AN ABSTRACT OF THE THESIS OF

Larissa Larocca de Souza for the degree of Master of Science in Horticulture presented on November 14, 2019

Title: Chemical Control of Suckers in Hazelnuts (*Corylus avellana*): Comparing Herbicide Efficacy, Spray Nozzle, and Carrier Volume

Abstract approved:

Marcelo L. Moretti

Hazelnuts (*Corylus avellana*) produce a prolific growth in the base of the trunk and roots, known as suckers, which are often removed in order to promote the development of a single trunk tree. Sucker removal facilitates cultural practices and mechanized operations, such as weed management and harvest. Sucker presence can be a source of pest and diseases, impact on fruit/shoot ratio, and reduce hazelnut yield. Thus, the removal of suckers is a crucial practice in hazelnut crop management.

Sucker removal can be done manually; however, it is time-consuming and labor-intensive. Chemical control is a cost-effective option, and it is a frequent method used by farmers in Oregon. Although different herbicides are registered for hazelnut sucker control, few studies provide information regarding the efficacy of these herbicides. Also, the available information is outdated.

The objective of this study was to compare the efficacy of registered herbicides, alone or in combination, for sucker control in hazelnuts. Two long-term trials and four short-term trials were conducted in 2017 and 2018 in commercial orchards in Western Oregon. Following label recommendations, studies started when suckers reached 15 cm. Fifteen treatments included: 2,4-D, carfentrazone, glufosinate, paraquat, pyrafluflen, and saflufenacil alone and in combination. Long-term trial treatments were reapplied after 28 days, in a total of four applications. In the short-term trials, only one application was made, and trials were terminated after 28 days. Assessments included: visual control, height, biomass, and cross-sectional area.

After the fourth application of the long-term trial, treatments containing 2,4-D, glufosinate, or paraquat resulted in 80% or greater sucker control; sucker height was at least 67% smaller, and biomass was 87% inferior compared to nontreated control. Carfentrazone and saflufenacil, alone, reduced sucker biomass by 58 and 67%, respectively, but were not effective as 2,4-D. Short-term studies confirmed long-term results. Results also suggest that multiple applications are needed during the entire growing season, emphasizing the importance of effective herbicides in hazelnut sucker management.

Herbicide efficacy can be affected by nozzle type and carrier volume. Frequently, the use of nozzles that produce larger droplets is associated with less coverage and, consequently, decreases of herbicide efficacy. However, the literature has shown that, in some cases, it is possible to keep herbicide efficacy while using a nozzle that produces larger droplets. Nozzles with air-induction technology are used to prevent the off-target movement of herbicide. Growers often increase carrier volume to compensate for the increase in droplet size.

The objective of this study was to compare carrier volume and nozzle type for the efficacy of 2,4-D and glufosinate. Six field trials were conducted in Western Oregon, including two long-term trials and two short-term trials. Treatments included: manual removal, 2,4-D at 1,060 g ai/ha, and glufosinate at 1,150 f ai/ha. Two different nozzle types (flat fan and TTI) and two different carrier volume (187 L/ha and 374 L/ha) were tested for both herbicides. Assessments included visual sucker control, height, biomass, and cross-sectional area. Results of long-term trials suggest that no difference was noticed between 2,4-D and glufosinate, and both resulted in excellent sucker control (>90%) after the fourth spray. Also, no difference was noticed between the two types of nozzles or carrier volume. Thus, both herbicides can be used for sucker control, and 187 L/ha is recommended since it can save water and refilling time compared to 374 L/ha. TTI nozzles are preferred over flat fan nozzles since drift risk is reduced while herbicide efficacy is maintained. This study provided relevant information for a more efficient and safer chemical sucker control.

Chemical Control of Suckers in Hazelnuts (Corylus avellana): Comparing Herbicide Efficacy, Spray Nozzle, and Carrier Volume

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Larissa Larocca de Souza, Author

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CHAPTER 1 **General introduction**

Hazelnuts in Oregon

The hazelnut (*Corylus avellana L.*) is one of the major nut crops in the word (Yildiz 2016), and it is widely distributed in Europe and Asia (Baron et al. 1985). Although there are species native to the Pacific Northwest (*Corylus cornuta*), the varieties cultivated in Oregon are European hazelnuts (*Corylus avellana*). Hazelnut seedlings bear their first nut from 3rd to 6th year, with the median being the 5th year (Mehlenbacher and Smith 1992). Hazelnut trees reach full maturity in about 12 years and remain productive for 40-50 years (Olsen 2013). Oregon's Willamette Valley currently produces more than 98% of the U.S. European hazelnut (*Corylus avellana*) crop, due to the ideal climate and soils of the region (Wiman et al. 2019b). Because of the devastation caused by the fungal disease Eastern Filbert Blight (EFB), caused by the pathogen *Anisogramma anomola*, the hazelnut industry in the Pacific Northwest has been in decline (Wiman et al. 2019b). Disease symptoms include branch dieback and cankers that can lead to tree death if not removed (Cameron 1976; Pinkerton et al. 1995; Wiman et al. 2019b). The release of EBF-resistant varieties by Oregon State in 2009 supported rapid growth of the hazelnut industry in Oregon (Wiman et al. 2019b). Acreage in the Willamette Valley nearly doubled in less than a decade

(Pacific Survey LLC, personal communication). Hazelnut is used mainly for hazelnut paste, candy, banking, and other purposes (Mehlenbacher 1990).

Suckers (basal sprouts)

Hazelnuts naturally grow as a multistemmed shrub; however, in the United States, hazelnuts are forced to grown as a single trunked tree by removing the basal sprouts, also known as suckers, to facilitate machine harvest. (Mehlenbacher and Smith 1992). By contrast, in Turkey, hazelnuts remain a multistemmed bush and the crop is harvested by hand (Yildiz 2016). Harvest takes place in the US between August and October, depending on the variety. Nuts drop onto the orchard floor, and are machine harvested, usually twice. A significant challenge to Oregon growers are the autumn rains, which can negatively impact hazelnut harvest and hazelnut quality.

Hazelnut suckers can negatively impact mechanized operations such as weed management and harvest, as well as yield (Mehlenbacher and Smith 1992), since suckers compete with the crop for nutrients and light. They also impact in the fruit/shoot ratio (Dolci et al. 2004).

The propensity for suckering varies with hazelnut variety (Tomasone et al. 2010) and propagation methods. A study comparing the propensity for suckering in different training systems – single trunk and multi-stemmed bush – found no difference between them (Radicati et al. 1992)

Although the literature about the impact of suckers on crop performance is not well documented in hazelnut, their presence and importance are noticed in other crops such as grape and tobacco. In grape, sucker presence may harbor pathogens due to overcropping, and interfere in the fruit/shoot ratio. (Dolci et al. 2004). Suckers also can affect vineyard cultural operations, such as weed control, mechanical harvest, diseases and pest control (Kang et al. 2012). In order to control suckers in hazelnut, multiple spray applications are required during the growing season. Sucker control options are limited in United States, mostly done by chemical or manual control. However, different methods, such as mechanical and thermal sucker control have been documented in Europe.

Sucker control methods

Manual removal

In this method, suckers are removed with hand tools such as pruning shears or hoes. The advantage of these methods is that sucker selection is possible should the grower want to rejuvenate the tree. However, this method is very labor and time intensive and thus expensive. (Serdar and Akyuz 2018). Furthermore, the activity is physically taxing for workers, with repetitive motion injuries possible.

Mechanical

Suckers can be removed with a motor scythe. This method can be less costly and time consuming than manual removal, but it does not allow sucker selection. Also, care is required to avoid truck damage with machinery (Serdar and Akyuz 2018).

Physical control

Physical sucker control is mostly done using flame torch or steam. One Italian study compared the efficacy of hazelnut sucker control by flaming or by steam (Tomasone et al. 2008). Results suggest that both methods were effective in controlling suckers, however flame torch used less gas was more time efficient compared to a steam machine, which is also more expensive. Both methods are used in organic orchards in Italy. Either method can harm the trunk and main branches, so experienced labor is required. Another limitation is that these machines are best used only on flat areas. No studies have been done in United States with these methods.

