop bed reached 53 °C (128 °F) then dried the hops statically at 53 °C until completion while and Farm E used the same, two-temperature approach but dried at 52 °C (125 °F) instead of 53 °C.

2.2 Kilning in-process measurements

During each kilning trial LogTags® HAXO-8 Humidity and Temperature Data Loggers (MicroDAQ Contoocook, NH) were placed below and above the hop bed to record temperature and relative humidity. Additionally, Omega 8 Channel USB Thermocouple Data acquisition modules (Omega Norwalk, CT) were used to monitor

temperature below the hop bed, in the kiln plenum, and within the hop bed at 7.6 cm, 30.5 cm, and 53.3 cm (3 inches, 12 inches, and 21 inches) from the bottom of the kiln. LogTag® and thermocouple couple temperature measurements for the kiln plenum temperatures were within 1 °C of each other.

2.3 Determining end of drying

In this study, the kilning was arrested based on how the commercial farm hosting the different trials would terminate the kilning process. Generally, this was done using a combination of moisture readings of the hop bed and tactile evaluations made by the hop kiln operators on each farm. The goal was to dry the hop to approximately 10 % moisture content.

2.4 Hop chemistry

All hop chemistry analyses were performed using ASBC methods of analysis to measure total oil content, alpha and beta acid (U.V. and HPLC), hop storage index, moisture content, and hop oil composition (GC-FID) [1].

2.4.1 Total Oil

Total oil content was determined using hydrodistillation, following ASBC Hops-13 [1]. Following distillation, the oil was collected in 3 mL amber vials with foil-lined closures. After collecting the oil and removing any water in the amber vials, the amber vials were flushed with N₂ and stored at –20 °C until compositional analysis.

2.4.2 Alpha and Beta Acids

The alpha and beta acid content was determined using two methods: U.V. Spectroscopy and High-Performance Liquid Chromatography (HPLC). Analysis was based on ASBC methods of analysis: Hops -6A and -14 [1].

2.4.3 Hop Storage Index

UV-Spectroscopy was used to measure hop storage index (HSI). Protocol for sample prep and materials follows the setup used in ASBC-Hop-6A, and analysis was carried out using ASBC Method of Analysis Hops-12 [1].

2.4.4 Moisture

During the drying process for each treatment, replicate hop cones from the bed were collected and moisture was analyzed using a Mettler Toledo HE53 Moisture Balance. When samples were evaluated in the lab for moisture, the samples were measured using ASBC Hops-4C method [1].

2.4.5 Oil Composition

Seventeen hop volatiles were the focus of this study and were chosen based on preliminary research and relevance in literature [11, 20]. The hop volatiles evaluated were: β -pinene, α -pinene, β -myrcene, R limonene, β -caryophyllene, β -farnesene, α -humulene, α -terpineol, citral (geranial and neral), nerol, geraniol, caryophyllene

oxide, geranic acid, geranial acetate, terpine-4-ol, and linalool. Hop oil compositional analysis was performed using an HP 5890 gas chromatograph with a flame ionization detector (FID) under modified conditions from ASBC Hops-17. Hop oils were diluted to 1 % with the 2-octanol/hexane solution in crimped glass vials. 1 μ L of the diluted hop oil was directly injected into the injection port held at 200 °C and operating in split mode (1:50) using the septum purge option. The analytical column was a Supelcowax 30 m x 0.25 mm x 0.25 μ m, and ultra-pure nitrogen was used as the carrier gas (a constant flow rate, 1 ml/min). The following temperature program was used: 60 °C holds for 1 min, 60 – 175 °C (3 °C/min) holds for 10 minutes, ramp to 230 °C (3 °C/min) 10 minutes. The target analyte concentrations in hop oil were then standardized on a per-mass basis using the total oil content determined during hydrodistillation.

2.4.6 Chemicals

Ethyl ether, A.C.S. grade toluene, HPLC grade methanol, phosphoric acid, and analytical standards for hop volatiles (> 99 % purity – analytes listed in "oil composition").

2.5 Brewing

For each harvest year, a subset of the hop samples was used in brewing trials to evaluate the impact kilning temperature had on the hops' brewing quality. For the 2018 harvest year, each temperature treatment from Farm A rep 2 and Farm D rep 1 were used for brewing with 8 total beers being made (4 beers made with Amarillo® hops, (49, 60, 71, and 82 °C (120, 140, 160, and 180 °F)) and 4 made with Simcoe® hops (49, 60, 71, and farm control (120, 140, 160, and farm control)). For the 2019 harvest year, each temperature treatment (the process control, 49, 60, and 71 °C (120, 140, and 160 °F)) from Farm A rep 2, Farm B rep 1, Farm D rep 1, and Farm E rep 2 were used in brewing trials, resulting in 16 beers total (8 beers made with Amarillo® hops and 8 beers made with Simcoe® hops).

Brewing trials were carried out using a single hop India pale ale style that was brewed with 100 % pale lager malt (Rahr Premium Pilsner, Rahr Shakopee, MN). The target original gravity was 14.8 °Plato. The target final beer specifications for the beers were 6.8 % alcohol by volume, 2.1 °P apparent extract, 4.4 °P real extract, and 40 IBU. During the brewing process, there was a hop addition at the beginning of a 60-minute boil (the amount of hops added determined by targeting a final beer bitterness of 40 IBU), a whirlpool addition (200g/hL for 2018 beers and 300 g/hL for 2019 beers), and a dry-hop addition at 3.0 – 3.2 °P for 72 hours (650 g/hL for 2018 beers and 800 g/hL for 2019 beers). Beers were fermented at 20 °C (68 °F) with ale yeast (Wyeast 1056, Wyeast Hood River, OR) for one week. Once diacetyl dropped below sensory detection levels, the beers were cooled to 1 °C (34 °F) and were clarified using a coarse sheet filter (Pall HS6000) to remove any remaining hop material. After filtration, the beers were pressurized and stored under CO₂ at 12 psi (0.83 bar).

