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# Chemical control of suckers in hazelnut orchards of western Oregon

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## Research Article

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## Abstract

Hazelnut naturally grows as a multi-stemmed tree. The basal sprouts, known as suckers, grow throughout the season. Suckers are removed to promote a single trunk that facilitates production mechanization and increased yield. In western Oregon, herbicides are the most common method of sucker control, and at least four applications per season are performed in the spring and summer seasons. This study evaluated the efficacy of foliar-applied herbicides currently registered for sucker control in hazelnuts. Season-long and short-term field studies were conducted to assess the efficacy of herbicides to control hazelnut suckers. In the season-long studies, four consecutive applications of treatments that contained 2,4-D, glufosinate, or paraquat provided 50% to 80% control, maintained sucker height at 50 cm or less as compared to 155 cm for the nontreated control, and reduced sucker biomass by 87% as compared to the nontreated control. The short-term study results confirmed the efficacy of 2,4-D, glufosinate, and paraquat for sucker control, and in this study, carfentrazone and saflufenacil reduced sucker biomass to a level comparable to 2,4-D or glufosinate treatment. These results confirm that 2,4-D, glufosinate, paraquat, carfentrazone, and saflufenacil can be used for sucker control in hazelnut and emphasize the necessity of multiple applications during the growing season to control suckers in hazelnut. Proper herbicide selection is important to control suckers with success.

## Introduction

Hazelnut is a tree or large shrub 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 farmgate value was $2.3 billion in 2016 (FAO 2019), with consumption expected to increase by 10.1% between 2020 and 2025 (Anonymous 2019). Global production was 835 millionkg in 2018, and leading producing countries include Turkey (62%), Italy (16%), Azerbaijan (6%), and the United States (6%) (FAO 2019). Hazelnuts are a traditional crop in Turkey, where the orchards are mostly grown as a multi-stemmed shrub along the hillside of the mountains, and the crop is harvested manually (Kaya-Altop et al. 2016). The average yield in Turkey was 700 kg $ha^{-1}$ of in-shell hazelnut in 2018 (FAO 2019).

Nearly all US hazelnut orchards are in the Willamette Valley of western Oregon. Hazelnut production is expanding in Oregon, with a nearly three-fold increase in hectarage in the last 10 yr to 31,800 ha in 2018; almost half of that hectarage was nonbearing or producing from plants less than 5-yr-old in the same year (USDA NASS 2019). The industry has been expanding since the early 2000s as a result of the release of new hazelnut varieties resistant to the devastating fungal disease known as eastern filbert blight, caused by the plant pathogen *Anisogramma anomala* (Peck) E. Müll (Molnar et al. 2010). In addition to disease-resistant varieties, hazelnut production in the United States remains economically competitive, in part because intensification and mechanization holds labor costs to 6% of total production costs (Miller et al. 2013). The hazelnut varieties grown in the United States naturally drop their fruit to the orchard floor, and the crop is harvested mechanically. The average yield in the United States was close to 2,600 kg $ha^{-1}$ in 2018, or 3.6 times greater than the yield reported in Turkey in the same year (FAO 2019).

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 the development of a single trunk, facilitating mechanized harvest (Mehlenbacher and Smith 1992). Suckers also affect mechanization and production practices in other crops. In vineyards, suckers can negatively affect operations such as tillage, herbicide sprays, harvest, pests, and disease control (Kang et al. 2012).

In addition to the operational challenges of multiple stems, suckers can weaken the growth of branches by competing for resources (Tous et al. 1992). Hazelnut suckers reduce the growth of the primary trunk, lengthen the juvenile phase, and reduce hazelnut yield (Mehlenbacher and Smith 1992); multi-stemmed plants may favor disease by reducing airflow within the canopy (Tomasone et al. 2008). Suckers may serve as a possible infection source of eastern filbert blight (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 may lead to substantial pathogen infestation and cause an imbalance in the fruit-to-shoot ratio (Dolci et al. 2004). In tobacco, suckers may reduce root growth and nutrient uptake (Weeks and Seltmann 1986).

Sucker control in hazelnut is labor-intensive (Serdar and Akyuz 2018). Sucker emergence and vigor are 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, such as disbudding the lower portion of the trunk, manual removal, thermal control, and chemical control (Dolci et al. 2000; Smith and Erdoğan 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 h of labor per hectare (Franco and Pancino 2008). Manual removal of suckers during the growing season is not economically feasible for most Oregon growers because of labor cost and availability. 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 because of 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 because of its 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, such as 2,4-D, paraquat, and glufosinate (Wiman et al. 2019). Still, effective control requires multiple applications, with reports of up to eight applications per season. However, four herbicide applications are recommended per season (Olsen and Peachey 2013). Changes in this practice may reflect both new varieties under cultivation and younger orchards in Oregon, as a result of industry expansion. 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.

## Materials and Methods

Two experiments were conducted to compare the efficacy of hazelnut sucker control using registered herbicides. The first study was a season-long management program comparing the effects of multiple applications of the same treatment in sucker control and growth. The number and frequency of applications followed local recommendations (Olsen and Peachey 2013). Based on the results of the first study in 2017, a second, short-term study was carried out in 2018 to evaluate the efficacy of the treatments after a single application. Field trials were conducted following recommended herbicide rates registered for use in hazelnuts in Oregon (Table 1).