Non-suckering cultivars

Italian breeding programs focus on development of improved cultivars for desirable characteristics, including reduced sucker aptitude (De Salvador et al. 2008). In 2015, one of the most widely grown cultivars ‘Tonda Gentile Romana’ was used in a clonal selection study, resulting in clones that produced fewer suckers than ‘Carazza’, ‘Foschini, ‘Iezzie’, or ‘Oroni’. In Spain, another study compared hazelnut rootstocks and suggested that the rootstocks ‘Dundee’, ‘Newberg’, and ‘MB-69’ improved the agronomic performance of ‘Negret N·9’(Rovira et al. 2012). However, such research is limited in United States where hazelnuts are largely reproduced by layering, or increasingly by micropropagation.

Chemical control

Studies on chemical control of sucker in hazelnut began in 1960 in Italy and the United States (Serdar and Akyuz 2018). The first active ingredients tested included:

aminotriazole, bromacil, chlorthiamid, dichlobenil, kernite, paraquat, dinoseb, diquat, cypromid, cacodylic acid, 2,4,5-T, dicamba and picloram (Reich 1970; Reich and Lagerstedt 1971; Germain 1973). Chemical control is a popular method for farmers because it requires less time and labor than other sucker control methods (Serdar and Akyuz 2018). Herbicides that can be used to control suckers are 2,4-D, glufosinate, paraquat, carfentrazone, and pyraflufen (Wiman et al. 2019a). Sucker spray applications are recommended between April and August as needed up to four times per year (Olsen and Peachy 2013). Although there are some chemicals options for sucker control available, information is limited regarding the efficacy of these chemicals. The objective of this study was to compare efficacy of herbicides registered for sucker control in hazelnut.

Spray technology

Many factors can affect herbicide efficacy including spray droplet size (Creech et al. 2015). Nozzle size and type, the pressure at which the liquid leaves the nozzle and droplet physical properties are factors that impact on droplet formation (Hanks 1995). Droplet size distribution is categorized by volume median diameter (VMD), with half of the total droplet volume is above the median size and the other half is below (Mueller and Womac 1997). Hanks (1995) showed that VMD is inversely correlated to pressure exerted on the spray solution.

The American Society of Agricultural and Biological Engineers (ASABE) developed standard droplet size categories for pesticide application reference. According to

ASABE standards, nozzles are characterized as producing very fine (<136 µm), fine (136-177 µm), medium (177-218 µm), coarse (218-349 µm), very coarse (349-428 µm), extremely coarse (428-622 µm) or ultra-coarse (>622 µm) spray droplets (ASAE 2009). Nozzles used in agriculture generally produce droplets ranging from 10 to greater than 1,000 µm diameter (Bouse et al. 1990). Droplet sizes above 200 mm tend to drift more easily (Etheridge et al. 1999).

A review study from Knoche (1994) showed that a decrease in droplet size led to an improvement in herbicide performance in 71% of the studies. In 20% of the studies, no change in efficacy was noticed, while in only 9% of the cases, herbicide efficacy decreased when reducing droplet size. Despite this lack of consensus, it is important to highlight that spray application efficacy is dependent on physical and biological parameters, such as droplet formation, movement to the plant surface, drop retention on the leaf surface, plant uptake and biological response (Reichard 1988; Merritt 1989; Brazes et al. 1991; Ebert and Downer 2008; Creech et al. 2015).

Herbicide drift, the movement of herbicide to non-target areas, can lead to crop injury and environmental pollution and is a concern whenever herbicides are employed. Concerns over drift have led to the implementation of drift reduction practices (Mueller and Womac 1997). One way to prevent off-target particle drift is though adjustments of spray equipment for droplet size (Fillmore 2014). Although increased nozzle droplet size can decrease drift risk, it can also negatively affect coverage, and ultimately lead to reduced herbicide efficacy.

Nozzle body types air induction (AI) nozzle contain a pre-orifice chamber to reduce pressure on the liquid inside the primary orifice can reduce the number of drift-prone droplets in the spray spectrum (Fillmore 2014). AI nozzles produce heavier droplets than regular flat-fan nozzles. Those heavier droplets are less prone to drift; however, spray coverage can also be comprised (Doruchowski et al. 2017). Frequently, growers try to compensate by increasing the spray volume (Doruchowski et al. 2017), but the relationship between spray volume and herbicide efficacy has not been made clear in the literature. Drift reduction nozzles producing large droplets over a wide range of spray pressure, and so minimize the drift potential of herbicide sprays (Etheridge et al. 1999).

Herbicide efficacy is also related to the retention of herbicide droplets on the leaf. Since plants vary in leaf surface texture and morphological structures, retention of droplets also varies among plant species. Studies regarding the effect of droplet size and carrier volume are available for a range of different weed species. However, there is no information about the effects of droplet size and carrier volume on hazelnut sucker control. Thus, another objective of this study is to compare different droplet sizes and carrier volumes on the efficacy of 2,4-D and glufosinate. A comprehensive understanding of droplet size and carrier volume on the efficacy of these herbicides could result in improved recommendations for sucker control in hazelnuts.

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CHAPTER 2 Chemical Control of Suckers in Hazelnut (*Corylus avellana*) in Orchards of Western Oregon

ABSTRACT

Hazelnuts naturally grow as a multi-stemmed tree with basal sprouts, or suckers, growing throughout the season. Suckers are removed to promote a single trunk that facilitates production mechanization and increase yield. Long- and short-term field studies were conducted to evaluate the efficacy of herbicides to control hazelnut suckers. In the long-term studies, four consecutive applications of treatments that contained 2,4-D, glufosinate or paraquat provided 80% control or greater, reduced sucker height to 50 cm or less as compared to 156 cm for the nontreated control, and reduced sucker biomass by 87% as compared to the nontreated control. Carfentrazone and saflufenacil reduced sucker biomass by 58 to 68% but were not as effective as repeated 2,4-D treatments. Results from the short-term studies indicated that carfentrazone and saflufenacil were also effective in controlling suckers and confirmed the efficacy of 2,4-D, glufosinate, and paraquat. These results emphasize the necessity of multiple applications during the growing season to control suckers in hazelnut and further confirm that the role effective herbicides play in sucker management.

Introduction

Hazelnut is a tree nut in the *Corylus* genus in the *Betulaceae* family native to northern temperate zones; it is also known as filbert or European hazelnut. Hazelnut-enriched diets are associated with a reduction in coronary heart disease and an improved cholesterol profile (Mercanligil et al. 2007), health benefits that promote its consumption. Worldwide, hazelnut consumption is expected to increase over the next years, reaching an estimated market value of $5.75 billion annually (Revord et al. 2019). Turkey produces 65% of global hazelnut production, followed by Italy (13%), Azerbaijan (4%), and the United States (3%) (FAOSTAT 2017). Nearly all U.S. hazelnut orchards are in the Willamette Valley of western Oregon. Hazelnut production is expanding in Oregon with acreage having increased almost three times in the last ten years to 78,603 acres in 2018. Nearly half of that acreage is a 1- to 5-year-old crop (Pacific Survey LLC, personal communication).

Production of hazelnut in the United States remains economically competitive in part because mechanization holds labor costs to 6% of total production costs (Miller, 2013). However, the growth habit of hazelnut poses inherent challenges for mechanization. Hazelnut produces prolific basal sprouts, also known as suckers, that originate from the lower part of the trunk and roots. Left untrained, hazelnuts grow into a multi-stemmed shrub. In Oregon, hazelnut suckers are removed to promote development of a single trunk, facilitating mechanized harvest (Mehlenbacher and Smith 1992). Sucker removal encourages the growth of the primary trunk, shortens the juvenile phase, and increases yield (Mehlenbacher and Smith 1992). Further, suckers competing for resources and weaken the growth of branches by (Tous et al. 1992); this may favor disease by reducing airflow within the canopy (Tomasone et al. 2008). Sucker removal reduces possible infection sources of eastern filbert blight, caused by the pathogen *Anisogramma anomala*, a devastating fungal disease in hazelnut (Murray and Jepson 2018). Suckers cause similar problems in other crops such as grapes and tobacco. In grapes, suckers increase the foliage per plant, which can lead to greater pathogen attack and cause an imbalance in the fruit/shoot ratio (Dolci et al. 2004). Suckers can negatively impact vineyard operations such as tillage, herbicide sprays, harvest, pests, and disease control (Kang et al. 2012). In tobacco, sucker control increases root growth and improves nutrient uptake (Weeks and Seltmann 1986).