2.6 Sensory methodology

Using the ASBC Sensory Analysis-13 Method, Difference-from-Control (DFC) [2], discrimination testing was performed on hop

Table 1 Outline of the experimental sample design and collected samples. Dimensions of commercial hop kilns in the United States range from 9.8 x 4.9 meters (32 x 16 feet) to 9.8 x 9.9 meters (32 x 32 feet) while pilot kilns are only 1.2 x 1.2 meters (4 x 4 feet)

Variety	Harvest year	Kiln type	Farm ID	Kiln dimensions (L X W in meters)	Bed depth (cm)	Temperature treatments (°C)	Total samples
Amarillo®	2018	Pilot-scale*	A	1.2 x 1.2	76	49, 60, 71, and 82	8
	2019	Commercial Full size	A	9.8 x 9.8	76	Control (63), 29, 60, and 71	9
	2019	Commercial Full size	B	9.8 x 9.8	76	Control (57), 29, 60, and 71	9
Simcoe®	2018 & 2019	Commercial Half-size	D	9.8 x 4.9	76	Control (53), 29, 60, and 71	16**
	2018 & 2019	Commercial Half-size	E	9.8 x 4.9	61	Control (52), 29, 60, and 71	12**
	2018	Commercial Half-size	F	9.8 x 4.9	61	Control (52), 29, 60, and 71	4

*Pilot kilns were operated at 49, 60, 71, and 82 °C (120, 140, 160, and 180 °F)

** for Farm D, 8 samples were collected in both 2018 and 2019 harvest years (16 total), for 2018

Farm E, due to technical difficulties, only one replicate was collected (4 samples,) and in 2019, 2 replicates were collected (8 samples total).

grinds and beer made from the hops from the various kilning treatments from each harvest. For hop grinds, panelists were given 5 grams of coarsely ground hop samples in a blind-coded and lidded, plastic 60 ml black cup. The black cups helped ensure evaluations were based on aroma only (not color or particle size), and the lids were used to contain the hop aroma within the cups. For the beer aroma evaluations, panelists were given 60 mL of each beer in a blind-coded, lidded 300 ml glass and asked to smell the beer orthonasally. Panelists were given a control hop grind or a control beer, labeled "control," and the 3-digit blind-coded test hops or beers. Panelists evaluated from 4 – 7 samples in a session, and the presentation order was randomized for each panelist. Panelists were instructed to compare the smell of the "control" with the test sample and to scale the differences using a continuous 0 – 6 scale, with 0 being "no difference" from the control and 6 being "extremely large difference" from the control. An external "positive" control (samples of the variety Strata®) was included in the test to evaluate panelist performance when given a sample that was very different from the control where a high DFC score would be expected. Prior to statistical analysis, those panelists who could not correctly identify the positive control were removed – for example in 2019, 32 panelists evaluated the samples, but 8 panelists could not identify the Strata® positive control so their data was removed leaving n=24 observations used in the final statistical analysis. Data from the positive control was removed from the statistical analysis. A limitation to the sensory work is that due to the COVID-19 pandemic descriptive analysis could not be carried out on the 2019 samples to

characterize the difference in treatments.

2.7 Calculation of fold change for hop chemistry

To concisely interpret how each hop analyte was impacted by kiln temperature, the fold change in each analyte as kiln temperature was changed from 49 to 71 °C (120 to 160 °F) was evaluated (Supplemental Fig. S1 and S2). The fold change calculation was performed by using the regression line from the measured data and dividing the estimated analyte concentration at 71 °C (160 °F) by the estimated concentration at 49 °C (120 °F). Estimates were

Table 2 Amarillo® hop measured temperatures of kiln plenum air and total drying time for each treatment. (– indicates there is no data point for that treatment, * indicates samples were dried in a pilot-scale kiln (1.2 meters by 1.2 meters). English units presented in the supplemental section (Table S1)

Amarillo® 2018 & 2019 temperatures and drying times							
Farm ID	Rep	Target Treatment (°C)	Hop bed depth (cm)	Measured Plenum Temperature (°C)		Drying time (hours)	
				2018*	2019	2018*	2019
Farm A	1	49	76	48	49	10.5	9.4
Farm A	1	60	76	59	61	7.1	6.2
Farm A	1	71	76	72	72	5.7	4.5
Farm A	1	82	76	79	–	–	3.9
Farm A	2	49	76	47	54	10.2	11.3
Farm A	2	60	76	61	–	7.4	5.6
Farm A	2	71	76	70	71	5.8	4.0
Farm A	2	82	76	79	–	–	3.5
Farm B	1	49	76	–	49	–	9.9
Farm B	1	60	76	–	62	–	4.8
Farm B	1	71	76	–	71	–	4.4
Farm B	2	49	76	–	51	–	10.7
Farm B	2	60	76	–	61	–	6.6
Farm B	2	71	76	–	–	–	3.8

Table 3 Simcoe® hop measured temperatures of kiln plenum air (Air On) and total drying time for each treatment. (– indicates there is no data point for that treatment). English units presented in the supplemental section (Table S2)

Simcoe® 2018 & 2019 temperatures and drying times							
Farm ID	Rep	Target Treatment (°C)	Hop bed depth (cm)	Measured Plenum Temperature (°C)		Drying time (hours)	
				2018	2019	2018	2019
Farm D	1	49	76	47	47	9.0	11.2
Farm D	1	60	76	57	58	7.0	7.5
Farm D	1	71	76	70	69	5.0	4.9
Farm D	2	49	76	50	47	8.3	12.5
Farm D	2	60	76	59	59	6.0	9.0
Farm D	2	71	76	67	69	4.8	6.3
Farm E	1	49	61	48	51	8.8	10.5
Farm E	1	60	61	67	63	5.0	6.3
Farm E	1	71	61	–	69	–	4.5
Farm E	2	49	61	–	46	–	13.3
Farm E	2	60	61	–	63	–	7.3
Farm E	2	71	61	–	69	–	4.7
Farm F	1	49	61	48	–	9.0	–
Farm F	1	60	61	54	–	7.0	–
Farm F	1	71	61	67	–	4.5	–

made because each treatment was not performed at exactly and 49 or 71 °C (Table 1 and 2).

