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Untapping Beer Terroir: Experimental Evidence of Regional Variation in Hop Flavor Profiles

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Abstract: Thanks in part to the push for localized supply chains, U.S. hop production is becoming more regionally diverse. Differentiation in geographies implies changes in growing climates and other environmental factors known to alter the flavor profiles of agricultural commodities used in food and drink. We use a chemical analysis, blind taste test, and choice experiment to identify whether the same hop cultivar grown in different regions induces a unique sensory profile in hops and beer. The chemical analysis and taste test provide evidence of hop terroir, while we find that brewers are willing to pay a premium for local hops.

Keywords: terroir; craft beer; hop demand
JEL Codes: Q13; L66

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1. Introduction

Scholars and practitioners have long maintained that tastes and flavors are a product of the environment in which an agricultural commodity is grown—a function of the climate, soil, topography, and surrounding plants. Most famously, wine markets have highlighted unique flavor profiles of terroir, generating substantial premiums for global appellations (Costanigro, McCluskey, and Goemans, 2010; Cross, Plantigna, and Stavins, 2011; 2017; Haeck, Meloni, and Swinnen, 2019; Huysmans and Swinnen. 2019; Meloni and Swinnen, 2018; Vaudour, 2002). The notion of terroir dates back to the seventeenth or eighteenth century and is frequently associated with viticulture, where climate, soil, and vine—in an interactive agroecosystem—contribute to the wine's distinct sensory attributes (Meloni et al., 2019; Van Leeuwen and Seguin, 2006). Studies on the role of terroir in flavor profiles extend past wine, leading to many geographic indicators especially in Europe (Deselnicu et al., 2013).

Though terroir has been extensively studied in other agricultural value chains, the concept has not been heavily explored in beer and hops. The omission of terroir in the beer literature has become even more important over the past few decades as the hop industry has undergone rapid expansion and diversification since the turn of the century. In the U.S. alone, hop acreage increased from 29,683 acres in 2012 to a record 58,930 in 2019 (Hop Growers of America, 2017; 2020b), a statistic driven largely by growth in the craft beer sector. The U.S. is now the world's leading hop producer, contributing 40% of global production in 2019 (Hop Growers of America, 2020b). The value of the U.S. hop industry reached a record $636,580,000 in 2019, while acreage and total production increased 2.6% and 4.7% from 2018, respectively. Moreover, the geographical dispersion of hop production has also increased in recent years: 29 states now report commercial hop production, while until 2014, hop production was tracked only in the Pacific Northwest (PNW) states of Washington, Oregon, and Idaho (Hop Growers of America, 2015; 2020b).

Different geographies imply different growing climates, rainfall, and other important environmental factors that have been found to substantially change the taste of other beverages (e.g., wine); however, little research has explored the role of regional variation in hop production on flavor profiles of beer. While recent literature suggests that hop origin should result in product differentiation among U.S. and international hops (Barry et al., 2018; Rodolfi et al., 2019), fewer studies have examined U.S. *regional* distinctions (Morcol et al., 2020; Van Holle et al., 2017). Regional differences might provide an important marketing opportunity for hop growers in unique growing regions. This study empirically tests whether the same hop cultivar grown in different regions of the U.S. induces unique chemical and sensory profiles in beer. Specifically, we profile hop oil volatiles and hop-oil-derived constituents in beer, conduct sensory analyses using blind taste tests, and perform a labeled, stated preference, discrete choice experiment to explore the role of hop terroir in beer. We focus our analysis of terroir on four Chinook hop samples (T90 pellets) from different U.S. growing regions: two from the PNW (Washington and Oregon) and two from Michigan (MI; one from Northern MI and one from Eastern MI), the leading hop producer outside the PNW (Hop Growers of America, 2020b).

We contribute to the regional studies literature in several ways. First, we summarize the literature on regional production and sensory variation of alcoholic beverages, paying special attention to the economic geography of hops. Second, we describe the results of chemical analyses of hops grown in different production regions, along with a more novel approach to isolating terroir in beers. We brewed a five-barrel (bbl) baseline beer in collaboration with a local microbrewery, separated the beer into five, one-barrel fermenters, and dry-hopped four fermenters with one of the four hop samples each.[1] These beers were then part of a blind taste test in which career beer industry professionals assessed the sensory profile of each beer to determine if there were hop-oil-derived distinctions. Chemical analyses confirmed differences in the hops and beer based upon geography and regional agricultural practices, and drinkers could identify aromatic differences within the blind taste test, while overall liking of the beers varied little among participants. These results indicate that terroir is indeed a biophysical reality, and marketing terroir could be a source of product differentiation for both hop growers and craft brewers. Finally, we assess brewer valuation of locally-grown hops using results from a discrete choice experiment (DCE) where 74 craft brewers answered a series of questions about hop-purchasing decisions. We find, *ceteris paribus*, that brewers in our sample would be willing to pay 35% more for hops grown in their home state than for hops from the PNW, indicating a strong preference for supporting local beer value chains and a perception that local hops taste different from non-local hops.

The remainder of this article is structured as follows. Section 2 provides a brief history of U.S. hop production and background into the notion of terroir, including the agronomics behind hop chemical composition and how terroir can serve as a marketing tool for growers outside the PNW. Section 3 presents our methodology, including the procedures for the chemical analysis, brewing process, and blind taste test. Section 4 presents our results, while Section 5 concludes the paper.

2. Background

History of U.S. Hop Production

[1] Dry hopping refers to the addition of hops to beer after it has been boiled and cooled to produce beer with stronger flavors and aromas. The brewing procedures are explained in greater detail in Section 3.2. The one-bbl fermenter that was not dry-hopped remained at the local microbrewery that partnered with us on this project.

Brewers have long maintained that hop origin has critical implications for the flavor profile of beer. In the nineteenth century, before the rise of industrialized agriculture, European brewers were especially critical of hops from the United States, arguing that American hops "derive a course, rank flavour and smell from the soil in which they grow, which no management, however careful, has hitherto succeeded in neutralising" (cited in Geiling, 2014). These negative perceptions slowly began to change at the turn of the 20th century, as botanists from the U.S. Department of Agriculture (USDA) created opportunities for American farmers to grow European cultivars including those deemed most popular in Germany (Stone, 2019). Throughout the 20th century, brewer perceptions of U.S.-grown hops shifted dramatically, and the United States has since become the leader in hop production, accounting for 40% of production worldwide. While most domestic commercial hop production is now concentrated in the PNW, hop cultivation was once a regionally diverse, locally-driven commodity extending back to colonial times (Knudson, Sirrine, andand Mann, 2020).

