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The Effects of Residue Tolerance on Pesticide Use, Hop Marketing and Social Welfare

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ABSTRACT

Pesticide use can mitigate production risks from pest and disease infestations. However, intensive pesticide use may result in large amount of pesticide residues, causing hop-quality damages and raising food safety issues. Pesticide use also leads to sizable negative ecological and environmental externalities. In respond to food safety and other socio-economic issues, policy makers, such as national governments and international organizations, pursue low pesticide residues by implementing tolerance which permits only a maximum concentration of agrichemical residues. This paper examines the social-economic impacts of the residue tolerance. To this end, a four-stage game theoretic model is outlined to characterize the stylized attributes of both domestic hop production and marketing. The model highlights the strategic interactions between hop growers, hop merchant and the government. Multiple market equilibria are characterized. The analysis contributes to a better understanding of social welfare which accommodates the environmental externalities of pesticide use. Simulations are conducted based on hop production information in the Pacific Northwest of the United States.

Keywords: Expected utility, hop production, input decision, production risk, social welfare.

1. INTRODUCTION

The majority of hop productions are concentrated in the Pacific Northwest region of the United States. Table 1 provides information for 3 leading hop production states: Washington, Idaho and Oregon. It should be noted that very few hops are produced for the spot market each year. In fact, on average over 90% of the hops are produced through forward contracted (Press: Hop Growers of Washington, 2008). Data indicates the year 2009 has the highest hop yield for all three states. Furthermore, Washington State's hop production has dominated the other two states' production over time. In 2008 for example, Washington State produced a total of 63,392 (1000 lbs.), accounting for 75% of the US commercial hop's production. In comparison, Oregon and Idaho accounted for 15.5% and 9.5% respectively.

TABLE 1. U.S. Hop Production, Rate of Pesticides Use and Residues by States, 2008-2014

	Area Harvested (acres)	Yield/Acre (lbs.)	Production (1000 lbs.)	Price/lbs. ($)
Idaho				
2008	3,933	1,841	7,239.8	4.00
2009	4,030	1,943	7,829.1	3.75
2010	2,331	2,129	4,962.6	3.30
2011	2,265	2,408	5,454.1	2.93
2012	2,423	1,745	4,227.6	2.69
2013	3,376	1,741	5,876.0	2.64
2014	3,743	1,847	6,913.8	2.75
Oregon				
2008	6,370	1,569	9,997.6	3.75
2009	6,108	1,948	11,896.7	3.63
2010	4,622	1,791	8,277.6	3.78
2011	4,202	1,908	8,019.4	3.79
2012	4,470	1,885	8,425.3	3.91
2013	4,786	1,786	8,549.1	3.68
2014	5,410	1,520	8,221.0	4.34
Washington				
2008	30,595	2,072	63,392.7	4.08
2009	29,588	2,533	74,952.1	3.54
2010	24,336	2,147	52,252.4	3.08
2011	23,320	2,200	51,308.1	3.06
2012	25,040	1,941	48,596.3	3.10
2013	27,062	2,029	54,918.8	3.68
2014	38,011	1,868	70,995.9	3.83

Source: National Hop Report-National Agricultural Statistics Service (NASS)

Hop growers face a substantial degree of production risk from pest/disease infestation. Possibly the most common pest infestations in hop production are two-spotted spider mite and powdery mildew. A notable example is the two-spotted spider mite (TSSM) injury in the 1998 production season, which was reported that some growers experienced as high as 60% reduction in yield. As a consequence, the overall Washington production was down an average of 10% (*Crop Profile for Hops in Washington, 2001*). Varied types of agrichemical inputs are applied each year to mitigate such pest damages. Table 2 provides national fungicide and herbicide usage for hop production in the United States. Information on several other selected crops, such as almond, cotton and tomato, are also provided for comparison. For example, the national fungicide use in hop production are 96,100 lbs. ai, 2,216,210 lbs. ai and 229,476 lbs. ai in 1992, 1997 and 2002, respectively. Table 2 also provides information on the values of maximum residue limits (MRLs) for different crops. The MRLs are presented as examples of residue tolerances. The data were collected from the Global MRL Database. As values of MRL usually depend on agrichemical types, information are provided on Phosphine as an example. The MRL for hops is 0.01 ppm, and it is 0.1ppm for both almonds and cotton.

TABLE 2. U.S. National Pesticides Use and the Maximum Residue Limits (MRL), by Crop, 1992, 1997, 2002

Commodity		Fungicides (lbs. ai)	Herbicides (lbs. ai)	MRLs-Phosphine (ppm)
Hops				0.01
	1992	96,100	29,112	
	1997	2,216,210	71,363	
	2002	229,476	28,645	
Almonds				0.1
	1992	3,080,204	978,650	
	1997	2,543,851	1,229,246	
	2002	1,793,341	1,342,773	
Cotton				0.1
	1992	2,117,635	29,419,214	
	1997	1,007,776	32,775,095	
	2002	977,108	21,784,568	
Tomatoes				0.01
	1992	8,763,772	676,980	
	1997	10,311,547	684,446	
	2002	10,311,723	520,920	

Source: National Pesticide Use Database (2002), Global MRL Database, Report: Pesticide use in the U.S. Crop production: 2002 with comparison to 1992&1997- Crop Protection Research Institute (CPRI).

Note: ‘ai’ denotes active ingredient.

Pesticide use with correct type and appropriate timing can mitigate hop production risks, such as seasonal spider mite and powdery mildew infestations (Gent et al., 2014; Campbell and Lilley, 1999; Woods et al., 2012). Overly sprayed pesticides, however, could lead to residue accumulation, inducing adverse agricultural consequences including hop-quality damages, food safety threats and pesticide resistance (Baker and Crosbie, 1993; Eom, 1994; Buzby et al., 1995; Wilson and Otsuki, 2004). Moreover, the negative ecological and environmental spillover effects of pesticide use have also been great considerations (Skevas et al., 2012, 2013). It has established that most of the sprayed pesticides will diffuse into environments, contaminating water, atmosphere (Pimentel, 1995; Ghimire and Woodward, 2013) and posing health hazards (Pingali et al., 1994; Athukorala et al. 2012; Okello and Swinton, 2010). Thus, understanding the farm-level pesticide adoption decision is of critical importance, given the social-economic and environmental impacts.