2.8 Statistical approach and data visualization

Statistical analysis for sensory evaluations was performed using XLSTAT® software (version 2018.5.52280, Addinsoft, New York). Analysis of variance (ANOVA) and Dunnett means comparisons were made. The model for the ANOVA had replicate and panelist set as random factors and temperature treatment as a fixed factor. The interaction between panelists and replicate was also evaluated using R (Version: 3.6.1 GUI 1.70, The R Foundation) ggplot2. Microsoft Excel (Version: 16.39, 2020 Microsoft, Redmond, WA) was used for data visualization.

3 Results and Discussion

3.1 Temperature and Drying Time

Not surprisingly, kiln temperature had an obvious impact on the drying time of the hops. In the commercial kilns, hops dried in approximately 5 – 6 hours at 71 °C (160 °F) versus 10 – 13 hours at 49 °C (120 °F), potentially doubling processing capacity. The average plenum temperatures and drying times are

reported in table 2 and 3, and a sample of bed temperature and drying times are visualized in figure 1.

When evaluating drying time, it is important to consider other factors contributing to the drying process such as airspeed, hop bed depth, hop variety, and kiln type (commercial vs. pilot) [15, 16]. In this study the airspeeds were not monitored. It is also important to consider that some hops were dried in commercial kilns outfitted with a sensor package designed by MeasureTek (Albany, OR, USA) that use information on bed weight via a load cell and plenum pressure to adjust fan speed as hops dry, thereby maximizing airflow through the bed while preventing blowouts from too high of air velocities. Bed depth was also not controlled in this study, so each grower dried hops using their “standard” bed depths (Tables 1 – 3).

3.2 Chemistry Analysis

Given that twenty chemical analytes were measured, the fold change in analyte concentration as kiln temperature was changed from 49 to 71 °C (120 to 160 °F) was calculated and summarized (Fig. 2). It is important to note there is inhomogeneity in hops which influences the variability in hop chemistry data. A fold change range of ± 15 % is represented by the dotted lines in figure 2 to reflect a low but inherent level of variability in chemistry. Thus, a greater than 15 %-fold change indicates there was a potentially significant impact on the analyte due to kiln temperature. It is also important to consider that the fold change was estimated over 22 °C (40 °F) ranging from 49 – 71 °C (120 – 160 °F). If kiln temperature was changed over a smaller range, such as 5 – 10 °C,

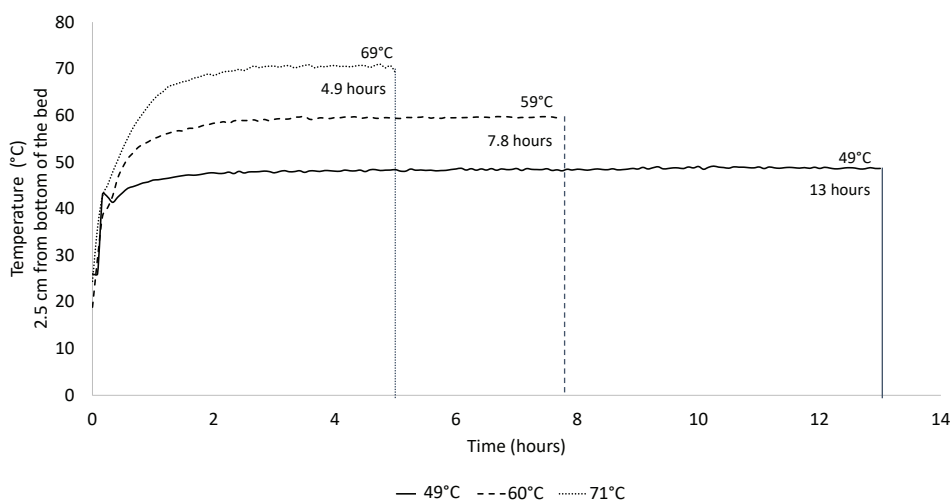


Fig. 1 Example of temperature data collected during drying from Farm D, Rep 1. Data displayed shows the relationship between hop drying temperature (measured 7.6 cm from the bottom of the hop bed) and time until drying was “called”