By the beginning of the 20th century, the United States was growing more hops than anywhere outside of Germany (Kopp, 2014). Although domestic acreage and production was on the rise, heightened disease and insect pressure devastated eastern and midwestern production, contributing to a shift in acreage to the western states. However, this shift was not without new industry issues. A growing temperance movement culminated in the passage of the 18th Amendment in 1919, which established Prohibition, and subsequently reduced the domestic demand for hops until the passing of the 21st Amendment in 1933, which repealed the 18th Amendment.[2]

[2] Though domestic demand was greatly reduced from 1920-1933 and many hop producers left the market, growers who continued cultivating hops benefitted from rising international beer consumption (Kopp, 2014).

From Prohibition to the modern era, the PNW solidified its place as the dominant hop producer. Washington state's Yakima Valley became the epicenter of commercial hop production in the 1950's (Kopp, 2014), while Oregon and Idaho producers also increased the number of acres dedicated to hop production. By the 1987 census, only Washington, Oregon, and Idaho produced hops at a commercial scale. In fact, hop production outside the PNW was not even tracked by the USDA until 2014 (Hop Growers of America, 2015).

Domestic hop acreage has continued to climb in recent years. From 2012 through 2016, U.S. hop acreage grew by 78%, from 29,683 to 52,963 acres (Hop Growers of America, 2017), and 2020 acreage in production is expected to eclipse 60,000 acres for the first time in U.S. history (USDA NASS, 2020). Recent growth is primarily due to an increased presence of craft beer in the marketplace: the number of craft breweries increased from 1,758 in 2010 to 8,275 in 2019 (Brewers Association, 2020). While craft beer accounts for just 13.6% of U.S. beer production volume, it accounts for nearly 50% of total U.S. hop usage (Watson, 2015). This disparity is due in part to differences in the styles of the beer brewed by craft and macro alternatives. Much of the growth in the craft brewing sector is attributed to flavor-forward, hop heavy India Pale Ales (IPAs) as organoleptic properties (i.e., intrinsic sensory characteristics such as flavor and aroma) are key drivers of consumer demand for craft beer. Many craft beer styles, specifically IPAs, use a great deal of hops compared to traditional American pilsners. While "hopping rates" can vary significantly, the average light lager produced by a macro-brewer may contain 0.2 pounds of hops per barrel of beer. In contrast, an IPA may contain up to four pounds of hops per barrel (Hop Growers of America, 2020a).

Hops are generally placed into one of two market categories: (i) high-alpha/bittering hops or (ii) aroma/dual purpose for organoleptic properties. While the commercial beer industry has its roots in high-alpha bittering hops, craft brewers often value novel flavor and aroma above traditional measures of hop quality (Lafontaine and Shellhammer, 2019). Indeed, modern-day craft brewers utilize a record number of hop cultivars: between 2009 and 2019, the number of hop cultivars found in craft beer production increased 82.2%, reaching 164 (Swersey, 2020). Given the shift in brewer (and consumer) preferences, growers have reallocated acreage devoted to bittering and aroma/dual purpose hops. In 2008, approximately 20% of total U.S. hop acreage was planted for aroma/dual purpose varieties. By 2012, acreage was evenly divided between the categories. Today, over 75% of hops grown in the United States are aroma/dual purpose varieties (Hop Growers of America, 2020b).

The rise of craft beer demand coincides with a notable shift in consumer preference toward local food and drink, so it follows that brewer preferences for inputs have also shifted toward local sources. The recent expansion of hop production has generated a geographic dispersion spanning 29 states in 2019 (Dobis et al., 2020; Hop Growers of America, 2020b). Indeed, states that were large producers in the late 19th century—New York, Wisconsin, and Michigan—have re-established commercial hop industries. In 2019, 2,386 acres of hops were harvested outside of the PNW; MI was the leading producer, accounting for nearly one-third of this output (720 acres), followed by New York (400 acres) and Wisconsin (297 acres) (Hop Growers of America, 2020b).

The Regional Agronomics of Hop Production

Along with the restored geographic dispersion of U.S. hop production comes variation in climatic factors that play an important role in hop agronomy. The hop plant is a perennial, photoperiod dependent plant, meaning day length determines the annual stages of production. The timing of each stage varies by growing location and cultivar, though hop harvest generally occurs between mid-late August through September. As day length throughout the growing season is determined by latitude, latitude plays a crucial role in hop production. In the northern hemisphere, hops grow best between the 35th and 55th parallels. In the northern hemisphere, hops grown below the 35th may achieve the appropriate number of nodes in the spring, resulting in a "split crop" and subpar yields; hops grown above the 55th parallel may not have enough time during the vegetative growth period prior to the switch to reproductive growth, also resulting in subpar yields (Turner et al., 2011). Further, ideal growth and yield require five to six weeks of freezing to near freezing temperatures while the hop plant is dormant.

Hop terroir is a relatively new topic, warranting further investigation into the mechanisms which might contribute to it. Indeed, a small but growing body of research suggests that the chemical composition of hops might be influenced by geographic origin (Barry et al. 2018; Forster and Gahr, 2014; Green, 1997; Jelínek et al. 2012; Kishimoto et al. 2008; Rodolfi et al. 2019; Van Holle et al. 2017). Plants produce primary metabolites essential for growth, development, and reproduction as well as secondary metabolites enabling the plants to adapt to biotic and abiotic conditions over time. Changes in the amount and ratios of secondary metabolites can lead to perceptible quality differences in many agricultural crops such as coffee (Tolessa et al. 2017), cocoa (Torres-Moreno et al., 2015), tea (Lee et al. 2015), and olive oil (Alonso-Salces et al. 2010; Foroni et al. 2017). In hops, the cones of female plants produce lupulin, a sticky yellow powder that contains secondary metabolites—hard resins (polyphenols), soft resins (α- and β-acids), and essential oils. These essential oils are volatile organic compounds that give hops their aroma. Over 450 volatiles have been chemically characterized in hop essential oil, but there are likely over 1,000 unique compounds (Roberts, Dufour, and Lewis, 2004). Prior research has found that many factors affect hop aroma and the resulting organoleptic properties of beer, including varietal distinctions based on genetics (Gros et al. 2012), environmental and biological factors (Jelínek et al. 2012), climate change (Mozny et al., 2009), plant age (Matsui et al., 2012), and production/post-harvest practices (Gabrielyan et al., 2018; Kishimoto et al., 2008; Matsui et al. 2016; Sharp et al., 2014). Despite the extensive agronomic research, fewer studies have focused explicitly on the economic value of hop terroir itself. This is of particular importance given the recent trends in the geographical dispersion of hop production. Although there are likely subtle geographically induced differences among hops produced in Washington, all Washington hops—69% of U.S. acreage—are grown exclusively within one Level IV ecoregion, whereas Michigan hops are grown in at least 17 Level IV ecoregions (EPA, 2020). As such, while each hop variety has a unique sensory profile, terroir suggests that the same hop variety can attain a different flavor profile if it is grown in a different ecoregion.