Sucker control in hazelnut is labor-intensive (Serdar and Akyuz 2018). Sucker emergence and vigor is variety-dependent (Tomasone et al. 2010). Sucker growth generally initiates in spring (April, in the Willamette Valley) and continues until late summer (September), requiring continuous removal during the growing season. Several methods of sucker control have been tested in hazelnut, including disbudding the lower portion of the trunk, manual removal, thermal control, and chemical control (Dolci et al. 2000; Smith and Erdogan 2001; Tomasone et al. 2010). Manual removal of suckers during the winter is the standard practice in Turkey, Italy, Spain, and the United States, requiring 12 to 15 hours of labor per hectare (Franco and Pancino 2008). Manual removal of suckers during the growing season is not economically feasible for most Oregon growers due to labor demands. Sucker removal can be ergonomically hazardous and exhausting work. Prolonged flexing of the back muscles and repetitive pruning movements cause work-related injury in the agricultural sector (Meyers et al. 2000). When suckers are left uncontrolled during the growing season, they grow large and require additional exertion and stress in the hands and wrists of pruning personnel.

Alternatives to sucker removal have been investigated. Steaming and flaming were not cost-effective options, and crop safety may be a concern (Tomasone et al. 2008). Mechanical sucker control has not been adopted in hazelnut due to crop damage concerns. In grape, mechanical de-suckering is common practice with commercially available equipment, but can damage young grape plants (Dolci et al. 2004). Chemical control is the most broadly adopted method due to low cost and time consumption compared to other methods (Serdar and Akyuz 2018). Herbicides are the standard practice for sucker control in commercial hazelnut production in Oregon (Olsen and Peachy 2013). Several herbicides are labeled for sucker control in hazelnut, including 2,4-D, paraquat, and glufosinate (Wiman et al. 2019a), and effective control requires multiple applications per season. Although four herbicide applications are recommended per season (Olsen and Peachy 2013), growers may apply six to eight applications per season. Changes in this practice may reflect new varieties under cultivation in Oregon. Available data on the efficacy of herbicide control of suckers are outdated (Reich 1970). The objective of this study was to evaluate the efficacy of registered herbicides for sucker control in hazelnut.

Material and Methods

Two experimental protocols were developed to compare the efficacy of hazelnut sucker control using registered herbicides. Study 1 was a season-long-management program comparing the effects of multiple applications of the same herbicide in sucker control. The number and frequency of applications followed local recommendations (Olsen and Peachy 2013). Based on the results of the first study in 2017, a second short-term study was designed in 2018 to evaluate the efficacy of a single application (Study 2). Field trials were conducted for sucker control in hazelnuts following recommend herbicides rates registered for use in hazelnuts in Oregon (Table 2.1. List of herbicides registered for sucker control in hazelnut, rates used in herbicides treatments, their manufacturers and contact information (Table 2.1).

Study 1. Season-long control of hazelnut suckers.

Two field studies were conducted in Amity, OR (45° 06' N 123° 17' W) in a well-drained Woodburn silt loam soil (USDA Soil Survey Staff 2017). The study orchard consisted of ten-year-old 'Jefferson' variety hazelnuts planted 6 m by 6 m with a single drip irrigation line. The experiment was initiated when suckers reached an average height of 15 ± 5 centimeters, as recommended on herbicide labels (15 to 22 cm height). A minimum of 15 suckers per plant, located within a 0.5 m radius of the tree base were present at the time of application. Treatments were applied using a

CO^2 backpack sprayer equipped with three nozzles (11002 Turbo TeeJet (TeeJet Technologies, Wheaton, IL). The sprayer was calibrated to deliver 187 L/ha at 275 kPa. Applications were made as a single pass to each side of the tree row. Treatments were reapplied every 28 days, May to August during each year of the study, for a total of four applications of the same treatment per season to each plot. Different areas of the orchard were used in each year of the experiment. Application details are provided in (Table 2.2). Treatments included herbicides applied alone or in tank-mixtures, in addition to manual removal and a nontreated control. Thirteen treatments were evaluated in 2017, and fifteen treatments in 2018. Three treatments were removed from the study because of poor performance in the first year, and five new treatments were included in 2018. Details about treatments are provided in Table 2.1.

Assessments included visual estimates of sucker control on a scale of 0 to 100%, with 0 as no control and 100% as complete control at 14 and 28 days after treatment (DAT). The height of 10 suckers from the soil surface to the tip of the shoot per plot was measured at 28 DAT. Stem caliper at the base of 20 suckers per plot (10 per tree) was measured at 28 following the final application of the season using a digital caliper (Fisherbrand™ Traceable™ Digital Calipers; Thermo Fischer Scientific; Waltham, WA). All suckers were harvested, dried at 70° C for four days, and the dried biomass was recorded. Sucker caliper diameter was transformed into a cross-sectional area using the equation:

$$A = \pi \left(\frac{D}{2}\right)^2 \qquad [1]$$

Where A is the cross-section area, D is the diameter, and π is a constant (3.14159).

Study 2. Short-term control of suckers

Four field trials were conducted in mature orchards in the Willamette Valley in 2018. Experiments followed similar methods as described previously, with the exception that these trials were terminated at 28 DAT. Two experiments were conducted in Canby (45° 17' N 122° 39' W), and two in Corvallis (44° 29' N 123° 13' W). Soils in the Canby orchards were a Latourell loam (USDA Soil Survey Staff 2017); the crop was rain-fed with trees spaced 6.1 by 6.1 meters. The first study in Canby was in a 12-year-old 'McDonald' hazelnut orchard. The study was initiated in early spring when suckers were 15 cm± 4 cm in height. The second Canby experiment was in a 5-year-old ‘Jefferson’ orchard and initiated in June when suckers were 16 cm+- 5 cm in height.

The Corvallis experiments were conducted in a 10-year-old 'Jefferson' orchard on a non-irrigated Chehalis silt loam (USDA Soil Survey Staff 2017). A different location within the same orchard was selected to initiate trials later in the season. The first trial was initiated when suckers were on average 15 ± 4 cm in height in the first trial, and the second one was initiated 14±6 cm in height. The average height of 10 suckers per plot was recorded at the beginning of each application. Sucker control, height, caliper, and biomass were measured 28 DAT as detailed in Study 1 methods.

Statistical Analysis. Study 1. The experiment was designed as a randomized complete block with 15 treatments and four replicates; the experiment was conducted twice. Each experimental unit included two hazelnut trees. The assumptions of normality and homogeneity were tested and not met for some measurements. Common data transformations tested did not correct the lack of normality or homogeneity. Therefore, untransformed data were used in the analysis. Data from all assessments were modeled using a generalized linear mixed model via PQL (Penalized Quasi-Likelihood) to account for data overdispersion and normality issues (Bolker 2017) using herbicide treatments as fixed effects. The blocking factor and experimental location and year were treated as random effects in the model. Means were compared using Tukey's HSD test, with a 95% confidence interval. Analyses were conducted using R software (R Software Project 2018) with the packages, lme4 (Bates et al. 2007), MASS (Venables and Ripley 2002), Multcomp (Hothorn et al. 2014), and Tidyverse (Wickham 2017). Full model (year included) and reduced model (year not included) were compared through analysis of variance, and no significant difference was found. Thus, data from the 2017 and 2018 trials were analyzed together.

Study 2. The experiments were arranged in a randomized complete block design with four replicates of two trees per plot. Data from the field experiments were submitted to analysis of variance (ANOVA) using the R program with significance level set at 0.05. Because a significant effect of location was observed, the data were analyzed separately by location.