Pesticide residue tolerance is commonly stipulated as general marketing criteria and primarily trading standard (e.g., the maximum residue limits, MRLs).[1] Permitting only a maximum concentration of agrichemical residues on hops at various production and marketing stages may largely affect growers' pesticide input decisions. For example, growers are likely to be more prudential about pesticide use in response to a stringent residue tolerance, thereby adopting a less pesticide-intensive management system. If this was the case, stringent tolerance should be indispensable to reduce farm-level pesticide use, bringing environmental and human-health benefits. Previous studies have identified farm-level behaviors, such as enhancing the pesticide use efficiency (Pimentel, 1995), selecting pesticide resistance varieties (Grogan and Mosquera, 2015), utilizing the integrated pest management (IPM) (Greene et al. 1985; Hall and Duncan, 1984; Mullen et al., 1997; McNamara et al.,1991; Hurd,1994; Cornejo et al., 1994; McDonald, 1994; Shennan, 2001; Kovach and Tette, 1988) and innovating production technologies (Abedullah et al. 2015), as primarily causes of pesticide reduction. Few studies, however, have examined the effects of food policies, such as the residue tolerance implementation, on farm-level pesticide decisions. Lichtenberg (1997) has showed that stricter quality standards (e.g., grading standards) for agricultural products are likely to reduce pesticide use. This paper, in the context of hop production,

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[1] MRLs are specified by the central government and relevant organizations, applied in both domestic and international trade, and are heterogeneous across countries and regions.

intents to bridges the gaps by outlying game theoretic models that allow policy makers, while attempting to pursue the environmental and social-welfare benefits, to impose residue tolerance in a contracted hop market.

Whereas residue tolerance seems to be social-economically indispensable, an exceedingly imposed tolerance may simply not be attainable for hop marketing. The majority of hops produced in the U.S. are through forward contract. Contracted hops, upon harvest, are delivered by growers to hop merchants, and sold to the brewing industry. Consequently, quality criteria plays a crucial role as hops move from the production to the marketing sector. Previously studies have realized that imposing quality standards could raise the qualities consumed (Ronnen, 1991) and lead to social welfare gains under certain economic circumstances (Leland, 1979; Shapiro, 1983; Bockstael, 1984). This study takes the pesticide residue tolerance as a primarily marketing standard for hops quality. Hop rejection may result if, by chemical inspection, the pesticide residues exceed the tolerance. Clearly, a loosely imposed tolerance may not be effective for food safety; conversely, a superimposed one could result in an uncovered contracted hop market due to lack of qualified hops. This study posits that the residue tolerance should be effective imposed for food safety consideration while still be attainable for most hops. While the quality standard is narrowly construed, which excludes many other important hop-quality attributes, the analysis may not apply to number of realistic cases but serves primarily as an initial assessment.

This study outlines a game theoretic approach that comprises of four agricultural market stages, capturing the stylized attributes of both domestic hop production and marketing. Specifically, the model lays out the government stage, the contract stage, the production stage and the transaction stage. Equilibrium is characterized in the sense of backward induction. Game theoretic framework has been commonly applied for various economic topics. For example, Lapan and Moschini (2007) presented a model of three market stages between the consumers, producers and the government to investigate the effects of genetically modified (GM) labeling on agricultural markets. Spulber (2012) developed a three-stage strategic innovation game between an inventor and an existing firm examining the effects of tacit knowledge on investment decisions. Lester (2011) developed a two-stage model of consumer’s ex-ante information and prices setting, by which he observed that increasing the fraction of informed buyers in a market may have an ambiguous effect on prices. This study outlines a four-stage model that comprises of following elements: (i) heterogeneous hop growers; (ii) a hop merchant in the contracted hop market, who purchases hops from growers and sells to brewers; and (iii) a government which identifies the optimal pesticide residue tolerance. The model characterizes the economic interactions among aforementioned participators throughout hop production and marketing stages. The analysis contributes to a better understanding of social welfare implications regarding the environmental externalities of pesticide use.

The structure of the paper is as follows. Section 2 theoretically outlines a representative hop grower's input decision in the production stage. Section 3 characterizes the hop market and section 4 describes the government problem. Equilibrium outcomes are characterized and are also compared. The paper ends with concluding remarks and discussions in Section 5.

2. THEORETICAL FRAMEWORK

The economic environment is twofold: First, hops are grown stochastically. Production disturbances come from pest and disease infestations, such as seasonal spider mite and powdery mildew hits. Thus bivariate outputs are random, consisting of hop yield y and pesticide residue s. Pesticide residue level, in the context of this study, is emphasized as hop-quality attribute among others (e.g., hops' mature level, moisture level). Second, there is a market for contracted hops. Because the majority of hops are produced through multi-year forward contract with very few produced for the spot market, most transactions take place in contracted hop market, in which growers deliver the contracted hops to the merchant. Whether or not the merchant will accept the delivery depends on descriptive hop-quality attributes. Thus a large amount of pesticide residues may cause rejection.

Four market stages are laid out to capture the features of hop production and marketing. The model is developed on the timeline of a growing season. The theoretical framework characterizes the strategic interactions between hop growers, a hop merchant and the government. In the first stage the government imposes a pesticide residue tolerance $\bar{s}$. The value of $\bar{s}$ can be thought as general marketing criteria for hops' quality or primarily trading standards (i.e., MRLs). It takes the simple form of a scalar. For example, the 0.01 ppm MRLs discussed earlier would be equivalent to $\bar{s} = 0.01$ in the model. While the tolerance level is often jointly determined by domestic and international organizations including Environmental Protection Agency (EPA), Food and Agriculture Organization (FAO) and World Health Organization (WHO), in what follows it presumes that, in general, a national (international) authority implements the residue tolerance.

The second-stage model characterizes market level interactions, namely the contract stage. In the contracted hop market, a hop merchant determines a multi-year forward contract comprising of a fixed hop price per pound ($\overline{p}$) and purchase quantity ($\overline{y}$). The purchase quantity is also known as contract size. While values of both variables should depend on hop aroma varieties, the model simply presumes a uniformly designed contract. The setting allows both variables to be deterministic, which are ‘locked in’ when the contract is issued.