Marketing Terroir

As local hop markets have emerged, growers have endured various production challenges, including higher production costs, new/different pest and disease challenges, sub-optimal growing conditions and weather patterns (compared to Yakima Valley, WA or Willamette Valley, OR), and less-developed processing chains (Lizotte and Sirrine, 2017; Sirrine et al., 2010). Thus, the growth of local beer value chains may be hindered by the perception of less consistent inputs, economies of scale, limited access to proprietary hops, and the role of forward contracts. Interested in expanding local supply chains despite these challenges, policy makers, growers, and other industry stakeholders are searching for ways to incentivize brewers to use more local hops. One potential alternative suggested in research by Staples, Malone, and Sirrine (2020) is to highlight the unique attributes of locally/regionally grown hops: specifically, to market terroir to both the brewer and the consumer.

One recent example of hop terroir is shown within the widely used Cascade hop. Washington-grown raw Cascade hops display cream caramel, blackberry, and mango notes with predominant citrus notes in cold infusion, whereas New Zealand raw Cascade hops are fruity, with peach, pineapple, and lavender blossom notes, and in cold infusion, they feature passion fruit, red berries, lemon, and grapefruit (Schönberger and Joh. Barth & Sohn, 2014). Because of its distinct aroma profile, New Zealand Cascade has been renamed Taiheke® (Kennedy, 2016).

Sensory differences can lead to the development of regional identities, or geographical indicators, that increase the economic benefits of agricultural crops to farmers and farming communities (Deselnicu et al., 2013; Meloni et al., 2019; Meloni and Swinnen, 2018). Brewers are clamoring for hops with unique brewing values that confer unique sensory characteristics in beer, as evidenced by Firestone Walker's Brewmaster Matt Brynildson's use of Michigan-grown hops in Firestone Walker's Luponic Distortion Revolution No. 006. Brynildson reports that "this beer showcases what happens when you take two familiar Northwest hop varieties and grow them 2,000 miles to the east. The typical piney, dank attributes of these hops are transformed into something much brighter, with a racy citrus quality" (Brynildson, 2018).

With *regional identities* comes the notion of nested names, which have become commonplace in the wine industry (Costanigro et al., 2011). *Nested names* describe a good with increasing specificity, reducing information asymmetries, and signaling product differentiation. For example, Washington Cascade and New Zealand Cascade (now known as Taiheke®) indicate an increased specificity of the sensory profile of the hops despite being the same cultivar. Thus, nested names provide additional information to the consumer, communicate ties to a local/regional community, and as is often the case in wine, can generate premiums for global appellations. Though this marketing strategy has not been widely employed across the U.S. beer supply chain, brewers are searching for innovative ways to differentiate their product from the competition. Terroir, coupled with a tie to the local community, may provide this avenue.

3. Methods and Materials

The empirical objectives of this study are threefold. First, we determine whether the geographical origin of the Chinook hop affects its chemical composition through laboratory chemical analyses of four hop samples harvested from four different Level IV eco-regions.[3] Secondly, we determine whether beer industry professionals perceive different organoleptic properties between beers using hops from the different regions. Here, we brewed a five-barrel baseline beer, divided the beer into five one-barrel vats, "dry-hopped" four of the vats each with Chinook hops from one distinct growing region, and conducted a blind taste test with a group of beer industry professionals. Finally, we used a discrete choice experiment (DCE) to test whether brewers are willing to pay a premium for these perceived differences. Detailed procedures for each stage of the analysis are described below.

3.1. Chemical Analysis

We were interested in whether hops from different regions are chemically distinct. Samples from two MI farms (one from Northern MI and one from Eastern MI) and two PNW farms (one from WA and one from OR) were obtained and sent to a professional laboratory for analysis. MI is an

[3] The Chinook hop was chosen because it is the fourth most-planted public variety cultivar in the PNW (Hop Growers of America, 2020b); it is a versatile cultivar utilized by several of the largest craft brewers in the country (Swarner, 2017); and it has grown well in Michigan since the re-emergence of the state's hop industry (Sirrine, 2020).

ideal candidate for PNW comparison as it lies on a similar latitude, has been growing commercial hops since at least 2008 (i.e., longer than most other non-PNW states now reporting commercial hop production), and is the leading hop producer outside of the PNW (Sirrine et al., 2011; Hop Growers of America, 2020).

Several volatile phytochemicals in hops contribute to aroma, but terpenes account for the majority of mass of these compounds in hop essential oils. Terpenes are commonly referenced as the basis of many recognizable odors detected in sensory analysis, and thus we conduct a terpene analysis to determine whether the hop samples exhibit differences in terpene count and terpene presence.[4] However, terpenes do not account for all the subtleties used in the evaluation of terroir. Thus, we also conduct an *unknowns analysis* for other classes of volatile chemicals, such as esters and similar small compounds that have an effect on the perceived hop aroma profiles (Eyres and Dufour, 2009).[5]

3.2 Blind Taste Testing and Sensory Analysis

To isolate the impact of hop origin on the flavor profile of beer, we employed the following brewing design. We collaborated with a MI microbrewery to brew a five-barrel (bbl) kettle of baseline beer. The wort, or unfermented beer, was brewed with 95% Wayermann pale malt and 5% Simpsons Crystal light malt. We added 45 oz. of PNW Cascade hops (7.2% α-acid) to the five bbl kettle. To initiate fermentation, White Labs California Ale yeast (WL001) was added to the wort. Once pitched, the beer sat at 67°F (19.4°C) for 10 days. The baseline beer was then brought

[4] Terpenes were extracted using a solvent (ethyl acetate) that co-elutes in gas chromatography with many smaller aroma compounds of interest such as esters. To search for and characterize additional unknown compounds, hop samples were also prepped using a solventless full evaporative technique, and the early eluting mass spectra (0-10 mins) was extracted and searched against a NIST library of GC/MS spectra.
[5] A detailed set of procedures and results to the terpene analysis and unknowns analysis are described in the Appendix accompanying this manuscript.

to 50°F (10°C), fined with a clarifying agent (Biofine) on day 12, and transferred to five one-bbl fermenters on day 14.