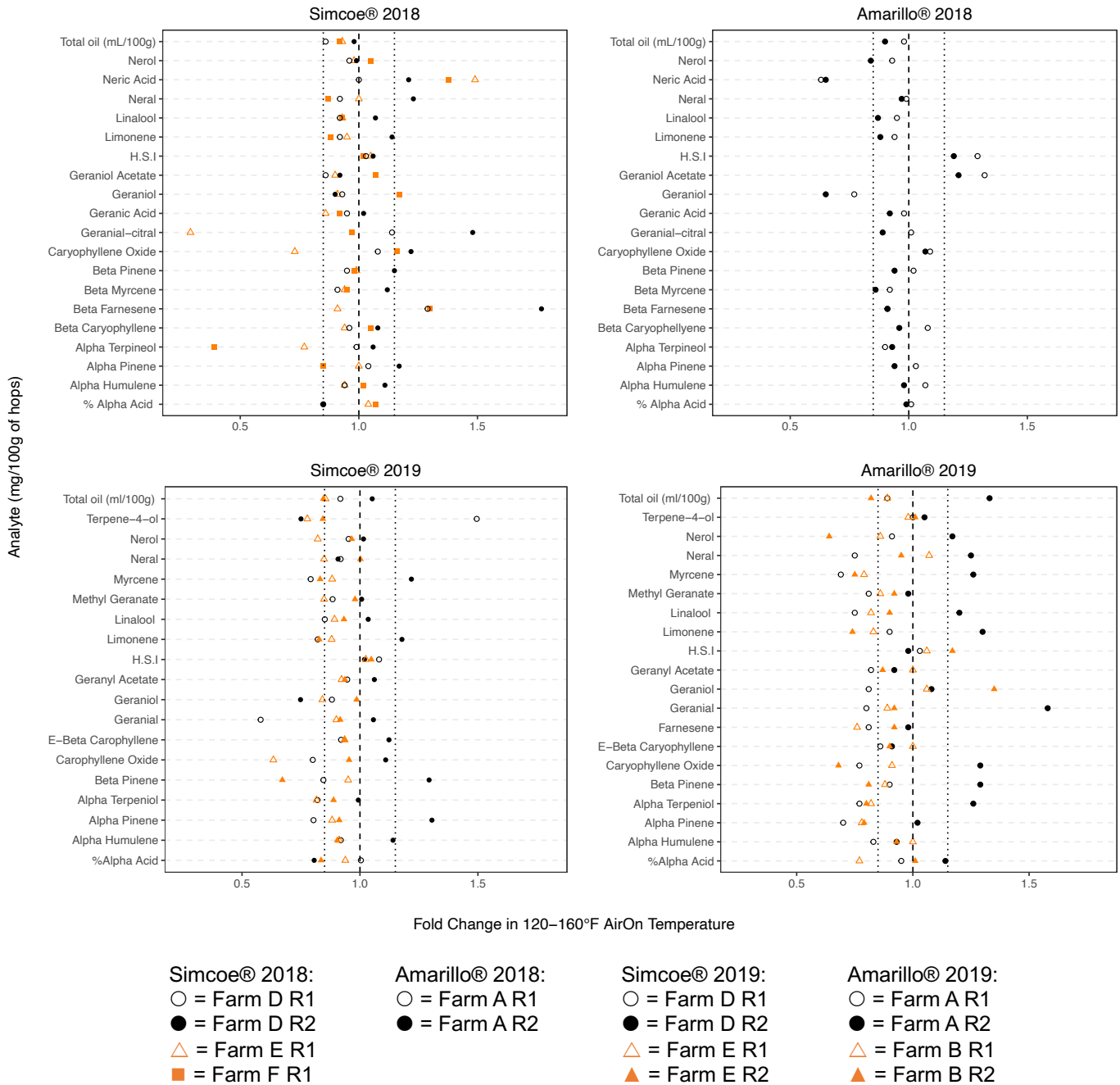


Fig. 2 Fold change in key hop oil analytes when comparing drying at 71 °C (160 °F) relative to 49 °C (120 °F). Values equal to 1 express there was no change in the analyte. If a point is on the left of the dashed line, it indicates a decrease in the analyte at 71 °C (160 °F) relative to 49 °C (120 °F) and while points on the right indicate an increase. Values equal to 0.75 indicate a 25 % decrease (0.75-fold reduction), and values equal to 1.25 indicate a 25 % increase (1.25-fold increase)

differences in analyte concentration that were present in examining 49 vs 71 °C might not be present. Overall, we saw a decrease in volatile concentrations when comparing drying at 71 °C (160 °F) to drying at 49 °C (120 °F). Nonetheless, the decreases typically were minimal, and more than half were in the range of a 0 – 10 % reduction in analyte concentration (or a fold change of 0.9).

For the Amarillo® variety, the volatiles fell in the range of a 0 – 25 % reduction (or a 0 – 0.75-fold change) though most analytes had a 15 % reduction or less (or a 0.85-fold reduction). Several analytes which are known to be important to hoppy flavor in beer like linalool, geraniol, and beta-pinene were found to be impacted in more so

Amarillo® than Simcoe® hops, which indicates that Amarillo® hops are more temperature sensitive from a hop chemistry perspective [9, 22]. For the Simcoe® variety, most chemistry analytes fell within a 15 % increase or decrease in concentration with drying at 71 °C (160 °F) relative to 49 °C (120 °F). Interestingly, a higher incidence of fold changes greater than 15 % were observed in the 2018 data at farms E and F meaning that analyte concentrations were higher in the 71 °C samples than the 49 °C one. When looking specifically at important aroma analytes such as linalool, geraniol and β-pinene, some decreases exceeding 15 % were observed for the 2019 data (i.e – geraniol and beta-pinene) but no similar decreases were observed in the 2018 data. Linalool showed re-

Table 4 Median DFC scores for 2018 hop grind and beer difference from control sensory data

2018 DFC Score Medians				
Treatment	hops (n = 73)		beer (n = 93)	
	Amarillo® Farm A	Simcoe® Farm D	Amarillo® Farm A	Simcoe® Farm D
Control	–	1.2	–	2.4
49 °C (120 °F)	4.1	1.6	2.5	3.4
60 °C (140 °F)	1.0	1.0	3.0	2.6
71 °C (160 °F)	1.9	1.9	3.0	3.0
82 °C (170 °F)	1.1	–	3.0	–

*Farm A 60 °C (140 °F) used as the control

In **bold** are samples scored as statistically different from the control (p-values ≤ 0.05 in Dunnett means comparison)

Table 5 Median DFC scores for 2019 hop grind and beer difference from control sensory data

2019 DFC Score Medians					
Hops (n = 21)					
Treatment	Rep	Amarillo® Farm A	Amarillo® Farm B	Simcoe® Farm D	Simcoe® Farm E
Control	Control	1.7	1.9	2.5	3.0
49 °C (120 °F)	1	4.1	2.6	3.0	3.4
60 °C (140 °F)	1	3.5	2.8	1.9	2.0
71 °C (160 °F)	1	2.5	2.6	3.0	3.0
49 °C (120 °F)	2	4.9	2.5	2.4	1.9
60 °C (140 °F)	2	5.5	2.5	2.0	2.2
71 °C (160 °F)	2	2	4.2	2.8	1.9
Beer (n = 24)					
Control	–	1.0	0.8	1	0.9
49 °C (120 °F)	–	2.0	1.6	2	1.8
60 °C (140 °F)	–	2.1	0.7	1.2	1.9
71 °C (160 °F)	–	0.7	1.8	1	1.5

In **bold** are samples scored as different from the control (p-values ≤ 0.05 in Dunnett means comparison)

silience in Simcoe® hops with less than 15 % reductions across both harvest years (see supplemental chemistry data file). Overall, Simcoe® hop chemistry was not significantly impacted by kilning temperature which is similar to published literature on kilning alpha varieties. Multiple studies from the 1938 – 1957 found alpha and beta acids were not impacted by kiln temperature [3, 28]. A 1957 study found that kilning reduces the oil content of hops (compared to wet, undried cones), but that the reduction is not temperature sensitive. That is, changes in kilning temperature did not impact the dried hop oil concentrations or oil composition [8]. More recent studies produced similar results to the study presented herein, albeit with a much smaller set of analytes. In these studies, important hop quality indicators like total oil, linalool, and beta-caryophyllene are not impacted by temperature and most analyte changes were less than 15 % [17, 19].