The third stage is the production stage. Before production starts heterogeneous hop growers choose pesticide inputs. Agrichemical pesticides are assumed to be the only factor of production, which is a vector of fungicides, pesticides and miticides etc., $x=\left(x_1,...x_m\right)$. Thus the intensity of pesticide use can be reflected by hop growers' decision on the level of x. When x is a null one may expect that growers use only biological based inputs and practices. The ‘organic’ hop production system can serve as an example of this case where hops are grown with no synthetic pesticides or chemical fertilizers. On the contrary, the conventional pest management method uses chemicals as the main pest control agents.

Both agricultural outputs are realized before the final stage, the transaction stage. In this stage the merchant chemically inspects pesticide residues upon hop delivery. The merchant rejects the contracted hops if the amount of the remained residues exceed the tolerance.

Optimal outcomes are obtained throughout the marketing and production stages. Working backwards, one may first look at growers’ optimal decisions. Growers maximize expected utility over the production stage by deciding pesticide input rate. In the upstream contract stage, the profit-maximizing merchant determines contracted hop price and quantity. Subgame perfect equilibrium emerges in this stage, namely the contract-stage equilibrium, in which both hop growers and merchant make their best commitments. In the first stage, the government maximizes the social welfare by optimally imposing the residue tolerance, which internalizes the adverse environmental externalities of pesticide use.

2.1 Hop Production

Stochastic production is modelled following the conceptual framework in Babcock and Hennessy (1996), where they estimated the corn yield distribution as a beta density function of nitrogen fertilizer input. So it assumes the hop yield (y) and pesticide residue (s) follow a bivariate distribution given pesticide inputs. And let $f_i\left(y_i, s_i \mid x_i\right)$ be the probability density function for grower *i*, which is differentiable in pesticide input x_i.

Previous studies have conceptually modelled crop yield using parametric distributions, such as beta distribution (Nelson and Preckel, 1989; Tirupattur, Hauser and Chaherli, 1996) and log-normal distribution (Jung and Ramezani, 1999). By using the moment-ratio diagrams, Sherrick et al. (2004) has evaluated a number of corn yield distributions including Normal, Beta, lognormal, Logistic and Weibull. Antle (2009) further tested the underlying assumption that agricultural output distributions are members of scale and location-scale families. Developmentally, Tolhurst and Ker (2015) proposed a mixture normal distribution for crop yields which embedded trend functions over time. Bivariate distribution specification, as proposed in this study, allows one to capture the simultaneous effects of pesticides on both hop yield and residue. For example, one may reasonably expect that intensively pesticide use beneficially reduces yield variability but adversely increases the residues at the same time. In the simulation study (Appendix C), the hop yield and residue are generated from bivariate normal distribution based on the U.S. hop production information.

2.2 The Representative Hop Grower

The population of hop growers are heterogeneously distributed across a continuum of types, where each type could represent the productivity. This section examines the optimal pesticide choice of a representative grower.

At the beginning of the production stage, the hop grower decides the optimal amount of pesticides to spray. In this stage, he takes as given the government-set residue tolerance $\bar{s}$. In the context of domestic production, the value of $\bar{s}$ can be thought as general marketing criteria for hops' quality. So hop delivery, while upon completion of production, is accepted if the realized residues are below $\bar{s}$. If delivery is rejected due to large residues, current paper assumes the grower can still deliver hops at a downgraded price in a secondary market. As suggested by Bockstael (1984), allowing the existence of secondary market for diverted products can improve the market efficiencies by providing potential returns to producers and permitting lower price to consumers. Therefore the grower negotiates a secondary-market price $\hat{p}$, which is decreasing in residue, $d\hat{p} / ds < 0$, i.e., lower price due to larger residues.[2]

Let w be the price vector for pesticides. Then if $s \leq \bar{s}$, the grower supplies hops primarily in the contracted hop market, deriving utility from deterministic profits $\pi_1 = \bar{p} \cdot \bar{y} - w \cdot x$. Otherwise he supplies hops in the alternative secondary-market, deriving utility from profits $\pi_2 = \hat{p}(s) \cdot y - w \cdot x$.

The following model describes grower *i*'s input decision at the beginning of a growing season. In this case he must take the expectation over the production period. Given some positive value of government-set tolerance $\bar{s}$, the contracted hop price $\bar{p}$ and quantity $\bar{y}$, he employs pesticides which maximizes the expected utility given by:

$$\max_x U_i = \max_x \int_0^a \int_0^{\bar{s}} u_i\left(\pi_{i1}\right) f_i\left(y_i, s_i \mid x_i\right) ds_i dy_i + \int_0^a \int_{\bar{s}}^b u_i\left(\pi_{i2}\right) f_i\left(y_i, s_i \mid x_i\right) ds_i dy_i. \quad (1)$$

The grower's risk preference is represented by the von Neumann-Morgenstern utility function $u(\cdot)$. In addition $u' > 0, u'' < 0$ for risk averse (Pratt, 1964). Setting up utility rather than profit as grower's objective largely because hop growers are viewed as individual decision makers rather than financial entities. Also it is of interest to identify a different objective distinguishing from a profit-motivated hop merchant. In addition, utility function accounts for risk aversion which may be more suitable given the production risks. In eq. (1) the expectation is taken over both random yield and pesticide residue. The first term is the expected utility over values of s that are below the government-set tolerance $\bar{s}$. The second term is the expected utility over values of s that are exceeding $\bar{s}$. It thus describes that the grower derives utility from contracted profits if residues meet the tolerance, and from secondary-market profits otherwise. The integration is calculated above zero for both (y, s) to ensure no nonnegativity agricultural outcomes.

The optimal level of pesticides x^* solves the first order condition $\frac{\partial U_i}{\partial x_i} = 0$:

$$\int_0^a \int_0^{\bar{s}} u\left(\pi_1\right) \frac{\partial f\left(y, s \mid x^*\right)}{\partial x^*} dsdy + \int_0^a \int_{\bar{s}}^b u\left(\pi_2\right) \frac{\partial f\left(y, s \mid x^*\right)}{\partial x^*} dsdy$$

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[2] Many may argue that questions on food safety are raised if hops can still be sold in this case. Current analysis theoretically posits that for some range of residues hops can still be sold rather than wasted in fields. Since the information on the downgraded price is unavailable for this study, it is modeled conceptually as a decreasing function of pesticide residues.

$$-w \cdot \left[\int_0^a \int_0^{\bar{s}} u'(\pi_1)\, f\left(y,s \mid x^*\right) dsdy + \int_0^a \int_{\bar{s}}^b u'(\pi_2)\, f\left(y,s \mid x^*\right) dsdy \right] = 0. \qquad (2)$$