Results and Discussion

Study 1 Long-term control

All treatments evaluated in this study had a significant effect on suckers (Table 2.3). At 14 days after treatment A (DAT-A), manual removal provided 89% sucker control, which was reduced to 78% at 28 DAT-A as a result of sucker regrowth. Most of the tested herbicides were comparable in efficacy to manual removal at 28 DAT-A except paraquat (1120 g ha^{-1}), and pyraflufen (70 g ai ha^{-1}) (Table 2.3). A general increase in efficacy was observed with 2,4-D and paraquat after the second application. The greatest control levels were observed with treatments containing 2,4-D, glufosinate plus carfentrazone, glufosinate, pyraflufen, saflufenacil, or paraquat (> 63% control) at 28 DAT-B (Table 2.3). Following the third and fourth applications, 2,4-D resulted in the greatest control, ranging from 92 to 99% control at 28 DAT-D, a control level similar to manual removal (93%) or paraquat (94%), glufosinate alone (84%) or in combination with carfentrazone (85%), pyraflufen (80%), or saflufenacil (90%). Carfentrazone at 35 g ai ha^{-1} and saflufenacil at 70 g ai ha^{-1} reduced sucker biomass by 67% and 81% compared to nontreated check, respectively (Table 2.5). No injury to the crop canopy, leaves or trunks was observed after any sucker control treatment during the course of these trials. Hazelnut suckers grew throughout the season, reaching 156 cm in the nontreated plots by the end of the study (Table 2.4). When removed monthly, sucker growth of 18 to 33 cm was observed. Treatments including 2,4-D, paraquat, and glufosinate plus carfentrazone suppressed sucker growth with sucker reaching from 39 to 52 cm (Table 2.4). Similarly, a reduction in sucker biomass by 87% to 96%, and in the cross-section area by 68% to 79% compared to the nontreated check was observed with these treatments(Table 2.5). In the case of biomass and sucker cross-sectional area reduction, saflufenacil was similarly effective to these treatments. All the treatments reduced the sucker cross-sectional area by at least 49% compared to nontreated (Table 2.5). Treatments with 2,4-D, glufosinate, paraquat, or saflufenacil reduced sucker biomass by at least 87% (Table 2.5**Error! Reference source not found.**). The results indicated that 2,4-D, paraquat, and glufosinate are effective options for sucker control. In general, tank mixtures did not improve the efficacy of these products; however, tank-mixes can be a good option when considering both weed and sucker control. Suppression of sucker growth during the season facilitates the winter manual pruning.

Study 2 Short-term control

The results of a short-term study indicate a significant effect of application timing. In agreement with Study 1, treatments containing 2,4-D, glufosinate, or paraquat controlled suckers to levels comparable to manual removal (81%), and reduced sucker height by 32 to 63% following the first application compared to the nontreated control (Table 2.6). Treatments with 2,4-D, glufosinate, and paraquat, reduced sucker biomass from 16 to 46 g plant^{-1} compared to the 126 g plant^{-1} present at the first application. Manual removal was the only treatment to reduce the cross-section area (Table 2.6)

The long-term and short-term studies discussed here confirm that 2,4-D, glufosinate, and paraquat are effective options for sucker control in hazelnuts. These findings agree with previous work that also reported that 2,4-D and paraquat were effective in controlling hazelnut suckers (Reich 1970). Direct comparison across studies is difficult because of different application methods. In the Reich, 2017 study, 2,4-D and paraquat were mixed at 0.25 % v/v in 378 liters of water and applied to suckers to the point of run-off rather than on a per hectare basis. This rate is still the recommendation on 2,4-D labels today, with a 2,4-D rate of 1.060 g ai ha^{-1} in 935 L ha^{-1} (Anonymous 1996). The present study shows excellent sucker control with one-fifth of the spray volume (187 L ha^{-1}); lower spray volumes can reduce application costs.

While the literature in sucker control in hazelnut is limited, chemical control of sucker in other crops has been studied. For instance, in a peach orchard, a single application of paraquat at 1.1 kg ai ha^{-1} or glufosinate at 1.2 kg ai ha^{-1} controlled plum root-stock suckers (Muro and Luri 1990). The authors reported that all tested herbicides were more effective than manual removal of suckers. In hazelnuts, paraquat and glufosinate were also effective (Table 2.4), but manual removal always resulted in reduced sucker height. It is important to emphasize that four consecutive treatments of the herbicide or manual removal were required to achieve the reported level of control in hazelnuts. Repetitive removal during the growing season would render manual sucker control economically unsustainable. The time required to remove suckers manually was reported to be 12 to 14.5 h ha^{-1} or approximately 80 to 97 seconds per tree in orchards planted at a density of 540 tree ha^{-1} (Franco and Pancino 2008). Larger diameter suckers required more time to effect removal. A de-suckering operation would cost between $135 to 163 ha^{-1} or approximately 2 to 2.4% of the total production costs based on the 2013 production costs and a minimum hourly wage of $11.25 ($6750 ha^{-1} -$year^{-1}$) (Miller et al. 2013). As for herbicides, multiple applications are also required, but the costs would be between 3- to 9-times lower with glufosinate and 2,4-D, respectively, than removing suckers manually. Growers cannot rely on a single mode-of-action to control suckers year-round, due to maximum allowable per season rates. In addition to sucker control, herbicide rotation is a key component of weed control programs to slow the development of selection for herbicide resistance (Norsworthy et al. 2012).

In this study, carfentrazone, and saflufenacil, in most instances, provided a similar control to glufosinate and paraquat but were not as effective as 2,4-D. The lower efficacy of these products could be attributed to sucker height impacting spray coverage and penetration. The common recommendation is to apply the herbicides when suckers are on average 15 cm height. Because sucker emergence is not uniform, variability in sucker height can be great. Further studies evaluating application parameters are required to improve the efficacy of sucker control with herbicides.

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Tables

Table 2.1. List of herbicides registered for sucker control in hazelnut, rates used in herbicides treatments, their manufacturers and contact information

Common name	Trade name	Rate	Manufacturer	Address and Website
		g ai[a]		
2,4-D acid	SABER®	1,060	Loveland Products, INC	Greeley, CO www.lovelandproducts.com
Carfentrazone	Aim® EC	35	FMC Corporation	Philadelphia, PA www.fmccrop.com
Glufosinate	Rely® 280	1,150	Bayer CropScience LP	Research Triangle Park, NC www.bayercropscienceus.com
Methylated seed oil	HASTEN®	1% v/v	Wilbur-Ellis Company	San Francisco, CA https://www.wilburellis.com
Nonionic adjuvant	RAINIER-EA®	0.25 % v/v	Wilbur-Ellis Company	San Francisco, CA https://www.wilburellis.com
Paraquat	Gramoxone® SL 2.0	1,120	Syngenta Crop Protection	Greensboro, NC www.syngentacropprotection-us.com
Pyraflufen	Venue®	70	Nichino America, Inc	Wilmington, DE www.nichino.net
Saflufenacil	Treevix®	49	BASF Ag Products	Research Triangle Park, NC www.agproducts.basf.com
Ammonium sulfate source	BRONC® MAX	1%	Wilbur-Ellis Company	San Francisco, CA https://www.wilburellis.com

[a] Herbicide rate expressed as the active ingredient, acid equivalent, or volume per volume, as appropriate.

Table 2.2. Sucker control in Oregon hazelnuts with herbicides: Application dates and environmental conditions for Study 1 and Study 2, 2017 and 2018.

Study	Location	Year	App	Day	Air Temp	RH (%)
1	Amity	2017	A	May, 8	66	40
		2017	B	Jun, 19	77	50
		2017	C	Jul, 18	83	36
		2017	D	Aug, 15	81	35
		2018	A	May, 1	55	62
		2018	B	May, 29	76	44
		2018	C	Jun, 26	74	47
		2018	D	Jul, 24	78	37
2	Canby	2018	A	May, 1	70	41
		2018	B	June, 11	73	31
	Corvallis	2018	A	May, 1	67	42
		2018	B	Jun, 12	78	33

APP=application, Temp= Temperature, RH= Relative humidity

Table 2.3. Percent sucker control at 14 and 28 days after treatment (DAT) in a mature hazelnut orchard located in Amity, OR in 2017 and 2018 (Study 1). Sequential applications were made in May (A), June (B), July (C) and August (D) of each year.