**Table 1.** List of herbicides used in the experiments to compare efficacy of hazelnut sucker control in Oregon orchards.

| Common name | Trade name | Manufacturer | Location |
|---|---|---|---|
| 2,4-D acid | Saber | Loveland Products | Greeley, CO |
| Carfentrazone | Aim EC | FMC Corp. | Philadelphia, PA |
| Glufosinate | Rely280 | Bayer CropScience | Research Triangle Park, NC |
| Paraquat | Gramoxone SL 2.0 | Syngenta Crop Protection | Greensboro, NC |
| Pyraflufen | Venue | Nichino America, Inc. | Wilmington, DE |
| Saflufenacil | Treevix | BASF Corp. | Research Triangle Park, NC |

### *Season-long Control of Hazelnut Suckers*

Two studies were conducted to evaluate the efficacy of the sequential application of herbicides to hazelnut suckers (Table 2). The first study was conducted in Amity, OR (45.06° N, 123.17° W) in 2017 and repeated in 2018 in a different section of the same orchard. The research site was located in a well-drained Woodburn silt loam soil (USDA 2017). The orchard consisted of 10-yr-old 'Jefferson' hazelnuts planted 6 m by 6 m and irrigated with drip irrigation; standard production practices were followed (Olsen and Peachey 2013). The experiment was initiated when suckers reached an average height of 15 ± 5 cm, as recommended (15 to 22 cm height) (Olsen and Peachey 2013). Trees had at least 15 suckers present within a 0.5-m radius of the tree base at the beginning of the experiment. 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$^{-1}$ at 275 kPa. Applications were made as a single pass to each side of the tree row. Treatments were reapplied every 28 d, from May to August, during each year of the study. Four applications of the same treatment were made per season to each plot. In 2017, applications were made on May 8, June 19, July 18, and August 15. In 2018, treatments were applied May 1, May 29, June 26, and July 24.

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 28 d after treatment (DAT), and visual estimates of crop injury. The height of 10 suckers from the soil surface to the tip of the shoot per plot was measured at 28 DAT. At 28 DAT after the last application, a digital caliper was used to measure the diameters of 20 suckers per plot (10 per tree) at the base of the suckers (Fisherbrand™ Traceable™ Digital Calipers; Thermo-Fischer Scientific, Waltham, WA). Sucker base caliper diameter was transformed into a cross-sectional area using the following equation:

$$A = \pi(r)^2 \quad [1]$$

where $A$ is the cross-sectional area, $r$ is the radius, and π is a constant (3.14159). All suckers were harvested, dried at 70 C for 4 d, and the dried biomass recorded. The cross-sectional area and biomass reduction were calculated by the difference between treated and nontreated plots divided by treated plots.

**Table 2.** Hazelnut sucker biomass per tree and average sucker cross-sectional area measured 28 d after the fourth herbicide treatment in the season-long experiment conducted in a mature hazelnut orchard located in Amity, OR in 2017 and 2018 (long-term study).

| Treatment [a] | Rate [b] | Biomass | Biomass reduction | Cross-sectional area | Area reduction |
|---|---|---|---|---|---|
| | g ai or ae ha$^{-1}$ | g plant$^{-1}$ | % | cm$^2$ | % |
| Nontreated | – | 1,238 a | – | 58 a | –– |
| Manual removal | – | 76 c | 96 a | 12 b | 86 a |
| 2,4-D | 1,060 | 125 c | 89 a | 19 b | 68 ab |
| 2,4-D + glufosinate | 1,060 + 1,150 | 78 c | 93 a | 14 b | 75 ab |
| Carfentrazone | 35 | 401 b | 68 b | 24 b | 59 b |
| Glufosinate | 1,150 | 80 c | 93 a | 17 b | 70 ab |
| Glufosinate + carfentrazone | 1,150 + 35 | 139 c | 89 a | 17 b | 73 ab |
| Paraquat | 1,120 | 95 c | 91 a | 13 b | 76 ab |

[a]The sequential applications were made in May (first), June (second), July (third), and August (fourth) of each year. Means are the average of two field experiments ($n = 8$). Means followed by the same letter within columns are not significantly different at $P < 0.05$ using Tukey's HSD test. The biomass reduction and cross-sectional area reduction are relative to the nontreated control. All treatments included ammonium sulfate source at 1% v/v (Bronc Max; Wilbur-Ellis, Aurora, CO) except manual removal and nontreated. Treatments with 2,4-D, carfentrazone, or paraquat included nonionic surfactant at 0.25% v/v (Rainier EA; Wilbur-Ellis, Aurora, CO).
[b]Herbicide rate expressed as the active ingredient, acid equivalent, or volume per volume, as appropriate.