The subscript *i* denoting the grower is omitted for convenience. The first line in eqn. (2) captures the overall effects of pesticides on the joint density ($\frac{\partial f\,(y,s \mid x)}{\partial x}$). The second line represents the cost effects of an increased pesticide. Thus when eqn. (2) holds, the effects of an increased pesticide on crop distribution must equal the increased production expenses. Solving eqn. (2) yields the optimal level of pesticides x_i^*. The grower's maximal expected utility is obtained at x_i^*, which is given by,

$$U_i = \int_0^a \int_0^{\bar{s}} u_i\left(\pi_{i1}\left(x_i^*\right)\right) f_i\left(y_i, s_i \mid x_i^*\right) ds_i dy_i + \int_0^a \int_{\bar{s}}^b u_i\left(\pi_{i2}\left(x_i^*\right)\right) f_i\left(y_i, s_i \mid x_i^*\right) ds_i dy_i. \qquad (3)$$

Eqn. (3) outlines the maximal expected utility when the grower optimally sprays pesticides. At x^*, the resulting distribution is $f\left(y,s \mid x^*\right)$. The contracted profits and secondary-market profits are $\pi_1\left(x^*\right)$ and $\pi_2\left(x^*\right)$, respectively.

The detailed proof of the second order condition is provided in Appendix A. A sufficient condition for the second order derivative to be negative is $\frac{\partial f\,(y,s \mid x)}{\partial x} > 0$, i.e., the overall effect on the joint distribution is positive. In this case the optimal pesticide decision satisfies the requirement to be local maximum. For the purpose of analysis, in what follows it is convenient to assume $\frac{\partial f\,(y,s \mid x)}{\partial x} > 0$, such that the second order condition is satisfied. This assumption allows for analytical simplifications in a number of ways, with intuitive interpretations. For example, one could consider a simple case when pesticides do not contribute directly to hop yield. Thus an increase in pesticides lead to an overall positive effect if it only increases the concentration of residues. On the other side, whereas the assumption provides analytical convenience, it should be noted that, in fact, the term $\frac{\partial f\,(y,s \mid x)}{\partial x}$ accounts for more complex effects. For example, early work portrayed the direct pesticides' contribution to crop yields by damage abatement function (Lichtenberg and Zilberman, 1986). However, such input effects cannot be empirically quantified without further data information. Antecedent includes Babcock and Hennessy (1996), who have parameterized corn yield as beta distribution and empirically estimated the effects of nitrogen fertilizer on yield distribution. Further, partial-moment functions, proposed by Antle (2010), allow one to characterize asymmetric effects of input on higher moments of output distributions. Input effects can also be examined by J-P production function (Just and Pope, 1979) which empirically estimated mean and variance (risk) as separated functions of inputs. Review of extensive empirical literature in this theoretical branch include Asche and Tveteras (1999), Isik and Khanna (2003), Eggert and Tveteras (2004) and Falco and Chavas (2009).

Therefore, it is of interest to look at a particular case when yield and residue are independent. It then allows one to look at the effects of pesticides on each marginal distribution. Let $g(y \mid x)$ and $h(s|x)$ denote the conditional marginal densities. Further assume $\int_{-\infty}^{\infty} yg(y|x)dy<\infty, \int_{-\infty}^{\infty} sh(s|x)ds<\infty$ for existence of the expectation and to avoid the possibility of infinity. Specifically, the term $\frac{\partial f(y,s|x)}{\partial x}$, which represents the pesticides' effects on the joint distribution, can be decomposed as

$$\frac{\partial f(y,s|x)}{\partial x}=\frac{\partial g(y|x)}{\partial x}h(s|x)+\frac{\partial h(s|x)}{\partial x}g(y|x). \tag{4}$$

Eqn. (4) breaks down the overall effects into effects on the marginal yield distribution, $\frac{\partial g(y|x)}{\partial x}$, and on the marginal pesticide distribution, $\frac{\partial h(s|x)}{\partial x}$. While pesticide use is likely to reduce the production variability, i.e., reducing the variance of yield distribution, which is risk-decreasing (Antle, 2010), one may reasonably expect that pesticide use also has a negative effect by increasing residue concentration.

Thus by eqn. (4) the FOC becomes,

$$\begin{aligned}&\int_0^a\int_0^{\bar{s}} u(\pi_1)\left[\frac{\partial g(y|x^*)}{\partial x^*}h(s|x^*)+\frac{\partial h(s|x^*)}{\partial x^*}g(y|x^*)\right]dsdy\\&\quad+\int_0^a\int_{\bar{s}}^b u(\pi_2)\left[\frac{\partial g(y|x^*)}{\partial x^*}h(s|x^*)+\frac{\partial h(s|x^*)}{\partial x^*}g(y|x^*)\right]dsdy\\&\qquad-w\cdot\left[\int_0^a\int_0^{\bar{s}} u'(\pi_1)g(y|x^*)h(s|x^*)dsdy+\int_0^a\int_{\bar{s}}^b u'(\pi_2)g(y|x^*)h(s|x^*)dsdy\right]=0. \quad (5)\end{aligned}$$

If pesticides only reduce yield variability (risk) but have no effect on residue (i.e., $\frac{\partial h(s|x)}{\partial x}=0$), eqn.(5) predicts that the optimal pesticide use is determined when the decreased production risks equal the increased costs. This trade-off between production risks and expenses, while interestingly consistent with prevailing consensus in plant pathology studies, justifies that the grower is likely to tolerance more production risks for a lower production expenses.