Four fermenters were dry-hopped with 16 oz. of Chinook hops, one for each of the four regions: Washington, Oregon, Northern MI, and Eastern Michigan. Dry-hopping refers to the process in which brewers add hops to their beer after the boil—often during the fermentation process—to introduce various flavors and aromas. Once the Chinook hops were added to each of the bbls, they settled for an additional 72 hours (3 days). Over this time, they remained at 50°F (10°C) before being cooled to 34°F (1.1°C) over the course of an additional 36 hours (1.5 days). Each of the final four beers had an alcohol content by volume of 5.0% and 40 international bitterness units. The beers were transferred to kegs and transported to the sites of the blind taste tests.

Blind taste testing occurred on two occasions: the first at the annual Great Lakes Hop and Barley Conference and the second at a regional brewery's headquarters. We utilized career beer professionals as opposed to a random sample of beer drinkers, as we anticipated more informed, expert opinions on the sensory profiles of the beers from industry members. Procedures were identical in both settings, and for conciseness, we summarize the first taste testing below.

Before the experiment began, participants were informed about the tasting protocol and were asked to read and sign a consent form agreeing to participate in this voluntary experiment and confirm they were over the age of 21. Participants were given four-ounce pours of the four beers, labeled Beer A, Beer B, Beer C, and Beer D. They were also given a paper survey containing a scoring table for eight beer aroma sensory attributes and one bittering attribute. Respondents were asked to rank the presence of each attribute on an eight-point scale (0=none, 1=very low, …, 7=very high) (Table 1).

[TABLE 1 HERE]

Once the respondents completed the sensory portion of the analysis, they were asked to answer valuation questions, provide demographics, and report craft beer consumption habits. Respondents were asked to state their overall liking of each beer, assessed via a seven-point Likert scale, and to rank the beers from most favorite to least favorite. Respondents were also asked to state their willingness to pay for a pint (16 oz.) of each beer from a taproom. Each participant was allotted as much time as needed to complete the taste testing and survey, though the procedures were completed in approximately one hour.

3.3 Discrete Choice Experiment

We used a labeled stated preference DCE to examine brewer preference for state, regional, and PNW hops.[6] DCEs have become commonplace in the economics literature, as they reveal tradeoffs consumers face in choice settings, allowing researchers to assess consumer valuation and willingness to pay for product attributes. Our DCE focuses on the tradeoff brewers make between growing region and price, allowing us to determine whether brewers are willing to pay a premium for hops grown in certain regions.

Respondents were presented with hypothetical purchasing decisions on eight occasions and were asked to select the alternative they would choose if they faced this choice in real life. Each choice task consisted of three potential hop purchasing alternatives that varied in multiple ways; the respondent could also choose to opt-out by not selecting an alternative. Respondents were instructed to envision each of the potential alternatives as the type of hops they purchase most often and the hops as being identical except for the attributes that we varied. Alternatives in each

[6] For parsimony, we present a condensed version of the theoretical motivation for the methodology. For a deeper discussion of the DCEs involving beer marketing, see Malone and Lusk (2019) and Staples et al. (2020).

choice task included a pound of pelletized *state-grown* hops, a pound of *Great Lakes-grown* hops, or a pound of *PNW-grown* hops. Alternatives also varied in price, $3.99, $5.99, $7.99, or $9.99 per pound, and some alternatives had received a Global G.A.P. (Good Agricultural Practices) certification label, indicating that the grower abides by higher agricultural standards. Figure 1 presents an example choice task.

[FIGURE 1 HERE]

DCEs derive their explanatory power from random utility maximization (RUM) theory, which suggests that consumers maximize utility by comparing the attributes across alternatives, subject to a budget constraint (McFadden, 1974). The RUM model suggests that consumer *i* receives indirect utility $U_{ijt} = V_{ijt}(\mathbf{X}_{jt}) + \varepsilon_{ijt}$ from selecting alternative $j \in \{home\ state\ hops, Great\ Lakes\ hops, PNW\ hops, no\ purchase\}$ on choice occasion t in the choice experiment. Indirect utility comprises two components: an observable (deterministic) component $V_{ijt}(\cdot)$ as a function of the attributes and alternatives included in the choice experiment (represented by the vector $\mathbf{X}_{jt}$) and an unobservable component, ε_{ijt}, assumed to be an independent and identically distributed (IID) type I extreme value error term. Individual *i* chooses alternative *j* if and only if $U_{ijt} > U_{ikt} \forall\ j \neq k$. However, as indirect utility is random, we can predict only the probability an individual will select an alternative in a given choice task.[7] By assuming the error term is type I IID extreme value, we estimate a conditional logit for the deterministic portion of utility, specified as:

(1) $$V_{ijt} = HomeState + GreatLakes + PNW + \beta GlobalGAP_{jt} + \mu Price_{jt},$$

[7] Mathematically, the probability individual *i* selects alternative *j* in choice task *t* is expressed as:

$$P_{ijt}(\mathbf{X}_{jt}) = \Pr(V_{ijt}(\mathbf{X}_{jt}) + \varepsilon_{ijt} > V_{ikt}(\mathbf{X}_{kt}) + \varepsilon_{ikt};\ \forall\ j \neq k\ )$$
$$= \Pr(V_{ijt}(\mathbf{X}_{jt}) - V_{ikt}(\mathbf{X}_{kt}) > \varepsilon_{ikt} - \varepsilon_{ijt};\ \forall j \neq k\ ).$$

Thus, only differences in utility matter; the absolute scale of utility is irrelevant.

where *HomeState*, *GreatLakes*, and *PNW* are alternative specific constants (ASCs) for the labeled alternatives and are equal to one if the respondent selects this alternative on a given choice task and zero otherwise; β and μ are marginal utility parameters; $GlobalGAP_{jt}$ is a dummy variable equal to one when the alternative has the certification label present and zero otherwise; and $Price_{jt}$ indicates the price of the alternative. Upon computing the parameter estimates for the ASCs and marginal utility parameters, we calculate average willingness to pay (WTP) and compare WTP across alternatives, determining the average premium brewers attach to hops from different regions.