When evaluating observed reductions in analyte concentration, it is important to keep in mind drying at 71 °C (160 °F) relative to 49 °C (120 °F) is a rather large temperature range from a commercial

standpoint. It is unlikely that a grower would vary temperatures by 22 °C, so the changes a hop grower would see in practice by making incremental changes in kilning temperature would likely be quite a bit smaller.

3.3 Sensory analysis

Hop grinds and single hop India pale ales (SHIPA's) were analyzed using a difference from control (DFC) test to determine if there were perceivable differences across the various temperature treatments. Each DFC test evaluated temperatures from one farm compared to the process control from that same farm. The process control sample represented a farm's standard regime for drying their hops. Generally, the hop and beer sensory data were not greatly impacted by temperature treatment for either Amarillo® or Simcoe®.

For the 2018 harvest year, samples from one farm for each variety were evaluated (Farm A for Amarillo® and Farm D for Simcoe®, shown in Table 4). Within the samples from each farm, one replicate was used for hop grind evaluations, and the other was used for brewing. Amarillo, Farm A, Rep 1 and Simcoe, Farm D, Rep 2 were used for hop grind evaluations and Amarillo®, Farm A, rep 2, and Simcoe®, Farm D, rep 1 were used for brewing. For the 2019 harvest year, hop grinds were evaluated for all farms and both reps. For the 2019 brewing trials, one rep from each farm was selected (Farm A R2, Farm B R1, Farm D R1, and Farm E R2) as shown in table 5.

For Simcoe® hop grind evaluations over two harvest years, no difference was found between the test controls (dried at 53 °C (128 °F) for farm D and 52 °C (125 °F) for farm E) and each of the temperature treatments, with the exception of the 2019 Farm E rep 2 71 °C (160 °F) treatment. For the Simcoe® beer evaluations, more differences were found in the 2018 beers than the 2019 beers. In 2018, the 49 °C (120 °F) and 71 °C (160 °F) were significantly different from the control (dried at 53 °C (128 °F)). For 2019, none of the temperature treatments were rated significantly different from the control. Figure 3 visualizes the DFC data for hop grinds where each data point is plotted for the 2019 beer DFC evaluations thereby offering insight into the variability of DFC scores panelists assigned to each sample. Most panelists gave lower scores for all samples indicating that there was general difficulty in detecting differences between sample treatments. While differences were found in some cases, qualitative assessments were not made to determine if these differences were positive or negative in nature. Given that

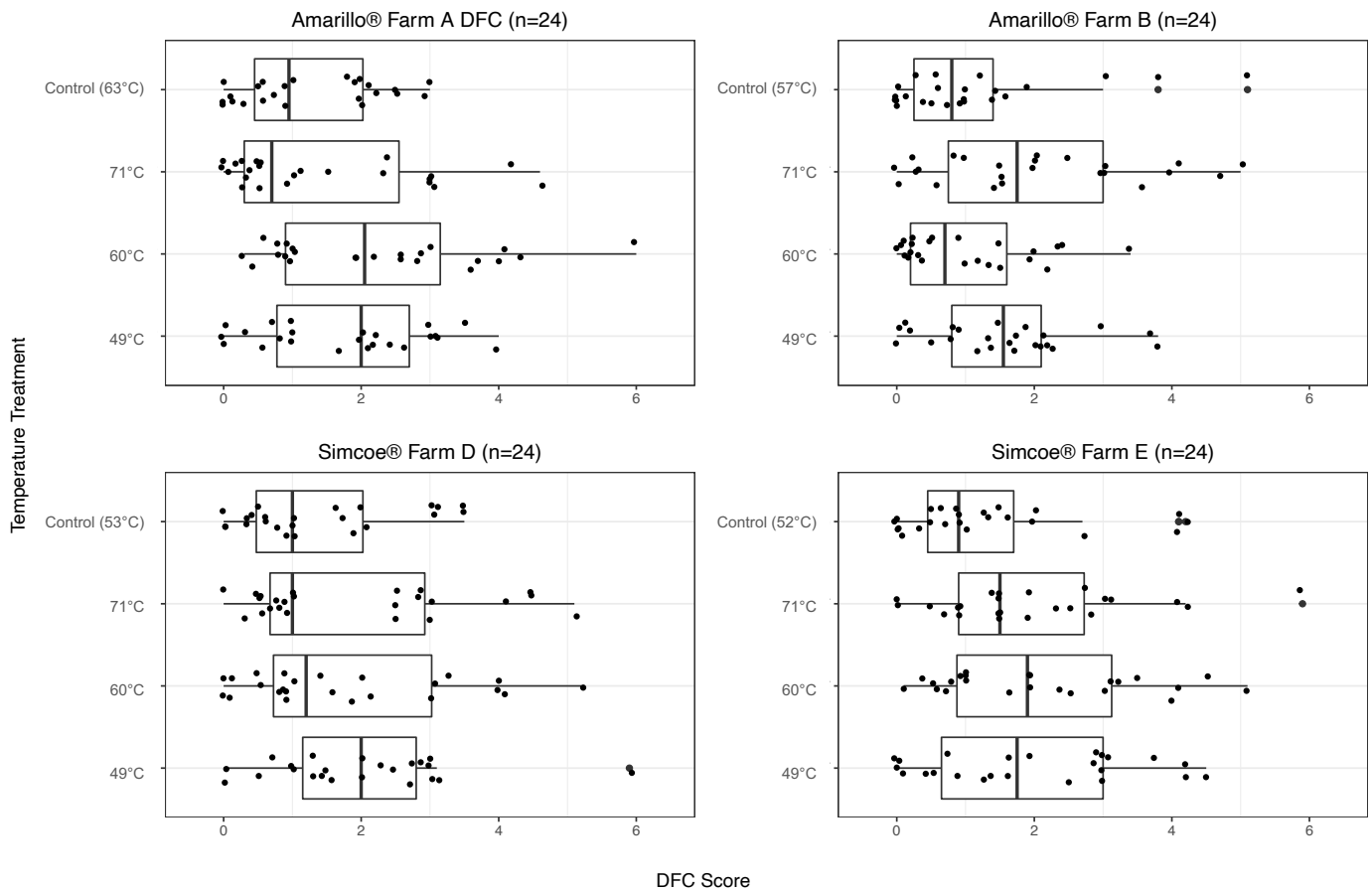


Fig. 3 DFC data from 2019 beer evaluations showing individual panelist evaluations (each point) and median DFC score (black lines in each box)