The grower in the production stage, while taking as exogenously given the government-set tolerance $\bar{s}$ and hop forward contract terms $\bar{y}$ and $\bar{p}$, optimally employs pesticides $x^*\left(\bar{s},\bar{y},\bar{p}\right)$ solving the F.O.C. By conducting comparative static analysis one can obtain,

$$\frac{dx^*}{d\bar{y}}=-\Delta^{-1}\bar{p}\left[\int_0^a\int_0^{\bar{s}}u'(\pi_1)\left[\frac{\partial g\left(y\,|\,x^*\right)}{\partial x^*}h\left(s\,|\,x^*\right)+\frac{\partial h\left(s\,|\,x^*\right)}{\partial x^*}g\left(y\,|\,x^*\right)\right]dsdy\right.$$
$$\left.-w\cdot\int_0^a\int_0^{\bar{s}}u''(\pi_1)\,g\left(y\,|\,x^*\right)h\left(s\,|\,x^*\right)dsdy\right],\tag{6}$$

$$\frac{dx^*}{d\bar{p}}=-\Delta^{-1}\bar{y}\left[\int_0^a\int_0^{\bar{s}}u'(\pi_1)\left[\frac{\partial g\left(y\,|\,x^*\right)}{\partial x^*}h\left(s\,|\,x^*\right)+\frac{\partial h\left(s\,|\,x^*\right)}{\partial x^*}g\left(y\,|\,x^*\right)\right]dsdy\right.$$
$$\left.-w\cdot\int_0^a\int_0^{\bar{s}}u''(\pi_1)\,g\left(y\,|\,x^*\right)h\left(s\,|\,x^*\right)dsdy\right],\tag{7}$$

$$\frac{dx^*}{d\bar{s}}=-\Delta^{-1}\left[\int_0^a\left[u(\pi_1)-u(\hat{\pi}_2)\right]\left[\frac{\partial g\left(y\,|\,x^*\right)}{\partial x}h\left(\bar{s}\,|\,x^*\right)+\frac{\partial h\left(\bar{s}\,|\,x^*\right)}{\partial x}g\left(y\,|\,x^*\right)\right]dy\right.$$
$$\left.-w\cdot\int_0^a\left[u'(\pi_1)-u'(\hat{\pi}_2)\right]\cdot h\left(\bar{s}\,|\,x^*\right)\cdot g\left(y\,|\,x^*\right)dy\right].\tag{8}$$

In eqn. (6)-(8) Δ is the second order condition. By earlier assumption (i.e., $\frac{\partial f\ (y,s\,|\,x)}{\partial x}>0$) $\Delta<0$. In this case and by eqn. (4), eqn. (6) and (7) are both positive. These conditions imply that, as either contracted hop price or size increases, the optimal level of pesticide use increases. For instance, larger forward hop transaction may provide incentives for more frequent pesticide applications, on the purpose of reducing pest damages. The detailed proofs of eqn. (8) are provided in the Appendix B, the key idea is to utilize the Leibniz's integral rule. Thus $\hat{\pi}_2=\hat{p}(\bar{s})\cdot y-w\cdot x$ is the secondary-market profit when the remained residue level is $\bar{s}$. And $h(\bar{s}\,|\,x)$ is the degenerate distribution when S takes the single value of $\bar{s}$. While a positive sign of eqn. (8) predicts less pesticide use when $\bar{s}$ is more stringent, unfortunately it cannot be unambiguously signed. The sign, however, depends on a number of factors including the degenerate distributions, pesticides' effects and the profit gap, among others.

To summarize, this section outlined a representative hop grower's pesticide input decision at the production stage. The optimal pesticide input x_i^* was determined where the effects on crop distribution equal the increased production expenses of an increased pesticide. Further, when hop yield and residue are independent, the optimal pesticide use can be pinned down when the decreased production risks equal the increased costs. Whereas permitting a residue tolerance may largely affect growers' pesticide input decisions, following sections provide analysis on optimal economic outcomes when the tolerance is set at polar values.

2.3 The Impact of Residue Tolerance

The analysis on $\bar{s} = 0$ is provided as a benchmark. It is of broad interest to glean insights from evaluating farm-level pesticide input decisions when residue tolerance is superimposed. If the tolerance permits absolutely no pesticide residue, hops are likely to be grown by less pesticide-intensive methods. If growers response by solely adopting biological based pest control methods rather than any agrichemicals, the production management system is organic. In fact, in the U.S., based on brewery demand, some varieties are grown organically without synthetic pesticides or chemical fertilizers. Implementing a tolerance stipulating absolutely no residue, on the other side, is unlikely to be attainable and feasible for domestic marketing or international trade, as few hops can be qualified for the residue inspection and supplied in the contracted hop market.

Consider grower's objective function in eqn. (1). When $\bar{s} = 0$, the first integral from 0 to $\bar{s}$ is cancelled out so the optimality problem reduces to,

$$\max_x U_i = \max_x \int_0^a \int_0^b u_i\left(\pi_{i2}\right) f_i\left(y_i, s_i \mid x_i\right) ds_i dy_i. \tag{9}$$

In eqn. (9), the grower makes up his mind on the pesticide use by maximizing expected utility in the secondary market. Largely because the government-imposed tolerance now is too strict to be meet as quality criteria, few hops are likely to be qualified for the residue inspection and can be supplied in the contracted hop market. Consequently, growers supply hops in the alternative secondary market, if there is no regulative barriers between markets.

The FOC reduces to

$$\int_0^a \int_0^b u\left(\pi_2\left(x^b\right)\right) \frac{\partial f\left(y, s \mid x^b\right)}{\partial x^b} dsdy \ - w \cdot \int_0^a \int_0^b u'\left(\pi_2\left(x^b\right)\right) f\left(y, s \mid x^b\right) dsdy = 0. \qquad (10)$$

The subscript *i* denoting the grower is omitted for convenience. The optimal rate of pesticides x^b (superscript 'b' may denote 'baseline') solves eqn. (10).

The optimal pesticide use is always lower when $\bar{s} = 0$ than that when $\bar{s}$ takes some positive value. Imposing an extremely strict tolerance leads to pesticide reduction. Less pesticide-intensive pest control can always be achieved by utilizing integrated pest management (IPM) practices including scouting, crop debris and maintain basal foliage. An early study, conducted by Kovach and Tette (1988), found that the New York apple growers who utilized comprehensive IPM practices used 30% less insecticides, 47% less miticides and 10% less fungicides than growers who did not. From sustainability prospective, sizeable ecological and social-economic benefits, such as environmental improvements and human health risk reductions, are obtained by less agrichemical inputs.

When $\bar{s} = 0$ the grower sprays optimal pesticides x^b and derives the expected utility in the secondary market,

$$U_i\left(x_i^b\right) = \int_0^a \int_0^b u_i\left(\pi_{i2}\left(x_i^b\right)\right) f_i\left(y_i, s_i \mid x_i^b\right) ds_i dy_i. \qquad (11)$$

Eqn. (11) outlines the expected utility when the grower optimally employs pesticides x^b. In this case, the resulting crop distribution is $f\left(y, s \mid x^b\right)$ and the secondary-market profits are $\pi_2\left(x^b\right)$.