4. Results

4.1. Chemical Analysis

We first conducted terpene analysis of the hop cultivars. Of the 34 terpenes analyzed, only ten were detected among all four growing locations. Figure 2 summarizes our findings. Three compounds—beta-myrcene, alpha humulene, and trans-caryophyllene—accounted for between 97% and 99% of the total mass of terpenes in each sample. Additionally, of the ten terpenes detected, geranyl acetate, which is commonly associated with floral or fruity aromas (Jirovetz et al., 2006), was not detected in Hop A and α-Pinene, which is commonly associated with pine aromas (Sharp et al., 2014), was not detected in Hop A and Hop B.

[FIGURE 2 HERE]

We also conducted an unknowns analysis. Though the unknowns analysis does not directly identify the hop compounds in the samples, it offers a qualitative chemical fingerprint which defines the terroir we perceive in sensory analysis. In other words, the unknowns analysis shows whether variation exists in the samples without being able to directly explain what these differences are. For example, if genetically identical cultivars are run through the unknowns analysis on multiple occasions, each run should lead to an identical chromatograph. However, our results show that although our samples were genetically identical cultivars (i.e., Chinook hops), the chromatographs for each sample vary quite significantly, indicating variation in perceived sensory flavor profiles. For a detailed discussion of the unknowns analysis, please see the Appendix accompanying this manuscript.

4.2 Blind Taste Testing and Sensory Analysis

Fifty-nine individuals participated in the blind taste testing: 47 at the industry stakeholder conference and 12 at the regional brewery's headquarters.[8] Participants were current beer industry stakeholders across the supply chain; the most common occupations for respondents were hop growers (47.2%) and brewers (24.5%). Of the 59 respondents, 91.3% reported consuming craft beer at least once a week. Table 2 presents summary statistics for the blind taste test, including the eight aroma attributes, the bitterness characteristic, and the valuation measures.[9]

[TABLE 2 HERE]

Given the limited observations, just three of the differences in means across sensory attributes in the beers were statistically significant. Beer A was perceived as more bitter than both Beer B and Beer C at the 5% level. Beer A was, on average, rated 3.42 out of 7 for bitterness, while Beer B and Beer C had a mean bitterness rating of 2.84 and 2.88, respectively. The remaining

[8] While 59 respondents is regarded as a small sample in most empirical analyses, it is not uncommon for studies utilizing sensory panels to comprise fewer than 20 participants; for example Van Holle et al. (2017) used 15 trained panelists for their sensory analysis of beer terroir using Washington versus Idaho hops.

[9] Sample size per sensory attribute differs across beers because four respondents did not include a zero in responding on a scale of zero to seven as instructed, leaving many attributes—including bitterness—blank. One potential alternative for the analysis is to replace blank spaces with zeros, as respondents may have misinterpreted instructions and only rated the attributes they found in the beers. The results presented here do not make this assumption, but the radar plots for this analysis are available upon reasonable request. No additional statistically significant results were found.

statistically significant difference was between Beer B and Beer D for the tropical aroma characteristic: the mean for Beer B was 2.41, statistically greater than that for Beer D, 1.79 at the 10% level. A more detailed discussion of the unknowns analysis explains this difference. Nonetheless, the findings of differences in mean scores for the sensory attributes, as well as different chemical compositions in the hop terpenes and the unknowns analysis, provide supporting evidence for hop terroir.

4.3 Discrete Choice Experiment

In collaboration with agricultural extension specialists in the land grant university system, a stated preferences DCE was distributed online to craft breweries in Michigan, Massachusetts, Ohio, Virginia, and Indiana via an email newsletter from each state's Brewer Associations' in early 2019. In total, 74 craft brewers competed the DCE. The majority of respondents were MI craft brewers (58 of the 74), while the remaining brewers were in Massachusetts (seven), Ohio (four), Virginia (three), and Indiana (two). As hops are a central input to beer production, each brewer purchases large quantities annually, meaning our respondents were familiar with the choice decisions we asked them to complete in the DCE.[10]

Table 3 presents marginal utility parameters and mean WTP for model (1). Each of the variables in the model is statistically significant at the 1% level with the expected sign. For each of the ASCs (*HomeState, GreatLakes, PNW)*, we calculate WTP as the parameter estimate of the location divided by the negative of the price parameter μ; for *GlobalGAP*, WTP is calculated as $-{}^{\beta}/_{\mu}$. The overall scale of WTP for the three regional locations is not overly telling, as brewer WTP is cultivar specific (i.e., the WTP for a pound of hops depends on the type of cultivar the

[10] See Staples, Malone, and Sirrine (2020) for additional details of the brewer sample.

brewer is purchasing). Thus, the percent differences between home state, Great Lakes, and PNW hops are of particular interest.

[TABLE 3 HERE]

Our results suggest that brewers are willing to pay up to 35% more for hops grown in their home state, holding all else constant. Several factors could drive this premium: brewer preference for supporting local growers, an expectation that beer drinkers are willing to pay a premium for beers produced with local hops, and/or a perception that local hops taste different from non-local hops. Indeed, our survey results provide supporting evidence for each of these three factors.

First, brewers believe that localness is good for the local economy and provides more money to farmers (Staples et al., 2020). As the craft brewing revolution has been built largely on an increased demand in consumer preference for localness and brewers understand the importance of local consumption in their taproom-driven business model, they may consider building community relations through supporting local agriculture.

Second, brewers may believe that their consumers will pay a premium for beers that use locally sourced hops. Brewers answered an open-ended valuation question asking what premium they expect their consumers would be willing to pay for a beer made with local hops, both for a pint in the taproom and a six-pack from a retail outlet. Here, 62% of brewers believe their consumers would pay a premium for a pint that uses local hops, with a mean premium of $0.92; 71% of brewers believe their consumers would pay a premium for a six-pack, with a mean premium of $1.26.

The final factor that could generate substantial premiums for state-grown hops is a perception that local hops taste different from non-local hops, irrespective of hop cultivar. In other words, hop terroir. After the choice experiment, we asked brewers to state their general agreement or disagreement with the following statement: "Local hops taste different from hops grown in other states." Of craft brewers in our sample, 90% generally agree with this statement.[11]

Our results also indicate brewers are willing to pay a $0.97 premium for hops with the Global G.A.P. certification, providing evidence that brewers understand the importance of quality and safety verification programs in food and agriculture and appreciate knowing their inputs are grown using high agricultural standards.