the trained panel found it hard to detect differences between the different treatments it is highly unlikely that the consumers would be able to detect this difference. Generally, the sensory evaluation results for Simcoe® suggest that Simcoe® hops seem to be only modestly impacted by kiln temperature from a sensory perspective (i.e. hops and beer). These results are consistent over two harvest years and align with observations from the chemical analysis.

When evaluating the sensory data for the Amarillo® hops, more treatments were scored significantly different from the process control in the hops than in beer evaluations. For the 2018 hop grind evaluations, panelists found the 49 °C (120 °F) and 71 °C (160 °F) significantly different from the control. The same observations were made for the 2018 beers. Interestingly, hops and beer from the 82 °C (180 °F) treatment were not found to be different from the process control. Such a high kilning temperature was used for academic/scientific purposes and is clearly outside the range of commercial kilning temperatures, but it was nonetheless surprising to see how it did not impact the hops or beer sensory properties. For the 2019 hop grind evaluations, panelists scored the 49 °C (120 °F) and 60 °C (140 °F) treatments different from the process control for Farm A, but for Farm B, only the 71 °C (160 °F) rep 2 treatment was different from the control. For the 2019 beer evaluations, the Farm A 60 °C (140 °F) and the Farm B 71 °C (160 °F) scored significantly different from the control. However, when evaluating the culmination of the 2018 and 2019 harvest data for Amarillo®, one can conclude that Amarillo® hops are only

slightly impacted by kiln temperature and differences detected in the hop grinds were larger than in the beer made with the same hops. When comparing these results to historical literature in hop drying, where hop evaluations were performed via hop rubs, temperature treatment did not result in differences in aromatic quality [28]. One study looked at beer brewed with hops dried at higher temperatures found the hops dried at 70 °C (158 °F) had the highest preference [5]. It is important to be mindful that historic studies primarily focused on hop acid preservation and not aroma quality parameters [7].

4 Conclusion

When combining hop chemistry and sensory evaluations, there is evidence that higher kiln temperatures can be used without sacrificing hop aroma quality. From a sustainability standpoint, lower kilning temperatures mean longer drying times and thus potentially higher energy inputs. Higher temperature kilning can give farmers more flexibility to harvest hops quicker and within a narrower maturity range. For example, with higher drying times hops could be kilned faster allowing for more hop varieties to be picked at more optimal timeframes given that most hop varieties ripen within a short window [10]. In addition, another benefit of increased hop drying temperature is that dextrin reducing enzymes responsible for hop creep have been found to be reduced with higher kilning temperature [18]. There is the potential for a

multitude of benefits from the hop growing and processing perspective if kiln temperature can be increased without impacting the aroma quality of hops. While promising, it is important to keep in mind other kilning parameters like airflow and bed depth are important quality parameters β -pinene considered. Finally, one must consider a range of important factors outside of kilning that may also impact hop quality, such as harvest maturity, hop field to field variation, farm management, climate, harvest year, and disease pressure [12, 14, 17].

Acknowledgements

The authors would like to acknowledge the Hop Research Council for funding this work and thank the hop growers from Crosby Hop Farm, Elk Mountain Farms, Loftus Ranches, Perrault Farms, and Virgil Gamache Farms for providing kiln space, hops, and guidance in the project design. The authors would also like to acknowledge the undergraduate students working in the Shellhammer lab at Oregon State University for their help with hop chemistry analyses.

Funding Sources

Funding for this study was provided the Hop Research Council (HRC).