Possibly few hops are expected to be qualified for the residue inspection in the contracted hop market if, in an extreme case, the tolerance is superimposed. Consequently, growers have to supply hops in alternative secondary market. In Lapan and Moschini (2007), the agricultural market was referred to as 'covered' if, at a particular price, the supply was at least equal to the maximum demand. In this sense, due to the lack of qualified hops, the contracted hop market with an exceedingly imposed residue criteria is unlikely to be covered. Conversely, if the imposed tolerance is sufficiently loose, all hops are expected to be qualified. The tolerance in this case, however, may not be an effective food safety standard. Next section presents analysis on optimal economic outcomes.

While an extremely stringent tolerance may not be feasible for domestic marketing sector, a loosely imposed tolerance may not be effective for food safety inspection. Therefore, a tolerance can serve as an efficient quality standard only if it is set in some reasonable interval.

First consider the case when residue tolerance $\bar{s} = b$, where b is the upper bound of pesticide residues. Then the grower's optimality problem in eqn. (1) reduces to,

$$\max_x U_i = \max_x \int_0^a \int_0^b u_i(\pi_{i1}) f_i(y_i, s_i \mid x_i)\, ds_i dy_i. \tag{12}$$

Eqn. (15) outlines that the grower derives expected utility in the contracted hop market given the government-set tolerance $\bar{s} = b$. The objective function is comparable to eqn. (9), but differs that in this case the grower derives expected utility from deterministic contracted profits π_1. For sufficiently loose tolerance all hops are expected to be supplied in the contracted hop market rather than the secondary market.

In general, there exists a sufficiently high residue level above which the imposed tolerance is referred to as sufficiently 'loose'. In this case hops are always expected to be qualified and be delivered by growers in the primary contracted market. For any loosely imposed residue tolerance, hops, during the marketing delivery, would always be qualified for the chemical inspection. Note that it is also possible for $s^{\max} = b$. Then a lax tolerance is $\bar{s} = b$ as specified earlier. As $b \to \infty$, one may also write $\bar{s} \in \left[s^{\max}, \infty\right)$.

Because $s^{\max}$ portrays the maximal amount of residues possibly remaining on hops, it must be $s_i \le s^{\max}$ for all growers. If the residue variables s_i are mutually independent each having distribution $h_i(s_i \mid x_i)$ as specified earlier, the probability of the residues below $s^{\max}$ is $\Pr\left(s_i < s^{\max}\right) = \int_0^{s^{\max}} h_i(s_i \mid x_i)\, ds_i$. Further, the density function of $s^{\max}$, $F\left(s^{\max}\right)$, can be defined as the joint probability of $s_i < s^{\max}$ for all growers, which is $F\left(s^{\max}\right) = \Pr\left(s_1 \le s^{\max}, s_2 \le s^{\max}, \ldots, s_n \le s^{\max}\right)$. Therefore,

$$F\left(s^{\max}\right) = \prod_{i \in \Theta} \int_0^{s^{\max}} h_i(s_i \mid x_i)\, ds_i. \tag{13}$$

For $\bar{s} \in \left[s^{\max}, b\right]$, grower's optimality problem can be written more generally as,

$$\max_x U_i = \max_x \int_0^a \int_0^{\bar{s}} u_i(\pi_{i1}) f_i(y_i, s_i \mid x_i)\, ds_i dy_i. \tag{14}$$

Eqn. (14) outlines that the grower derives expected utility in the contracted hop market when the tolerance is loosely imposed in the interval $\left[s^{\max}, b\right]$. In this case hops are likely to be delivered in the contracted market and growers are able to fulfill the hop contract.

The optimal rate x^m (superscript ‘m’ denote ‘max’) solves the F.O.C.,

$$\int_0^a \int_0^{\bar{s}} u_i\left(\pi_{i1}\right) \frac{\partial f_i\left(y_i, s_i \mid x_i^m\right)}{\partial x_i^m} ds_i dy_i - w \cdot \int_0^a \int_0^{\bar{s}} u_i{}'\left(\pi_{i1}\right) f_i\left(y_i, s_i \mid x_i^m\right) ds_i dy_i = 0. \tag{15}$$

Eqn. (15) determines the optimal pesticide use given a laxly stipulated residue tolerance. Again, it outlines that the effects of an increased pesticide must equal the increased production costs.

At the optimal rate x^m grower obtains the maximal expected utility

$$U_i\left(x_i^m\right) = \int_0^a \int_0^{\bar{s}} u_i\left(\pi_{i1}\left(x_i^m\right)\right) f_i\left(y_i, s_i \mid x_i^m\right) dsdy. \tag{16}$$

Eqn. (16) characterizes the maximal expected utility when the grower optimally sprays pesticides x^m . In this case, the resulting crop bivariate distribution is $f\left(y, s \mid x^m\right)$ and the contracted profit is $\pi_1\left(x^m\right)$.

3. The Hop Merchant

In practice, one grower may contract different hop varieties with multiple merchants. For analytical conveniences the model simply presumes that there is only one profit-motivated merchant in the contracted hop market. Consequently, the merchant can also be viewed as a processor, who buys contracted hops from growers and sells them to brewers. He also inspects contracted hop delivery and stocks hops in the warehouse. In general, he performs all the relevant marketing functions between the government-level and the farm-level.

In this intermediate stage, the merchant determines contracted hop price $\bar{p}$ and quantity (size) $\bar{y}$. These two variables are set uniformly to all hop growers, who are heterogeneously distributed across a continuum of types $\theta_i \in \Theta = \left[\underline{\theta}, \bar{\theta}\right]$. Let $t\left(\theta\right)$ be the probability density function. Here θ can be interpreted as the productivity of hop production which is known by the government, the merchant and growers.

The merchant obtains profits from reselling contracted hops to the brewing industry. Let p be the hop selling price and c be the incurred unit operational costs including storage, chemical inspection and transportations. Thus the merchant’s revenue is $p\bar{y}$ from reselling, and costs are contract payment and operations, $\overline{py} + c\bar{y}$.