5. Discussion

Is hop terroir a marketing construct and/or a biophysical reality? Using a professional chemical analysis, blind taste test, and DCE, we study whether hops from different geographical origins induce unique chemical compositions, distinct sensory profiles, and varying WTP. Our results suggest that the chemical structure of four Chinook hop samples varied, sensory differences were detected among beer professionals, and brewers are willing to pay a premium for locally grown hops—a premium potentially driven by a preference to support the local economy and local agriculture, a belief that the consumer is willing to pay a premium, and/or a perception that local hops have a local *terroir*.

Marketing terroir thus becomes a potential source of product differentiation for both growers selling to brewers and brewers selling to consumers, particularly when coupled with a heightened consumer demand for local inputs. Even if the average beer drinker is unable to detect or taste the difference between the beers brewed with hops from different regions, knowing the hops are sourced from a given region could tell a compelling story about the agriculture, the

[11] Responses are based on a seven-point Likert scale from *strongly disagree* to *strongly agree*. General agreement with the statement is defined as the sum of responses to *somewhat agree* (15% of respondents), *agree* (41%), and *strongly agree* (34%).

product quality, and the journey from the hop yard to the pint glass. As such, consumers may be willing to pay a premium for this designation, as is often the case with wine (Deselnicu et al., 2013). Further, brewers may choose to buy hops from different geographical regions or from a local source irrespective of consumer willingness to pay for local hops, either because they personally believe the hops have a distinct sensory profile or because they wish to support locally grown hops.

This study has three primary limitations. First, isolating the effect of geographical location on flavor profile is inherently difficult. Outside of geographical location and climate, farming practices such as nitrogen application, irrigation, and harvest time can factor into the final sensory profile. However, the differences in chemical composition are promising indicators that terroir is indeed a biophysical reality. Second, although brewing a baseline beer, transferring it to smaller fermenters, and dry-hopping with the hops from different geographical regions was thought to be the most effective way to isolate the regional aromatic properties of the hop cultivar, if we adjusted the brewing process, we might find more notable differences between the beers. Finally, hypothetical choice experiments are subject to hypothetical bias, where respondents are not punished for suboptimal decision making. However, this hypothetical bias is likely consistent across alternatives, suggesting that while overall WTP for each alternative may be inflated, the premium placed on local hops should be relatively consistent with actual purchasing preferences (Lusk and Schroeder, 2004). This consistency is critical because the local versus non-local premium is our primary interest, as price per pound is cultivar specific.

Future research across disciplines is needed to further understand the extent of, and the demand for, terroir in beer. More work is needed to determine how terpenes, esters, and other compounds translate to consumer sensory valuation. Further, future studies should examine consumer preference for local hops, as it is still unclear whether they are willing to pay a premium for local hops. Even so, the results of our study support the potential expansion of localized, regional flavor profiles in beer value chains. From the geographical distinctions in hop sensory profiles to the brewer premium for locally sourced hops, we may continue to see the development of beer value chains outside the PNW based on emphasizing terroir, the demand for local food, and the history of hop production.

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Tables and Figures

Table 1: Sensory profile ranking system as presented to the participants

0	**1**	**2**	**3**	**4**	**5**	**6**	**7**
none	very low	low	low-medium	medium	medium-high	high	very high

Aroma characteristics	**Beer A**	**Beer B**	**Beer C**	**Beer D**
Stone fruit				
Citrus				
Tropical				
Floral				
Pine				
Onion/garlic				
Woody/earthy				
Herbal/grassy				

Table 2. Blind taste test aroma, bitterness, and valuation summary statistics

	Sample Average (st. dev.)			
Characteristic	**Beer A**	**Beer B**	**Beer C**	**Beer D**
Aroma				
Stone fruit	1.70	1.84	1.69	1.60
	(1.70)	(1.93)	(1.66)	(1.65)
Citrus	2.53	2.42	2.33	2.29
	(1.90)	(1.64)	(1.59)	(1.74)
Tropical	1.98	2.41[a]	2.09	1.79[a]
	(1.86)	(2.07)	(1.61)	(1.70)
Floral	2.49	2.40	2.31	1.98
	(1.96)	(1.75)	(1.54)	(1.61)
Pine	2.11	1.66	1.66	2.05
	(1.91)	(1.54)	(1.46)	(1.68)
Onion or Garlic	0.56	0.76	0.65	0.63
	(1.20)	(1.36)	(1.31)	(1.23)
Woody or Earthy	2.06	1.89	1.81	1.79
	(1.98)	(1.94)	(1.75)	(1.61)
Herbal or Grassy	2.09	2.36	1.96	1.94
	(1.51)	(1.99)	(1.61)	(1.51)
Bitterness	3.42[b]	2.84[b]	2.88[b]	3.09
	(1.46)	(1.44)	(1.27)	(1.42)
Overall liking (1 to 7)	4.97	4.61	4.75	4.73
Average rating (1=favorite, …, 4=least favorite)	2.39	2.40	2.58	2.61
Average WTP per pint	$4.56	$4.50	$4.47	$4.53

[a] Indicates a statistically significant difference at the 10% level.

[b] Indicates a statistically significant difference between Beer A and Beers B and C at the 5% level.

Footnotes: Sample sizes differ between aroma characteristics and valuations (average rating, overall liking, and WTP per pint) due to misinterpretations on behalf of respondents.

Table 3. Marginal utility parameters and mean willingness to pay estimates

Variable	**Coef. (rbst. st. error)[a]**	**Mean WTP**
HomeState	5.38***	$15.91
	(0.61)	
GreatLakes	3.87***	$11.43
	(0.56)	
PNW	3.97***	$11.74
	(0.53)	
GlobalGAP	0.33**	$0.97
	(0.13)	
Price	-0.34***	---
	(0.05)	
Number of observations	592	
Log-likelihood	-479.19	

[a] Superscripts ***,**, and * denote statistical significance at the one, five, and ten percent level, respectively.