5 References

- ASBC Methods of Analysis, online. Method Hops 6. α - and β -Acids in Hops and Hop Pellets, Hops 12. Hop Storage Index, Hop Method 13. Total Essential Oils in Hops and Hop Pellets by Steam Distillation, Hops 16. Iso- α , α -, and β -Acids in Hop Extracts and Isomerized Hop Extracts by HPLC, Hops 17. Hop Essential Oils by Capillary Gas Chromatography-Flame Ionization Detection. American Society of Brewing Chemists, St. Paul, MN, U.S.A.
- ASBC Methods of Analysis, online. Sensory Analysis Method- 13 Difference-from-Control (DFC). Approved 2009. American Society of Brewing Chemists, St. Paul, MN, U.S.A.
- Burgess, A. H.: Summary of Work on Hop Drying, The Institute of Brewing Research Scheme, (1940), pp. 6.
- Cantwell, D. and Swersey, C.: 2019 BA (Brewer's Association) Hop Usage Survey, Brewer's Association: The New Brewer, **36** (2019).
- Cosbie, A. J. C.: The Effect of Temperature of Drying on the Value of Hops, The Institute of Brewing Research Scheme, **43** (1937), no. 1, pp. 9-16.
- Doe, P. E. and Menary, R. C.: Optimization of the Hop Drying Process with Respect to Alpha Acid Content, J. agric. Engng Res., **24** (1979), no. 3, pp. 233-248.
- Henderson, S. M. and Miller, G. E.: Hop Drying Details and In-bale Quality, edition: 1914.
- Howard, G. A. and Slater, C. A.: Effect of ripeness and drying of hops on the essential oil, Journal of the Institute of Brewing, **64** (1957), no. 3, pp. 234-237.
- Lafontaine, S. R.; Pereira, C. B.; Vollmer, D. M. and Shellhammer, T. H.: The Effectiveness of Hop Volatile Markers for Forecasting Dry-hop Aroma Intensity and Quality of Cascade and Centennial Hops, Brewing Science, **71** (2018), no. 11/12, pp. 116-140.
- Lafontaine, S. R. and Shellhammer, T. H.: How Hoppy Beer Production Has Redefined Hop Quality and a Discussion of Agricultural and Processing Strategies to Promote It, MBAA TQ, **56** (2019).
- Lafontaine, S. R. and Shellhammer, T. H.: Investigating the Factors Impacting Aroma, Flavor, and Stability in Dry-Hopped Beers, MBAA TQ, **56** (2019), pp. 13-23.
- Lafontaine, S. R.; Varnum, S.; Roland, A.; Delpech, S.; Dagan, L.; Vollmer, D. M.; Kishimoto, T. and Shellhammer, T. H.: Impact of harvest maturity on the aroma characteristics and chemistry of Cascade hops used for dry-hopping, Food Chemistry, **278** (2019), pp. 228-239.
- Lewis, M. J. and Young, T. W.: Brewing Second Edition, 2. edition: Kluwer Academic/Plenum Publishers, 2002.
- Matsui, H.; Inui, T.; Oka, K. and Fukui, N.: The influence of pruning and harvest timing on hop aroma, cone appearance, and yield, Food Chemistry, **202** (2016), pp. 15-22.
- Nielsen, T. P.; Smith, P.; Peacock, V. and Garden, S.: Kiln Air Temperature, Bed Depth and Air Volume Flow Rate Effects on the Quality and Production of Hops (oral presentation), Master Brewers Association of Americas, 2013, Austin, TX,
- Peacock, V.; Arendt, B.; Thiel, R.; Gura, M. and Chadwick, L.: A Comparison of Hop Drying with Unheated, Dehumidified Air Versus Traditional Drying with Heated Air, MBAA TQ, **55** (2018), no. 3, pp. 63-66.
- Raut, S.; Gersdorff, G. J. E. V.; Münsterer, J.; Kammhuber, K.; Hensel, O. and Sturm, B.: Impact of Process Parameters and Bulk Properties on Quality of Dried Hops, Processes, **8** (2020), no. 11.
- Rubottom, L. N.; Lafontaine, S. R.; Hauser, D. G.; Pereira, C. and Shellhammer, T. H.: Hop kilning temperature sensitivity of dextrin-reducing enzymes in hops, American Society of Brewing Chemists, 2021.
- Rybka, A.; Heřmánek, P. and Honzík, I.: Effect of drying temperature in hop dryer on hop quality, Research in Agricultural Engineering, **67** (2021), no. 1, pp. 1-7.
- Schönberger, C. and Kostecky, T.: 125th Anniversary Review: The Role of Hops in Brewing, Journal of the Institute of Brewing, **117** (2011), no. 3, pp. 259-267.
- Stone, M. L.: Modeling of Deep Hop Bed Drying, Engineering Science, 1982.
- Takoi, K.; Tokita, K.; Sanekata, A.; Usami, Y.; Itoga, Y.; Koie, K.; Matsumoto, I. and Nakayama, Y.: Varietal Difference of Hop-Derived Flavour Compounds in Late-Hopped/Dry-Hopped Beers, BrewingScience, **69** (2016), no. 1-2, pp. 1-7.
- Tartar, H. V. and Pilkington, B.: The effect of kiln-drying at 145F on the composition of the hop, The Journal of Industrial and Engineering Chemistry, 1912.
- Tartar, H. V. and Pilkington, B.: Hop Investigations, edition: 1918.
- Thompson, J. F.; Stone, M. L. and Kranzler, G. A.: Modified Flow Rate and Temperature Hop Drying, American Society of Agricultural Engineers, **28** (1985), no. 4, pp. 1297-1300.
- Vollmer, D. M. and Shellhammer, T. H.: Influence of Hop Oil Content and Composition on Hop Aroma Intensity in Dry-Hopped Beer, Journal of the American Society of Brewing Chemists, **74** (2016), pp. 242-249.
- Watson, B.: The Hop Pendulum: A History of the American Hops Market, 2020.
- Watson, G. A.: Effect of drying temperature and air-speed on hop quality, Journal of the Institute of Brewing, **64** (1958), no. 3, pp. 242-247.
- Weber, K. A.; Jangaard, N. O.; Robert T. and Foster, R. T. I.: Effects of Postharvest Handling on Quality and Storage Stability of Cascade Hops, Journal of the American Society of Brewing Chemists, **37** (1979), no. 2, pp. 58-60.
- Weingart, F.: German Drying Technologies – a little seminar on Hop Drying, March 2016, Traverse City.

Supplemental Materials

Table S1 Imperial units for Amarillo® hop measured temperatures of kiln plenum air and total drying time for each treatment. (– indicates there is no data point for that treatment, * indicates samples were dried in a pilot-scale kiln (4 feet by 4 feet))

Amarillo® 2018 & 2019 temperatures and drying times							
Farm ID	Rep	Target Treatment (°F)	Hop bed depth (inches)	Measured Plenum Temperature (°F)		Drying time (hours)	
				2018*	2019	2018*	2019
Farm A	1	120	30	119	120	10.5	9.4
Farm A	1	140	30	139	141	7.1	6.2
Farm A	1	160	30	162	161	5.7	4.5
Farm A	1	180	30	174	–	–	3.9
Farm A	2	120	30	117	129	10.2	11.3
Farm A	2	140	30	142	–	7.4	5.6
Farm A	2	160	30	158	159	5.8	4.0
Farm A	2	180	30	175	–	–	3.5
Farm B	1	120	30	–	120	–	9.9
Farm B	1	140	30	–	144	–	4.8
Farm B	1	160	30	–	160	–	4.4
Farm B	2	120	30	–	124	–	10.7
Farm B	2	140	30	–	142	–	6.6
Farm B	2	160	30	–	*	–	3.8

Table S2 Imperial units for Simcoe® hop measured temperatures of kiln plenum air (Air On) and total drying time for each treatment. (– indicates there is no data point for that treatment)