		Sucker control [a]							
Treatment	Rate [b]	A		B		C		D	
		14 DAT	28 DAT	14 DAT	28 DAT	14 DAT	28 DAT	14 DAA	28 DAT
	(g ai/ha)	%							
Nontreated	0	0 a	0 a	0 a	0 a	0 a	0 a	0 a	0 a
Manual removal	0	89 f	78 d	93 d	84 f	87 e	74 e	97 g	93 e
2,4-D	1060	41 c	50 cd	66 c	80 ef	82 de	86 e	89 e-g	95 e
2,4-D + carfentrazone	1060 + 35	70 d-f	58 cd	79 cd	71 d-f	81 de	80 e	88 e-g	92 e
2,4-D + glufosinate	1060 +1150	72 d-f	75 d	75 cd	78 d-f	82 de	87 e	94 fg	94 e
2,4-D + pyraflufen	1060 + 35	62 c-f	65 cd	58 c	75 d-f	76 de	83 e	94 e-g	99 e
2,4-D + saflufenacil	1060 + 49	60 c-f	73 cd	68 cd	78 d-f	78 de	81 e	97 fg	99 e
Carfentrazone	35	51 cd	50 cd	58 c	43 c	36 c	39 c	38 c	46 c
Glufosinate	1150	70 d-f	70 cd	70 cd	63 de	71 de	75 e	79 ef	84 e
Glufosinate + carfentrazone	1150 + 35	87 ef	65 cd	85 cd	73 d-f	66 de	75 de	82 e-g	85 e
Glufosinate + pyraflufen	1150 + 70	62 c-f	63 cd	61 c	63 d-f	65 de	68 de	72 de	80 de
Glufosinate + saflufenacil	1150 + 49	65 c-f	73 cd	85 cd	73 d-f	75 de	72 de	81 e-g	90 e
Paraquat	1120	66 c-f	44 c	69 cd	68 d-f	78 de	76 e	85 e-g	94 e
Pyraflufen	70	10 b	15 b	10 b	15 b	16 b	10 b	10 b	10 b
Saflufenacil	49	50 c-e	65 cd	68 cd	55 cd	55 cd	53 cd	57 d	58 cd

[a] Means followed by the same letter within columns are not significantly differ at P = 0.05 using Tukey’s test.

Table 2.4. Sucker height (cm) at 14 and 28 days after treatment (DAT) in a mature hazelnut orchard located in Amity, OR in 2017 and 2018 (Study 1). The sequential applications were made in May (A), June (B), July (C) and August (D) of each year.

		Height							
Treatment	Rate	A		B		C		D	
	(g ai/ha)	---cm---							
Nontreated	0	58	c	73	c	136	e	156	d
Manual removal	0	18	a	19	a	33	a	21	a
2,4-D	1060	30	ab	39	a-c	51	a-c	50	ab
2,4-D + carfentrazone	1060 + 35	23	a	45	a-c	50	a-c	42	ab
2,4-D + glufosinate	1060 + 1150	27	ab	28	ab	39	ab	45	ab
2,4-D + pyraflufen	1060 + 35	34	a-c	43	a-c	55	a-c	52	a-c
2,4-D + saflufenacil	1060 + 49	26	ab	34	a-c	41	a-c	39	ab
Carfentrazone	35	26	ab	59	bc	77	c	110	cd
Glufosinate	1150	29	ab	39	a-c	51	a-c	51	ab
Glufosinate + carfentrazone	1150 + 35	14	a	15	a	46	a-c	43	ab
Glufosinate + pyraflufen	1150 + 70	32	a-c	44	a-c	59	a-c	72	bc
Glufosinate + saflufenacil	1150 + 49	28	ab	36	a-c	49	a-c	70	bc
Paraquat	1120	31	ab	41	a-c	50	a-c	52	ab
Pyraflufen	70	49	bc	79	c	125	de	164	d
Saflufenacil	49	33	a-c	50	a-c	71	b-d	85	b-d

[a] Means followed by the same letter within columns are not significantly differ at P = 0.05 using Tukey’s HST test.

Table 2.5. Sucker biomass (g) and cross-sectional area (mm2) at the end of season in a mature hazelnut orchard located in Amity, OR in 2017 and 2018 (Study 1). Biomass was collected 28 days after the final of four sequential applications.

Treatment	Rate	Biomass	Biomass reduction	Cross-sectional area	Area reduction
	(g ai/ha)	(g)	(%)	(mm)^2	(%)
Nontreated	0	1235 c	0 c	59 b	0 d
Manual removal	80	76 a	94 a	12 a	80 a
2,4-D	68	124 a	90 a	19 a	68 a-c
2,4-D + carfentrazone	80	54 a	96	12 a	79 a
2,4-D + glufosinate	76	78 a	94 a	14 a	76 a-c
2,4-D + pyraflufen	68	156 ab	87 ab	19 a	68 a-c
2,4-D + saflufenacil	75	45 a	96 a	15 a	75 a-c
Carfentrazone	59	400 b	67 b	24 a	59 bc
Glufosinate	71	80 a	94 a	17 a	71 a-c
Glufosinate + carfentrazone	69	144 ab	88 ab	18 a	69 a-c
Glufosinate + pyraflufen	59	140 ab	89 a	24 a	59 a-c
Glufosinate + saflufenacil	76	118 ab	90 a	14 a	77 a-c
Paraquat	78	95 a	92 a	13 a	78 ab
Pyraflufen	49	1203 c	2 c	30 ab	49 c
Saflufenacil	71	229 ab	81 ab	17 a	70 a-c

[a] Means followed by the same letter within columns are not significantly differ at P = 0.05 using Tukey’s HST test.

Table 2.6. Percentage of sucker control, sucker height (cm), biomass (g), and cross-sectional area at 28 days after treatment (DAT) of Study 2 in Canby and Corvallis in 2018.

		Control							
Treatment	Rate	Control		Height		Biomass		Cross-sectional area	
		First	Second	First	Second	First	Second	First	Second
	(g ai/ha)	(%)		(cm)		(g plant^{-1})		(mm)^2	
Nontreated	0	0 f	0 e	24 a	25 a	126 a	48 a	8 a	8 a
Manual removal	0	81 a	79 a	9 d	9 d	14 c	6 c	5 a	3 b
2,4-D	1060	83 a	76 a	11 cd	15 cd	25 bc	13 bc	5 a	5 ab
2,4-D + glufosinate	1060 +1150	68 a-d	67 ab	12 bcd	15 cd	25 bc	16 bc	4 a	6 ab
2,4-D + pyraflufen	1060 + 35	66 a-d	58 ab	15 bcd	18 abc	46 bc	27 bc	8 a	8 a
2,4-D + saflufenacil	1060 + 49	75 ab	58 ab	13 bcd	22 abc	16 bc	21 bc	4 a	5 ab
Carfentrazone	35	48 cde	37 cd	15 bcd	21 abc	55 b	30 ab	6 a	8 ab
Glufosinate	1150	66 a-d	65 ab	14 bcd	19 abc	22 bc	24 ab	5 a	7 ab
Glufosinate + carfentrazone	1150 + 35	70 abc	65 ab	13 bcd	17 a-d	21 bc	18 bc	5 a	5 ab
Glufosinate + pyraflufen	1150 + 70	58 b-e	60 ab	15 bcd	17 a-d	26 bc	21 bc	5 a	6 ab
Glufosinate + saflufenacil	1150 + 49	81 a	66 ab	9 d	16 a-d	8 c	17 bc	4 a	5 ab
Paraquat	1120	60 a-d	57 abc	14 bcd	17 a-d	24 bc	25 abc	5 a	7 ab
Pyraflufen	70	36 e	25 d	18 ab	24 av	58 b	32 ab	6 a	6 ab
Saflufenacil	49	45 de	48 bcd	17 abc	20 abc	35 bc	30 abc	5 a	5 ab

[a] Means followed by the same letter within columns are not significantly differ at P = 0.05 using Tukey’s HST test.

CHAPTER 3 **Effect of carrier volume and nozzle type on the performance of 2,4-D and glufosinate in hazelnut sucker control (*Corylus avellana*) in Orchards of Western Oregon**

Introduction

Herbicides are the most common practice to control suckers in hazelnuts in Oregon. Hazelnut naturally grows as a multi-stem bush, but are trained as a single trunk by pruning suckers benefiting mechanization and yield (Mehlenbacher and Smith 1992). The vigorous growth of suckers requires four herbicide applications or more during the growing season (Olsen et al. 2013). Ensuring effective herbicide application for sucker control is critical to minimize production costs, such as winter pruning.