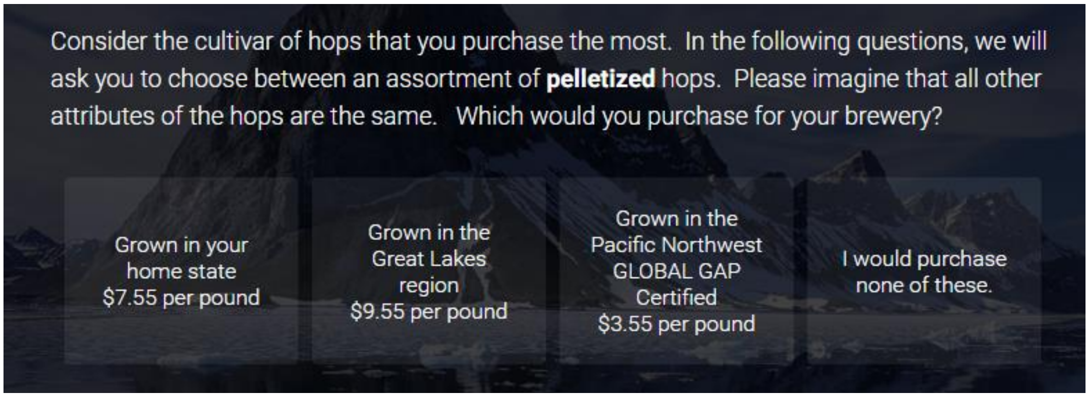

Figure 1. Example choice task

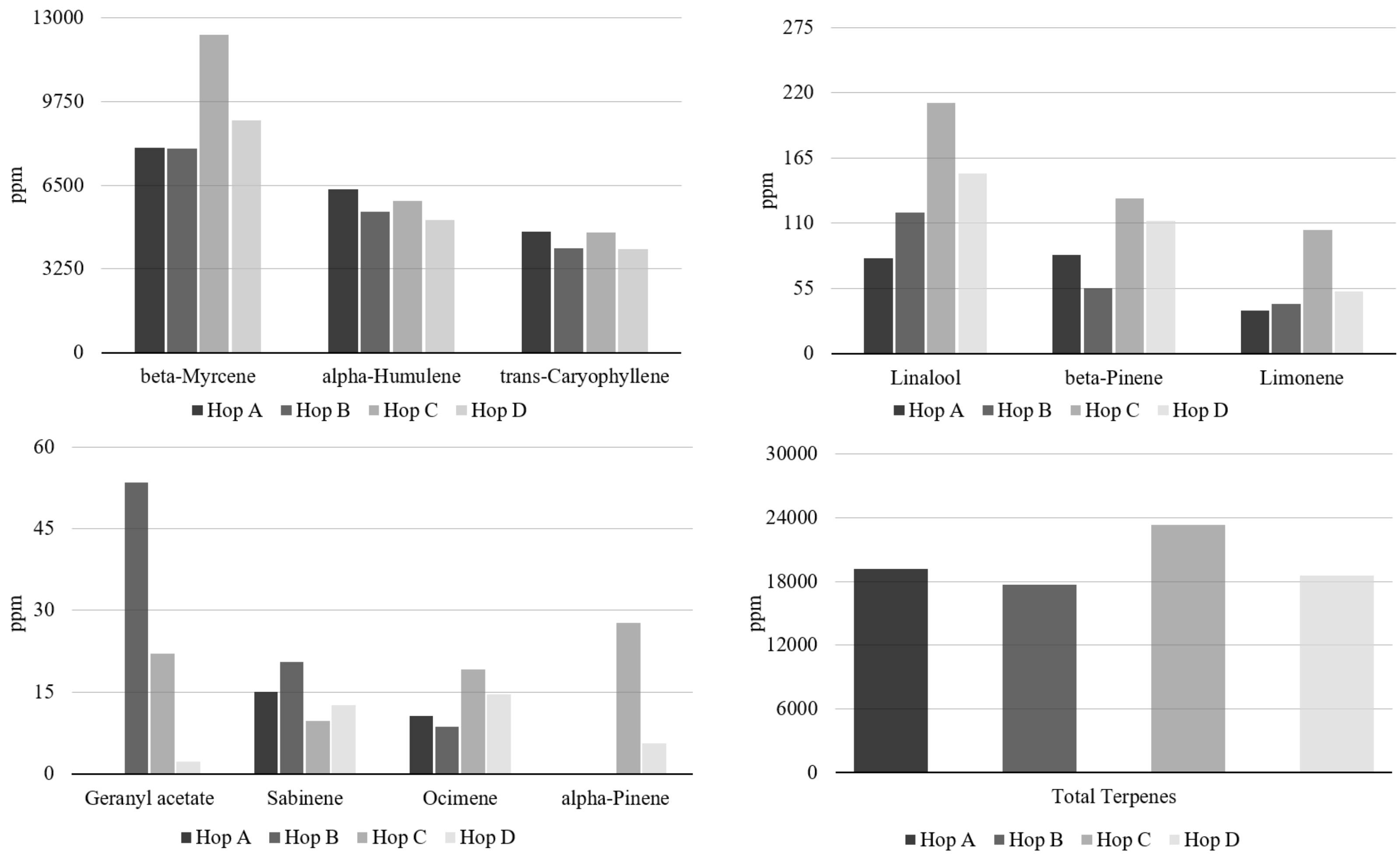

Figure 2. Relative concentration of ten terpenes in four Chinook hop samples

Appendix: Unknowns Analysis

We conduct an unknowns analysis to better understand hop terroir. To search for and characterize additional unknown compounds, hop samples were analyzed on headspace GC/MS using a solventless full evaporative technique. The early eluting mass spectra (8.5-20 mins) was extracted and searched against a NIST library of GC/MS spectra (National Institute of Standards, 2020).

While hundreds of compounds were identified in the unknowns analysis showing the complexity of hop volatiles, very simply the method is indicative of a unique chemical fingerprint which defines the terroir we perceive in sensory analysis. In other words, the unknowns analysis can show us whether variation exists in the samples without being able to directly explain what the complexity of these differences contribute to our olfactory perception. The results to the unknowns analysis for the four hops samples are presented in Figure 1. The *x-axis* shows elapsed time from 8.5 to 20 minutes, and the y-axis measures counts, or relative presence of a given unknown compound.