The merchant, in the contracted hop market, would maximize profits,

$$\max_{\{\bar{p},\bar{y}\}} \Pi = \max_{\{\bar{p},\bar{y}\}} \int_{\underline{\theta}}^{\bar{\theta}} \bar{y} \cdot [p - \bar{p} - c] t(\theta) d\theta \tag{17}$$

s.t.

$$U(\theta) \geq \bar{U}(\theta), \qquad \forall \theta \in \Theta \tag{18}$$

Eqn. (17) and (18) lay out the merchant's optimality problem in the contracted hop market (Figure 1). The secondary market is not emphasized in merchant's optimality problem as it accounts for small fraction in marketing sector. In eqn. (17) $U(\theta)$ is the grower's production-stage maximal expected utility at the optimal pesticide input x^*. The reservation utility $\bar{U}$ can be derived from agricultural activities, such as land renting, fishing, other than hop production. Without loss of generality it could also be set to zero across all types. Eqn. (18) is the participation constraint (PC) indicating that for all growers the expected utility is at least equals to the reservation utility. Therefore, in the contract stage the hop merchant maximizes profits, subject to the constraint that all growers maintain at least the reservation utility.

In general, assume it is separable across type so that the optimality problem may be conveniently derived for each type. The optimal level of contracted hop price and size solve the Kuhn-Tucker conditions,

$$\frac{d\Pi}{d\bar{p}} = -\bar{y} + \lambda(\theta) \cdot \frac{\partial U(x^*,\theta)}{\partial x^*} \cdot \frac{\partial x^*(\theta)}{\partial \bar{p}} \leq 0, \tag{19}$$

$$\frac{d\Pi}{d\bar{y}} = p - \bar{p} - c + \lambda(\theta) \cdot \frac{\partial U(x^*,\theta)}{\partial x^*} \cdot \frac{\partial x^*(\theta)}{\partial \bar{p}} \leq 0, \tag{20}$$

In eqn. (19) and (20) λ_i is the Lagrange multiplier for each grower. Its value can be interpreted as the shadow price of grower's expected utility. The first term in eqn. (19) represents the marginal profits brought by an increased contracted hop price to the merchant. The second term represents the incentive effect to the hop grower. Similarly, in eqn. (20) the first term represents the marginal profits brought by an increased contracted quantity to the merchant. The second term represents the incentive effect to the hop grower.

The contract-stage equilibrium profits are obtained when the merchant, in the contracted hop market, receives hop deliveries from growers and sells to the brewers. However, possibly no hop delivery can take place in the contracted hop market when, in extreme case, $\bar{s} = 0$.

Superimposing a tolerance as the quality standard can lead to uncovered contracted hop market, as in Lapan and Moschini (2007), when few hops are qualified. In this case all hops are supplied in the alternative secondary market. Because few hops are supplied in the contracted hop market when $\bar{s}=0$, the merchant cannot possibly obtain any profits, so $\Pi=0$.

Conversely, if given a loosely imposed tolerance, the merchant is expected to receive all hop deliveries in the contracted hop market. Because hops can always be qualified for the residue inspection, in equilibrium the merchant obtains aggregated profits by selling all contracted hops to the brewer. In this case the hop merchant's profits are given by,

$$\Pi_1=\int_{\underline{\theta}}^{\bar{\theta}} \bar{y}^*(\bar{s})\cdot\left[p-\bar{p}^*(\bar{s})-c\right]t(\theta)\,d\theta, \tag{21}$$

If the tolerance is loosely stipulated, the merchant accepts hop delivery from all growers and resells to the brewer. Thus the equilibrium profit is aggregated over all growers.

If $\bar{s}$ is imposed more effectively, the merchant, however, accepts delivery only from growers whose hops are qualified for the residue inspection. If residue is monotonically increasing in type (productivity), the equilibrium profits can be obtained by aggregating over producers below a critical type $\hat{\theta}$, which is,

$$\Pi_2=\int_{\underline{\theta}}^{\hat{\theta}} \bar{y}^*(\bar{s})\cdot\left[p-\bar{p}^*(\bar{s})-c\right]t(\theta)\,d\theta, \tag{22}$$

where $\hat{\theta}$ is the critical type of producer whose hops' residues exactly meet the residue tolerance. Therefore by the monotonicity, growers below $\hat{\theta}$ are those whose hops are qualified. Thus the merchant receives contract hops from this group of producers, and resells hops to the brewer.

4. The Government

The government maximizes social welfare incorporating the environmental damage from pesticide use. Let $d_i>0$ denote a constant marginal damage imposed by grower *i*'s pesticide use. Thus a grower who uses x_i units of pesticides would impose damage $d_i x_i$ upon the environment. The linear damage function can be defined as

$$D(x,\theta)=d(\theta)\cdot x(\theta). \tag{23}$$

It follows directly that $D_x>0$, i.e., environmental damage increases in pesticide use. The damage function is similar to the specification in Bourgeon and Chambers (2008) where they measured the social welfare by accommodating a nonlinear environmental damage function of farming activity. Gramig et al. (2009) also modelled social welfare by incorporating the negative externalities as an expected damage of infectious disease outbreaks.

Thus the government maximizes social welfare by imposing residue tolerance $\bar{s}$, which is measured by aggregating all growers' expected utility and hop merchant's profits minus the environmental damages, which is given by,

$$\max_{\{\bar{s}\}} SW = \int_{\underline{\theta}}^{\bar{\theta}} U\left(x^{*},\theta\right)t\left(\theta\right)d\theta + \Pi - \int_{\underline{\theta}}^{\bar{\theta}} D\left(x^{*},\theta\right)t\left(\theta\right)d\theta \tag{24}$$

s.t.

$$\Pi \geq 0 \tag{25}$$

The first term in eq. (24) represents the aggregated contract-stage equilibrium expected utility. The second term represents hop merchant's equilibrium profits. The third term is the aggregated environmental damages due to pesticide use. Eqn. (25) outlines the participation constraint (PC) ensuring non-negative profits to the hop merchant. Thus the government, in the first stage, maximizes the overall social welfare subject to the constraint that the hop merchant maintains non-negative business profits.