Simcoe® 2018 & 2019 temperatures and drying times							
Farm ID	Rep	Target Treatment (°F)	Hop bed depth (inches)	Measured Plenum Temperature (°F)		Drying time (hours)	
				2018	2019	2018	2019
Farm D	1	120	30	117	117	9.0	11.2
Farm D	1	140	30	134	136	7.0	7.5
Farm D	1	160	30	158	156	5.0	4.9
Farm D	2	120	30	122	116	8.3	12.5
Farm D	2	140	30	138	139	6.0	9.0
Farm D	2	160	30	152	157	4.8	6.3
Farm E	1	120	26.5	118	123	8.8	10.5
Farm E	1	140	26.5	152	145	5.0	6.3
Farm E	1	160	26.5	–	156	–	4.5
Farm E	2	120	26.5	–	115	–	13.3
Farm E	2	140	26.5	–	145	–	7.3
Farm E	2	160	26.5	–	156	–	4.7
Farm F	1	120	26.5	118	–	9.0	–
Farm F	1	140	26.5	130	–	7.0	–
Farm F	1	160	26.5	152	–	4.5	–

Fold change calculation for measured hop chemistry analytes

The fold change in each analyte as kiln temperature was changed from 49 °C (120 °F) to 71 °C (160 °F) was used to interpret how each hop analyte was impacted by temperature. For example, the beta-myrcene concentration for 2019 Simcoe® Farm D rep 1 went

from 2125 mg/100 g of hops at 49 °C (120 °F) to 1680 mg/100 g of hops at 71 °C (160 °F), representing a 0.79-fold reduction in beta-myrcene or a 21% decrease (Figure S1). In contrast, the 2019 Simcoe® Farm D rep 2 beta-myrcene went from 1942 mg/100 g of hops at 49 °C (120 °F) to 2365 mg/100 g of hops at 71 °C (160 °F). This represents a 1.22-fold increase or a 22 % increase in myrcene (Fig. S2).

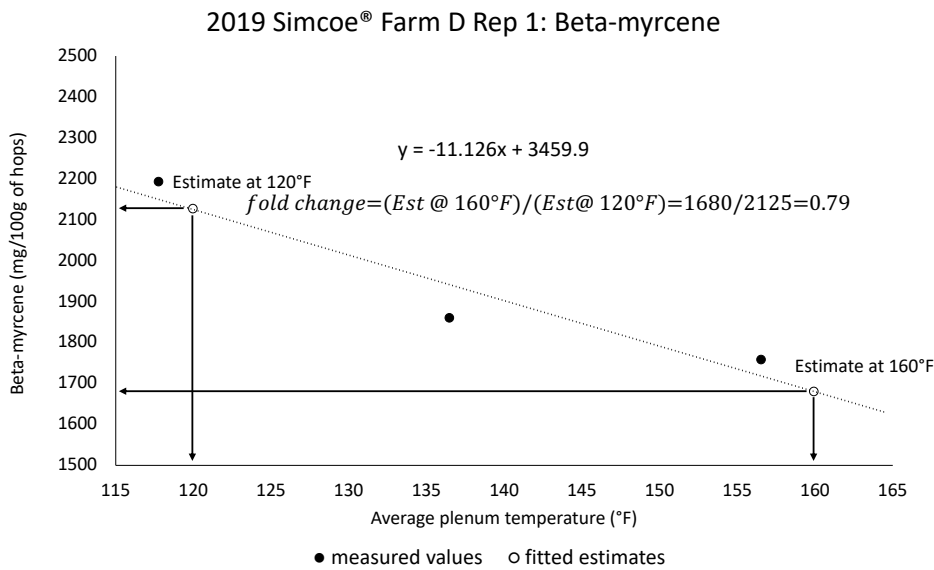


Fig. S1 Graphic showing measured data points of the oil composition analysis for beta-myrcene Farm D Rep 1. The graphic outlines how fold change was calculated for figure 2. This example shows a negative slope relationship with temperature resulting in a fold change reduction of 0.79 or a 21 % decrease in Beta-myrcene concentration

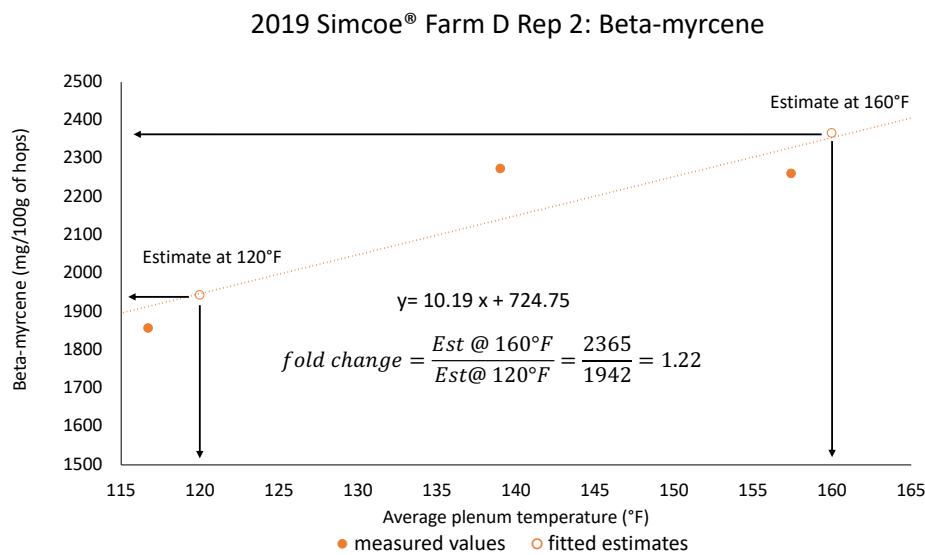


Fig. S2 Graphic showing measured data points of the oil composition analysis for beta-myrcene Farm D Rep 2. The graphic outlines how fold change was calculated for figure 2. This particular example shows a positive slope relationship with temperature resulting in a fold change increase of 1.22 or a 22 % increase in Beta-myrcene concentration