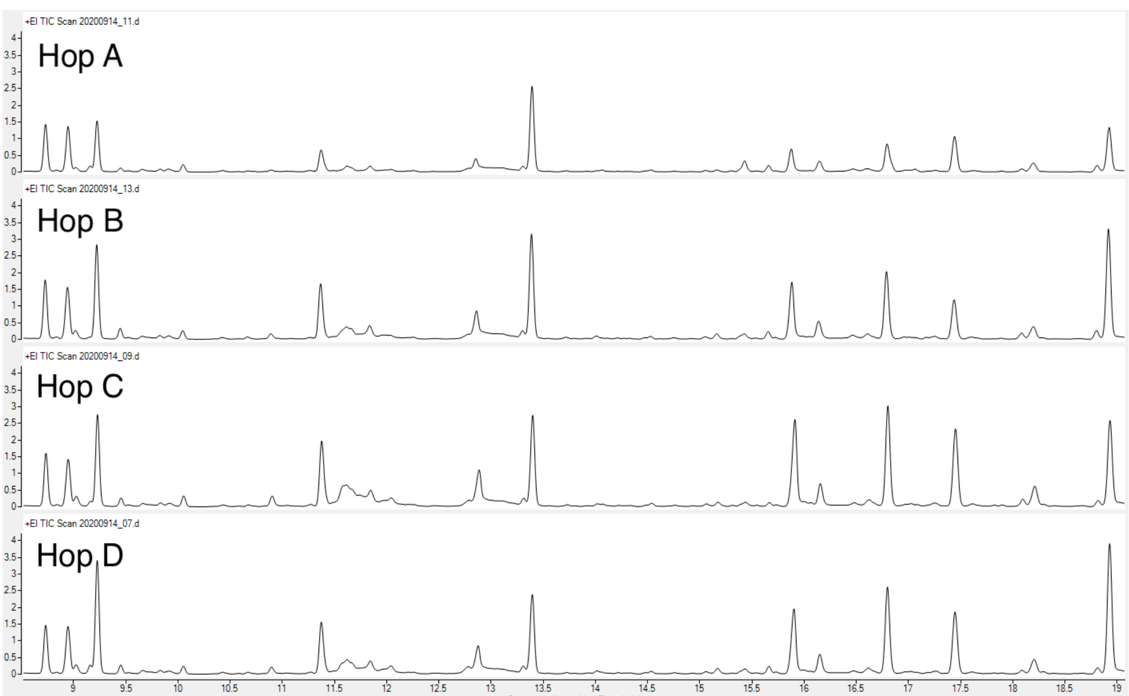

Figure 1. GC/MS chromatogram of early eluting volatile compounds from four Chinook hop samples.

Differing peak heights of these unknown compounds give an analytical representation of the variability of the chemical makeup. This variability, or hop aroma fingerprint, is attributed to the terroir effect of growing the same variety in different locations. To see the variability in the hop aroma fingerprints, we would like to specifically bring attention to peaks at time: 9.25 minutes, 15.75 to 16 minutes, and 19 minutes. Across panels, we see significant variation amongst unknowns counts for the hop samples.

For example, consider the peak 19 minutes into the unknowns analysis. According to the NIST library, this is likely the peak for methyl butyrate, an ester with a pineapple aroma (NIST GC/MS Library, 2017). Figure 2 magnifies the chromatogram around this peak and overlays the four hop samples. We see significant variation among the four hop samples, where Hop B peaks slightly earlier than the other hop samples, and Hop D has the largest count overall.

It is critical for us to note that although Hop D has the highest peak, it does not necessarily imply that it should have the largest overall pineapple aroma. Methyl butyrate is just one of the many esters contributing to a tropical fruit aroma, and it is not just the presence of one ester that matters, but the presence relative to all other components that form our perception of that aroma.

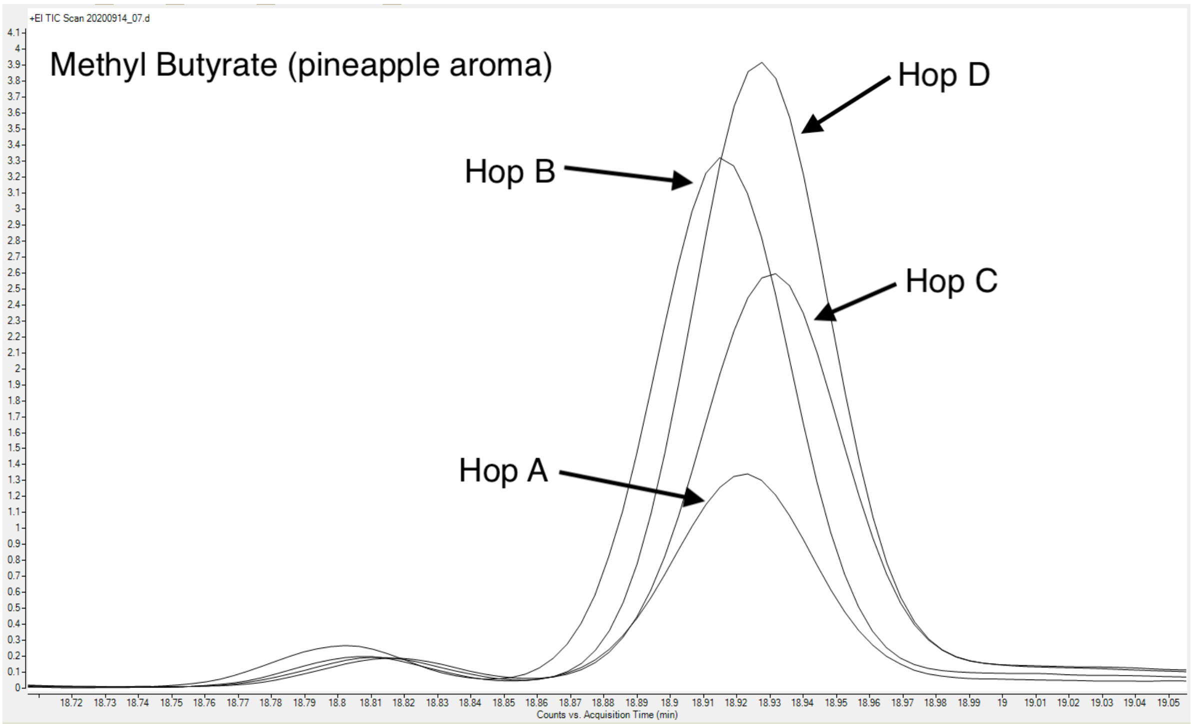

Figure 2. The likely methyl butyrate peak for each hop sample

Appendix References

National Institute of Standards and Technology (n.d.). Libraries, tools, and services. *Mass Spectrometry Data Center of U.S. Department of Commerce*. Available at: https://chemdata.nist.gov/