An exceedingly imposed tolerance could lead to an equilibrium in which the hop growers employ low level of pesticides, and hop merchant receives zero profit. Because if the tolerance, as primary hop-quality standard, is too stringent to be meet, few hops are expected to be qualified and be delivered to the hop merchant in the contracted hop market. While the contracted hop market is uncovered due to the lack of qualified contracted hops, the hop merchant, indeed, cannot possibly sell hops to the brewers. In this case the equilibrium social welfare is,

$$SW = \int_{\underline{\theta}}^{\bar{\theta}} U\left(x^{b},\theta\right)t\left(\theta\right)d\theta - \int_{\underline{\theta}}^{\bar{\theta}} D\left(x^{b},\theta\right)t\left(\theta\right)d\theta, \tag{26}$$

Thus an extremely stringent tolerance leads to an overall equilibrium in which all growers apply low levels of pesticides. In addition, since all growers supply hops in the secondary market, the hop merchant's equilibrium profits are zero in the contracted hop market. The equilibrium social welfare is simply measured by the aggregated expected utility minus the environmental damages from pesticide use.

Other possible equilibria exist. For example, consider if the tolerance is sufficiently loose, the the Kuhn-Tucker condition becomes,

$$\begin{aligned}&\int_{\underline{\theta}}^{\overline{\theta}} U_x(\theta)\cdot\left[x_{\bar{s}}^{m}(\theta)+x_{\bar{y}}^{m}(\theta)\,\overline{y}_{\bar{s}}^{*}+x_{\bar{p}}^{m}(\theta)\,\overline{p}_{\bar{s}}^{*}\right]t(\theta)\,d\theta+\int_{\underline{\theta}}^{\overline{\theta}}\left[\overline{y}_{\bar{s}}^{*}\left[p-\overline{p}^{*}-c\right]-\overline{p}_{\bar{s}}^{*}y^{*}\right]t(\theta)\,d\theta\\ &\qquad-\int_{\underline{\theta}}^{\overline{\theta}} D_x(\theta)\cdot\left[x_{\bar{s}}^{m}(\theta)+x_{\bar{y}}^{m}(\theta)\,\overline{y}_{\bar{s}}^{*}+x_{\bar{p}}^{m}(\theta)\,\overline{p}_{\bar{s}}^{*}\right]t(\theta)\,d\theta\\ &\qquad+\tau\int_{\underline{\theta}}^{\overline{\theta}}\left[\overline{y}_{\bar{s}}^{*}\left[p-\overline{p}^{*}-c\right]-\overline{p}_{\bar{s}}^{*}\overline{y}^{*}\right]t(\theta)\,d\theta\le 0\end{aligned}\tag{27}$$

with equalities when participation constraint (PC)'s nonbinding (i.e., the hop merchant's business profits are strictly positive). In eqn. (27) $U_x, x_{\bar{s}}^{m}, x_{\bar{p}}^{m}, x_{\bar{y}}^{m}, \overline{y}_{\bar{s}}^{*}, \overline{p}_{\bar{s}}^{*}$ are the first derivatives. τ is the Lagrange multiplier for the participation constraint. The value of τ can be interpreted as the shadow price representing the marginal social welfare from an increased profits. Therefore, the first term and the second term represent the marginal social welfare effects in terms of marginal utility and marginal benefits respectively. The third term represents the marginal cost in terms of environmental damages. The last term represents the incentive effect of tolerance to the hop merchant.

Last, but not the least, consider a equilibria when a more effective residue tolerance is implemented, the Kuhn-Tucker condition becomes,

$$\begin{aligned}&\int_{\underline{\theta}}^{\overline{\theta}} U_x(\theta)\cdot\left[x_{\bar{s}}^{*}(\theta)+x_{\bar{y}}^{*}(\theta)\,\overline{y}_{\bar{s}}^{*}+x_{\bar{p}}^{*}(\theta)\,\overline{p}_{\bar{s}}^{*}\right]t(\theta)\,d\theta+\int_{\underline{\theta}}^{\overline{\theta}}\left[\overline{y}_{\bar{s}}^{*}\left[p-\overline{p}^{*}-c\right]-\overline{p}_{\bar{s}}^{*}\overline{y}^{*}\right]t(\theta)\,d\theta\\ &\qquad-\int_{\underline{\theta}}^{\overline{\theta}} D_x(\theta)\cdot\left[x_{\bar{s}}^{*}(\theta)+x_{\bar{y}}^{*}(\theta)\,\overline{y}_{\bar{s}}^{*}+x_{\bar{p}}^{*}(\theta)\,\overline{p}_{\bar{s}}^{*}\right]t(\theta)\,d\theta\\ &\qquad+\tau\int_{\underline{\theta}}^{\hat{\theta}}\left[\overline{y}_{\bar{s}}^{*}\left[p-\overline{p}^{*}-c\right]-\overline{p}_{\bar{s}}^{*}\overline{y}^{*}\right]t(\theta)\,d\theta\le 0\end{aligned}\tag{28}$$

In eqn. (28) $U_x, x_{\bar{p}}^{*}, x_{\bar{s}}^{*}, x_{\bar{y}}^{*}, \overline{y}_{\bar{s}}^{*}, \overline{p}_{\bar{s}}^{*}$ are the first derivatives. τ is the Lagrange multiplier for the participation constraint. Similarly, the first term and the second term in eqn. (28) represent the marginal social welfare effects in terms of marginal utility and marginal benefits respectively. The third term represents the marginal cost in terms of environmental damages. The last term represents the incentive effect of tolerance to the hop merchant. The optimal residue tolerance solves eqn. (37).

5. CONCLUSION AND DISCUSSION

Many forces during the hop production and marketing process affect a grower's chemical input decision. This paper presents four market-stage game characterizing the strategic interaction between hop growers, hop merchant and the government. The model characterizes hop growers' decision making in a stochastic production setting, as well as hop merchant's decision making in the market sector. The study also considers the social-economic effects and the environmental benefits of implementing a pesticide residue tolerance. Novel insights are gleaned from evaluating farm-level behavior when residue tolerance is imposed in different theoretical intervals. Results indicate that hops growers are likely to adopt a less pesticide-intensive production system given an extremely stringent residue tolerance. 'Switching' behavior may serve as an example, such as integrated pest management (IPM) may be adopted to reduce pesticide residues. Multiple market equilibria are characterized and social welfares are presented in different scenarios. Finally, several points worth discussing. This study envisioned the level of pesticide residues as hop-quality attribute. It should be noted that quality factors are evaluated subjectively and the threshold for acceptable is variable depending on many factors, including potential use of the crop and market conditions. In addition, quality standards may also go up when the contract price is higher than the spot market price. Finally, for crops intended for extraction of alpha-acids, quality is not as an important issue as the entirely yield. As discussed, the model and simulation evidences are not a definitive study, but rather provide an initial assessment of situations in hop production.

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