The performance of an herbicide is affected by a complex spray process, interlinking many aspects related to the target, and abiotic aspects (Kudsk 2002). Carrier volume and droplet size are spray quality parameters that can interfere with the herbicide efficacy. It is well established that spray coverage improves with increasing spray volume up to a certain point. In broad terms, herbicide efficacy is optimized with spray volumes between 100 L ha-1 to 400 L ha-1 (Knoche 1994), and efficacy is greater with smaller droplets (Butts et al. 2018). Droplet size interaction with coverage has been studied, and, in general, smaller droplets increase coverage when compared to bigger droplets (Knoche 1994). Coverage is more important for contact herbicide efficacy. Studies have shown that changes in droplet size may increase or have no impact on efficacy for systemic herbicides (Etheridge et al. 2001; Feng et al. 2003; Creech et al. 2016).

The biology and structure of the application target are important when considering droplet size. For instance, the monocotyledon plants mostly present a vertical structure, which makes small droplets prone to be retained better than larger droplets (Knoche 1994). Previous studies emphasized the significance of droplet size on drift prevention ((Hewitt 1997; Johnson et al. 2006; Bueno et al. 2017; Butts et al. 2018; Butts et al. 2019). Larger droplets are less prone to drift, and droplet size is greatly determined by the nozzle type and spray pressure (Hilz and Vermeer 2013). Because of both economics and environmental concerns, reducing spray drift and application volume while maintaining the herbicide efficacy is a goal for growers and applicators (Etheridge et al. 2001). However, lower spray volumes coupled with larger droplets can decrease spray coverage, compromising herbicide efficacy (Doruchowski et al. 2017).

The recommendations for sucker control with herbicides have not changed for many years, and the hazelnut industry has a perception that high carrier volumes are required for efficacy. That perception is probably based on the work developed for spot application using up to 935 L ha-1 (Reich 1970). Growers commonly utilize between 233 to 467 l ha-1 for sucker control regardless of the herbicide used. Two herbicides commonly used for sucker control are 2,4-D and glufosinate. Glufosinate efficacy was reported to be optimal between 140 and 281 l ha^{-1} with medium to coarse droplet sizes when compared across several plant species (Creech et al. 2015). For best performance with 2,4-D, carrier volumes between 94 and 281 L ha^{-1} were recommended while the droplet size did not influence efficacy (Creech et al. 2015), or very coarse droplets were beneficial (Creech et al. 2016)). The size of spray droplets are, in part, affected by spray nozzles, and drift-reduction nozzles are an effective option to produce larger droplets (Etheridge et al. 1999). The nozzles most commonly used in hazelnut orchards are flat fan nozzles that generate mostly fine droplets. The objective of this study is to compare the use of drift-reduction nozzle with flat fan nozzles for control of hazelnut suckers and its interaction with spray volume and herbicide.

Materials and Methods

Two experimental studies were designed to compare the effect of the spray nozzle and carrier volume on hazelnut sucker control. A long-term study (Study 1) was designed to compare treatments after multiple applications following current recommendations (Olsen et al. 2013). A short-term study (Study 2), followed a similar treatment structure, but evaluations were concluded 28 days after treatment.

Study 1. Long-term

The season-long field trials were conducted in Amity, OR (45° 06'N 123° 17'W) in a well-drained Woodburn silt loam soil (USDASoil Survey Staff 2017) during 2017 and 2018. The selected orchard was 10-year-old ‘Jefferson’ variety planted 6 by 6 m with a single drip irrigation line. Following label recommendations, the experiment started when suckers reached 14 ± 5 centimeters. Suckers were present in all trees with at least 15 suckers located within a 0.5 m radius of the tree base. Treatments were applied using a CO2 backpack sprayer equipped with a three-nozzle boom. Each treatment included one pass to each side of the trees. Four applications were performed during the season every four weeks between May to August. Treatments were conducted with different trees in the same orchard in 2018. The experiment was replicated four times arranged in a randomized complete block 2 by 2 by 2 factorial design with herbicide, nozzle type, and carrier volume as factors. The herbicides compared were 2,4- D (Saber, Loveland Products, Loveland CO) at 1060 g ai ha^{-1}, and glufosinate (Rely 280, BASF, Durham, NC) at 1150 g ha^{-1}. Herbicides were applied at 187 or 374 L ha^{-1} with a nozzle size of 0.75 and 1.5 L/min^{-1}, respectively. The nozzle types tested were the extended range (XR) flat-fan nozzle with no drift control and a pre-orifice, air induction, turbulence chamber Turbo TeeJet Induction (TTI) (TeeJet Technologies, Glendale Heights, IL). Operating at 275 KPa of pressure and water, these nozzles should generate fine and ultra-coarse droplets, according to the manufacturer. A manual pruning was included as a control, and suckers were removed at the same time treatments were applied. An experimental plot consisted of eight trees. Spray information is provided in (Table 3.1).

Assessments:

Visual estimates of sucker control using a scale of 0 to a 100, where 0 is no control and 100 is complete control, and the height of 10 suckers per plot was assessed at 28 DAT days after each application. Sucker biomass and cross-sectional area were collected 28 days after the last treatment. Finally, all suckers were harvested, dried at 70 C for four days, and dry biomass was recorded. Visual crop damaged was also observed during the experiments. The cross-sectional area was measured by recording the diameter of 20 suckers per plot, using a caliper (Fisherbrand™ Traceable™ Digital Calipers; Thermo Fischer Scientific; Waltham, WA). Diameter data was transformed into a cross-sectional area using the equation above:

$$A = \pi \left(\frac{D}{2}\right)^2 \qquad [1]$$

Where A is cross-section area, D is diameter, and π is a constant (3.14). Aboveground biomass data and cross-sectional areas were expressed as a percent reduction compared to the nontreated check.

Study 2. Short-term

A total of four trials were conducted in 2018. Trials followed the same treatment design as described previously except that treatment was applied once, and the experiment was concluded in four weeks. Two trials were placed in Canby (45° 17' N 122° 39' W), which presented Latourell loam soil area (USDASoil Survey Staff 2017). Trees were spaced by 6 to 6 meters and were only naturally irrigated by rain. The 'McDonald'hazelnut trees had approximately 12-year-old and were not irrigated by rain. The first trial was initiated when suckers were 15 cm+/-4 centimeters (cm) long during May, and the second one was initiated in June when sucker presented 14+/- 4 centimeters. Details of spray applications and weather conditions are described in (Table 3.2).

Two other trials were placed in Corvallis (44°29'N 123°13 W) in 'Jefferson' hazelnut trees that on Chehalis silt loam soils (USDASoil Survey Staff 2017). The first trial started in May, when suckers reach 16 +/-5 cm long. In June, the second trial was placed in the same orchard, but in different trees when suckers were 14+/-5 cm. The same assessments described in the long-term study were performed in all short-term trials.

Statistical Analysis.

A randomized complete block design was used with four replicates, and data was submitted to analysis of variance (ANOVA) using Tukey's test with a confidence level of 95%. Statistical analysis was done using R software. Orthogonal contrasts were analyzed using the JPM program (SAS Institute, Cary, NC 27511). This approach was selected due to the desirable comparisons that would not be adequate by performing all pairwise comparison of all the treatments, including undesirables' comparisons. The null hypothesis was that differences between the least square mean for the preplanned contrasts were equal to zero. Hence, the main three contrast were planned: (1) comparison between 2,4-D and glufosinate, (2) comparison of 187 L/ha and 374 L/ha and, (3) comparison of flat fan nozzles and TTI nozzles. For the long-term study, the year did not differ from each other. Thus, data from both years were analyzed together. For the short-term study, differences were noticed for location, but not application and data from Canby and Corvallis were analyzed separated.

Results and Discussion

Study 1 Long-term

Sucker control with glufosinate at 1150L/ha or 2,4-D at 1060 L/ha were not different (Table 3.3). At 14 days after the first application, glufosinate provided greater sucker control in general than 2,4-D. These herbicides also provided similar efficacy to manual removal. However, after the 28 DAA-A, both herbicides presented similar efficacy. It is possible to notice that sucker control has increased with the additional applications, which support growers' practice that spray applications are necessary during multiples times in the season. At 28 DAA-D, all treatments presented at least 90 %of sucker control (Table 3.3). Although the efficacy of 2,4-D and glufosinate were similar, plants treated with 2,4-D presented symptoms of stem epinasty followed by leaf necrosis. Suckers treated with glufosinate were chlorotic and wilted, followed by leaf necrosis as well.

Treatments with 187 L/ha and 374 L/ha presented similar results for all the parameters: sucker control, height, biomass, and cross-section (Table 3.6). Although no difference in herbicides was noticed, contrasts were made to compared differences between carrier volumes by herbicides, and again, no significant differences were noticed (Table 3.6). These results suggest that growers can save water by sprayings both 2,4-D and glufosinate at 187 and still have great sucker control compared to 374 L/ha. Further, a smaller carrier volume can present a direct impact on machinery use and equipment efficiency.

Regarding droplets size, orthogonal contrast indicated no differences between treatments at the end of the season for sucker control, biomass, height, and cross-sectional area (Table 3.6). TTI nozzles presented similar results to flat fan nozzles for both herbicides when it was analyzed together or separated. These results imply that even when using an anti-drift spray technology, it is possible to maintain the efficacy of 2,4-D and glufosinate.

Study 2 Short-term control

Most of the results from the short-term study supported the findings of the long-term study. Glufosinate and 2,4-D did not differ regarding sucker control, presenting similar efficacy at both locations (Table 3.8). When comparing droplet sizes, differences were observed for glufosinate in Corvallis, but no Canby. However, differences notices between flat fan and TTI nozzles were only 3% of sucker control (Table 3.7), which is a small difference. For sucker height, the same pattern was observed. Again, no differences among herbicides, and carrier volume, but glufosinate efficacy was different when comparing flat fan and TTI nozzles.

Regarding biomass and cross-section parameters, orthogonal contrasts indicated differences for 2,4-D and glufosinate at both locations (Table 3.8). For 2,4-D on Canby, the difference between 187 and 374 L/ha was observed for 2,4-D. However, when you compare the means, both volumes presented only 5 grams difference between means (13 and 18 g, respectively) (Table 3.8). For biomass, the difference in glufosinate with flat fan and TTI nozzles was also noticed.

These results suggest that both glufosinate and 2,4-D are suitable herbicides for sucker control. For both herbicides, no differences were noticed between carrier volume, which suggests that growers can use 187 L/ha instead of 374 L/ha and, maintain herbicides efficacy. Regarding droplets sizes, only for glufosinate, a slight difference was noticed when compared to flat fan and TTI nozzles; however, it still presented a good sucker control (>70%). Thus, using anti-drift nozzles to minimize drift risk are recommended for both herbicides.

The present study is in accordance with the previous finding that 2,4-D provides good sucker control (Serdar and Akyuz 2018). Although glufosinate is a registered herbicide for hazelnut sucker control, no studies have been published to date on the efficacy of hazelnut suckers.

According to Knoche, 19% of contact herbicides presented no change in efficacy as droplet size increased. For systemic herbicides, this percentage was 24 (Knoche 1994). It is important to point out that these results are applied only in the doses tested in the experiments. Lower rates could provide different results from the ones observed in this study.

Regarding carrier volume, overall, the results are in accordance with findings reported by Kruger (2014) that efficacy of 2,4-D did not decrease with the decrease in carrier volume. However, no previous reports indicated how 2,4-D efficacy varies with different carrier volumes for sucker control. This research highlights the need for maintaining herbicide efficiency, avoiding off-target movement by selecting appropriate application technology. Moreover, beyond nozzle type and carrier volume, other factors that impact spray drift, such as spray characteristics, settings, and environmental conditions, need to be taken into consideration to mitigate spray drift.

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Tables

Table 3.1. List of treatments with details.

Treatment	Herbicide	Rate [a](g ai/ha)	Nozzle Type	Droplet Size	Carrier Volume (L/ha)
1	Manual Removal		-		-
2	2,4 - D [b, c]	1,060	Flat Fan 11002	Fine (F)	187
3	2,4 - D [b, c]	1,060	TTI	Ultra Course (UC)	187
4	2,4 - D [b, c]	1,060	Flat Fan 11002	Fine (F)	374
5	2,4 - D [b, c]	1,060	TTI	Ultra Course (UC)	374
6	Glufosinate [c]	1,150	Flat Fan 11002	Fine (F)	187
7	Glufosinate [c]	1,150	TTI	Ultra Course (UC)	187
8	Glufosinate [c]	1,150	Flat Fan 11002	Fine (F)	374
9	Glufosinate [c]	1,150	TTI	Ultra Course (UC)	374

[a] Herbicide rate expressed as active ingredient ammonium sulfate at 1% v/v

[b] Ammonium sulfate at 1% v/v

[c] Nonionic surfactant at 0.025% v/v

Table 3.2. Application dates and environmental conditions for Study 1 and Study 2 during 2017 and 2018.

Study	Location	Year	App	Day	Air Temp	RH (%)
1	Amity	2017	A	May, 8	66	40
		2017	B	Jun, 19	77	50
		2017	C	Jul, 18	83	36
		2017	D	Aug, 15	81	35
		2018	A	May, 1	55	62
		2018	B	May, 29	76	44
		2018	C	Jun, 26	74	47
		2018	D	Jul, 24	78	37
2	Canby	2018	A	May, 1	70	41
		2018	B	June, 11	73	31
	Corvallis	2018	A	May, 1	67	42
		2018	B	Jun, 12	78	33

Abbreviations: APP=application, Temp= Temperature, RH= Relative humidity.

Table 3.3. Sucker control (%) at 14 and 28 days after treatment (DAT) in a mature hazelnut orchard located in Amity, OR in 2017 and 2018 (Study 1). The sequential applications were made in May (A), June (B), July (C), and August (D) of each year.

				Sucker Control							
				A		B		C		D	
Treatment	Rate [a]	Volume	Nozzle	14 DAT	28 DAT	14 DAT	28 DAT	14 DAT	28 DAT	14 DAT	28 DAT
	(g ai/ha)	(L/ha)		---(%)---							
Manual removal	-	-	-	90	79	91	83	90	70	92	96
2,4 - D [b,c]	1,060	187	Flat Fan	45	57	73	78	88	90	91	94
2,4 - D	1,060	187	TTI	38	58	67	76	85	85	93	94
2,4 - D	1,060	364	Flat Fan	39	58	65	76	89	89	91	93
2,4 - D	1,060	364	TTI	36	53	69	75	76	82	89	94
Glufosinate	1,150	187	Flat Fan	60	58	59	62	90	78	83	92
Glufosinate	1,150	187	TTI	61	54	65	67	85	84	88	94
Glufosinate	1,150	364	Flat Fan	71	58	77	64	68	76	88	93
Glufosinate	1,150	364	TTI	64	51	63	61	75	74	80	90

[a] Herbicide rate expressed as active ingredient ammonium sulfate at 1% v/v

[b] Ammonium sulfate substitute (Bronc Max) at 1% v/v in all treatment including 2,4-D or glufosinate.

[c] Nonionic surfactant (Rainer NIS) at 0.25% v/v was included in all treatments with 2,4-D.

Table 3.4. Sucker height (cm) at 28 days after treatment (DAT) in a mature hazelnut orchard located in Amity, OR in 2017 and 2018 (Study 1). The sequential applications were made in May (A), June (B), July (C), and August (D) of each year.

				Height			
Treatment	Rate [a]	Volume	Nozzle	A	B	C	D
	(g ai/ha)	(L/ha)		------------------------------(cm)---------------------------			
Manual removal	-	-	-	28	30	36	15
2,4 - D [b, c]	1,060	187	Flat Fan	34	37	41	45
2,4 - D	1,060	187	TTI	36	41	46	48
2,4 - D	1,060	364	Flat Fan	32	37	39	42
2,4 - D	1,060	364	TTI	33	41	46	49
Glufosinate	1,150	187	Flat Fan	32	41	48	51
Glufosinate	1,150	187	TTI	33	39	43	44
Glufosinate	1,150	364	Flat Fan	28	41	50	53
Glufosinate	1,150	364	TTI	33	43	50	54

[a] Herbicide rate expressed as active ingredient ammonium sulfate at 1% v/v

[b] Ammonium sulfate substitute (Bronc Max) at 1% v/v in all treatment including 2,4-D or glufosinate.

[c] Nonionic surfactant (Rainer NIS) at 0.25% v/v was included in all treatments with 2,4-D.

Table 3.5. Sucker biomass (g) and cross-section area at 28 days after treatment D (DAT) in a mature hazelnut orchard located in Amity, OR in 2017 and 2018 (Study 1). The sequential applications were made in May (A), June (B), July (C), and August (D) of each year.

Treatment	Rate [c]	Volume	Nozzle Type	Biomass	Cross-sectional area
	(g ai/ha)	(L/ha)		(g)	(mm^2)
Manual removal	-	-	-	77	9
2,4 - D [b, c]	1,060	187	Flat Fan	106	11
2,4 - D [b, c]	1,060	187	TTI	132	11
2,4 - D [b, c]	1,060	364	Flat Fan	145	13
2,4 - D [b, c]	1,060	364	TTI	111	13
Glufosinate [c]	1,150	187	Flat Fan	199	13
Glufosinate [c]	1,150	187	TTI	131	12
Glufosinate [c]	1,150	364	Flat Fan	147	12
Glufosinate [c]	1,150	364	TTI	139	14

[a] Herbicide rate expressed as active ingredient ammonium sulfate at 1% v/v

[b] Ammonium sulfate at 1% v/v

[c] Nonionic surfactant at 0.025% v/v

Table 3.6. Orthogonal contrast for Long-term study 1 in Amity in 2017 and 2018.

	Control (%)	Height (cm)	Biomass (g)	Cross-sectional area (mm^2)
2,4-D vs Glufosinate	74 vs 72	41 vs 43	123 vs 154	12 vs 13
187 L/ha vs 374 L/ha	74 vs 73	41 vs 42	142 vs 135	12 vs 13
Flat Fan vs TTI	74 vs 72	41 vs 42	149 vs 128	13 vs 12
2,4-D 187 L/ha vs 2,4-D 374 L/há	75 vs 73	41 vs 40	119 vs 128	11 vs 13
2,4-D Flat Fan vs 2,4-D TTI	75 vs 73	39 vs 43*	125 vs 122	12 vs 12
Gluf 187 L/ha vs Gluf 374 L/ha	72 vs 72	41 vs 44	165 vs 143	13 vs 13
Gluf Flat Fan vs Gluf TTI	73 vs 71	43 vs 42	173 vs 135	13 vs 13

* denote orthogonal contrasts significant at the 5% levels.

Table 3.7. Sucker control (%), height (cm), biomass (g), and cross-sectional at 28 days after treatment (DAT) in Canby and Corvallis in 2018 (Study 2).

				Control							
Treatment	Rate [a]	Volume	Nozzle Type	Control		Height		Biomass		Cross-sectional area	
				Canby	Corvallis	Canby	Corvallis	Canby	Corvallis	Canby	Corvallis
	(g ai/ha)	(L/ha)		(%)		(cm)		(g)		(mm$^{2)}$	
Manual removal	-	-	-	89	69	19	30	19	21	2	3
2,4 - D [b, c]	1060	187	Flat Fan	95	76	17	25	17	9	3	4
2,4 - D [b, c]	1060	187	TTI	96	74	16	29	16	13	5	3
2,4 - D [b, c]	1060	364	Flat Fan	87	73	24	30	24	13	6	3
2,4 - D [b, c]	1060	364	TTI	88	75	24	29	24	10	4	4
Glufosinate [c]	1680	187	Flat Fan	92	79	19	29	19	18	5	6
Glufosinate [c]	1680	187	TTI	89	74	24	28	24	15	5	5
Glufosinate [c]	1680	364	Flat Fan	86	79	26	25	26	20	6	6
Glufosinate [c]	1680	364	TTI	84	71	25	30	25	20	6	5

[a] Herbicide rate expressed as active ingredient ammonium sulfate at 1% v/v

[b] Ammonium sulfate at 1% v/v

[c] Nonionic surfactant at 0.025% v/v

Table 3.8. Orthogonal contrasts for Short-term study in Canby and Corvallis in 2018.

	Control		Height		Biomass		Cross-sectional area	
	Canby	Corvallis	Canby	Corvallis	Canby	Corvallis	Canby	Corvallis
2,4-D vs. Glufosinate	88 vs. 91	76 vs. 74	24 vs. 20	28 vs. 28	15 vs. 11**	18 vs. 11**	6 vs. 4*	5 vs. 4**
187 L/ha vs. 374 L/ha	90 vs. 89	77 vs. 73	12 vs. 22	27 vs. 29	12 vs. 14	15 vs. 15	5 vs. 5	5 vs. 4
Flat Fan vs. TTI	93 vs. 86**	76 vs. 74	19 vs. 25**	28 vs. 28	11 vs. 15	14 vs. 16	5 vs. 5	5 vs. 4
2,4-D 187 L/ha vs. 2,4-D 374 L/ha	89 vs. 86	79 vs. 72	23 vs. 24	27 vs. 29	13 vs. 18**	19 vs. 17	6 vs. 6	6 vs. 5
2,4-D Flat Fan vs. 2,4-D TTI	90 vs. 95	77 vs. 75	22 vs. 26	28 vs. 27	15 vs. 16	16 vs. 20	5 vs. 6	5 vs. 5
Gluf 187 L/ha vs. Gluf 374 L/ha	91 vs. 92	74 vs. 74	20 vs. 20	28 vs. 29	11 vs. 10	11 vs. 12	4 vs. 4	4 vs. 4
Gluf Flat Fan vs. Gluf TTI	96 vs. 87**	75 vs. 74	16 vs. 24**	27 vs. 30	8 vs. 13**	11 vs 11	4 vs. 5	4 vs. 4

** and * denote orthogonal contrasts significant at the 1 and 5% levels, respectively.

Table 3.9. Analysis of variance for Study 2 in Canby and Corvallis in 2018.

Response	Variable	DF	Sum of Squares	Mean Square	F-statistic	P-value
Control	Treatment	8	2067.64	258.45	2.95	0.0046
Control	Application	1	1856.17	1856.17	21.19	< 0.001
Control	Location	1	9392.84	9392.84	107.22	< 0.001
Control	Residuals	133	11651.67	87.61		
Biomass	Treatment	8	1655.54	206.94	4.35	< 0.001
Biomass	Application	1	716.70	716.70	15.06	< 0.001
Biomass	Location	1	252.97	252.97	5.32	0.0227
Biomass	Residuals	131	6233.66	47.59		
Height	Treatment	8	645.52	80.69	1.44	0.1862
Height	Application	1	0.72	0.72	0.01	0.9102
Height	Location	1	1617.38	1617.38	28.83	< 0.001
Height	Residuals	133	7460.92	56.10		
Cross-sectional area	Treatment	8	145.98	18.25	4.23	< 0.001
Cross-sectional area	Application	1	0.76	0.76	0.18	0.6756
Cross-sectional area	Location	1	2.82	2.82	0.65	0.4201
Cross-sectional area	Residuals	133	573.76	4.31		

Abbreviation: DF, degrees of freedom

CHAPTER 4 General conclusions

This work provided relevant information regarding the efficacy of registered herbicides for sucker control in hazelnut. As the literature is limited, insufficient information was available for hazelnut growers regarding chemicals options for sucker control. This study found that 2,4-D, glufosinate, and paraquat are the most effective chemical options available at this time for sucker control in hazelnut. These herbicides can be as effective as manual removal; with the added benefit that they are less labor and time-consuming. To be effective, manual removal must be carried out multiple times during the year, making it too costly for many growers. Further, this work suggests that multiple herbicide applications are required because suckers grow throughout the growing season. Herbicide rotation is recommended to reduce the selection of herbicide resistance in nearby weed populations.

This work also provides recommendations for spray technology in hazelnut sucker control. Although an increase in droplet size is often associated with a decrease in herbicide efficacy, our results suggest that in the case of 2,4-D or glufosinate at 1060 g ai/ha and 1150 g ai/ha, respectively, no difference in sucker control was noticed regardless of droplet size. Further, the decrease from 374 L/ha to 187 L/ha did not impact the efficacy of these herbicides. In summary, both 2,4-D and glufosinate provided the same efficacy results when droplet size was increased, and the carrier volume was reduced. These results suggest that the application of both chemicals for sucker control should be made with an ultra-coarse droplet, through air induction nozzles at 187 L/ha. Following these recommendations, growers could decrease drift risk, protecting the crop, and reduce environmental contamination while maintaining herbicide efficacy. This work provided recommendations for greater efficacy, while reducing herbicide drift, a major concern for growers and the population. As other chemistries become available, they should be compared to this work and to other sucker control methods

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