**Table 3.** Hazelnut sucker percentage control, height, dry biomass, and cross-sectional area 28 d after treatment of the short-term experiments in Oregon orchards.[a]

| Treatment [b] | Rate [c] | Control | Height | Biomass | Cross-sectional area |
|---|---|---|---|---|---|
| | g ai ha$^{-1}$ | % | cm | g plant$^{-1}$ | cm$^2$ |
| Nontreated | 0 | – | 24 a | 87 a | 8 a |
| Manual removal | 0 | 80 a | 9 d | 10 f | 4 b |
| 2,4-D | 1,060 | 79 ab | 13 cd | 19 c–f | 5 ab |
| 2,4-D + glufosinate | 1,060 + 1,150 | 68 a–d | 14 cd | 21 b–f | 5 ab |
| 2,4-D + pyraflufen | 1,060 + 70 | 62 cde | 16 cd | 36 bcd | 8 a |
| 2,4-D + saflufenacil | 1,060 + 49 | 64 a–d | 17 bc | 18 def | 5 ab |
| Carfentrazone | 35 | 41 fg | 18 abc | 42 bc | 7 ab |
| Glufosinate | 1,150 | 64 bcd | 16 bc | 23 b–f | 6 ab |
| Glufosinate + carfentrazone | 1,150 + 35 | 67 a–d | 15 c | 19 c–f | 5 ab |
| Glufosinate + pyraflufen | 1,150 + 70 | 58 de | 16 bc | 23 b–f | 6 ab |
| Glufosinate + saflufenacil | 1,150 + 49 | 73 abc | 13 cd | 13 ef | 5 ab |
| Paraquat | 1,120 | 58 de | 16 bc | 25 b–f | 6 ab |
| Pyraflufen | 70 | 29 g | 21 ab | 45 b | 6 ab |
| Saflufenacil | 49 | 46 ef | 18 abc | 33 b–e | 5 ab |

[a]Means are the average of four field experiments ($n = 16$) conducted in hazelnut orchard located in Canby and Corvallis, OR in 2018 (short-term study).
[b]All treatments included ammonium sulfate source at 1% v/v (Bronc Max; Wilbur-Ellis, Aurora, CO) except manual removal and nontreated. Treatments with 2,4-D, carfentrazone, or paraquat included nonionic surfactant at 0.25%v/v (Rainier EA; Wilbur-Ellis, Aurora, CO). Means followed by the same letter within columns are not significantly different at $P = 0.05$ using Tukey's HSD test.
[c]Herbicide rate expressed as the active ingredient, acid equivalent, or volume per volume, as appropriate.

## Short-Term Control of Hazelnut Suckers

Four field trials were conducted in mature orchards in the Willamette Valley in 2018. Experiments included 13 treatments and a nontreated control and followed methods similar to those described previously, with the exception that these trials were terminated at 28 DAT. The treatments included saflufenacil at 49 g ai ha$^{-1}$, 2,4-D at 1,060 g ai ha$^{-1}$ in combination with saflufenacil at 49 g ha$^{-1}$, glufosinate at 1,150 g ai ha$^{-1}$ in combination with saflufenacil at 49 g ha$^{-1}$, pyraflufen at 70 g ai ha$^{-1}$, 2,4-D at 1,060 g ae ha$^{-1}$ in combination with pyraflufen at 70 g ha$^{-1}$, glufosinate at 1,150 g ha$^{-1}$ in combination with pyraflufen at 70 g ha$^{-1}$ (Table 3). Two experiments were conducted near Canby, OR (45.17° N, 122.39° W), and two near Corvallis, OR (44.29° N, 123.13° W). Soils in the Canby orchards were a Latourell loam (USDA 2017); the crop was rain-fed with trees spaced 6.1 m by 6.1 m. The first study in Canby was in a 12-yr-old 'McDonald' hazelnut orchard. The study was initiated on May 1, when suckers were 15 cm ± 4 cm in height. The second Canby experiment was in a 5-yr-old 'Jefferson' orchard and started when suckers were 16 cm ± 5 cm in height on June 11. The Corvallis experiments were conducted in a 10-yr-old 'Jefferson' orchard on a nonirrigated Chehalis silt loam (USDA 2017). Two different locations within the same orchard were selected. The first trial was initiated on May 1, when suckers were on average 15 ± 4 cm in height in the first trial, and the second trial was initiated on June 12, when suckers were 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 diameter, biomass, and crop injury were measured 28 DAT as detailed in the previous section.

## Statistical Analysis

### Season-long Control of Hazelnut Suckers

The experiment was designed as a randomized complete block with eight treatments and four replicates; the experiment was conducted twice. Each experimental unit included two hazelnut trees. The individual trees were treated as subsamples, and assessments were averaged for each plot.

Statistical analysis was performed in RStudio 1.2.5042 (R Studio Team 2020) using a generalized linear mixed model (GLMM) with the package glmmTMB version 1.01 (Brooks et al. 2017). The experimental year, block, and interactions were considered random effects, as the goal was to estimate the effects of treatments over a broader scope (Moore and Dixon 2015). A GLMM with beta distribution was used to analyze the percentage control and crop injury data (Stroup 2015), using beta family and logit function in glmmTMB. This package allows the beta regression analysis with

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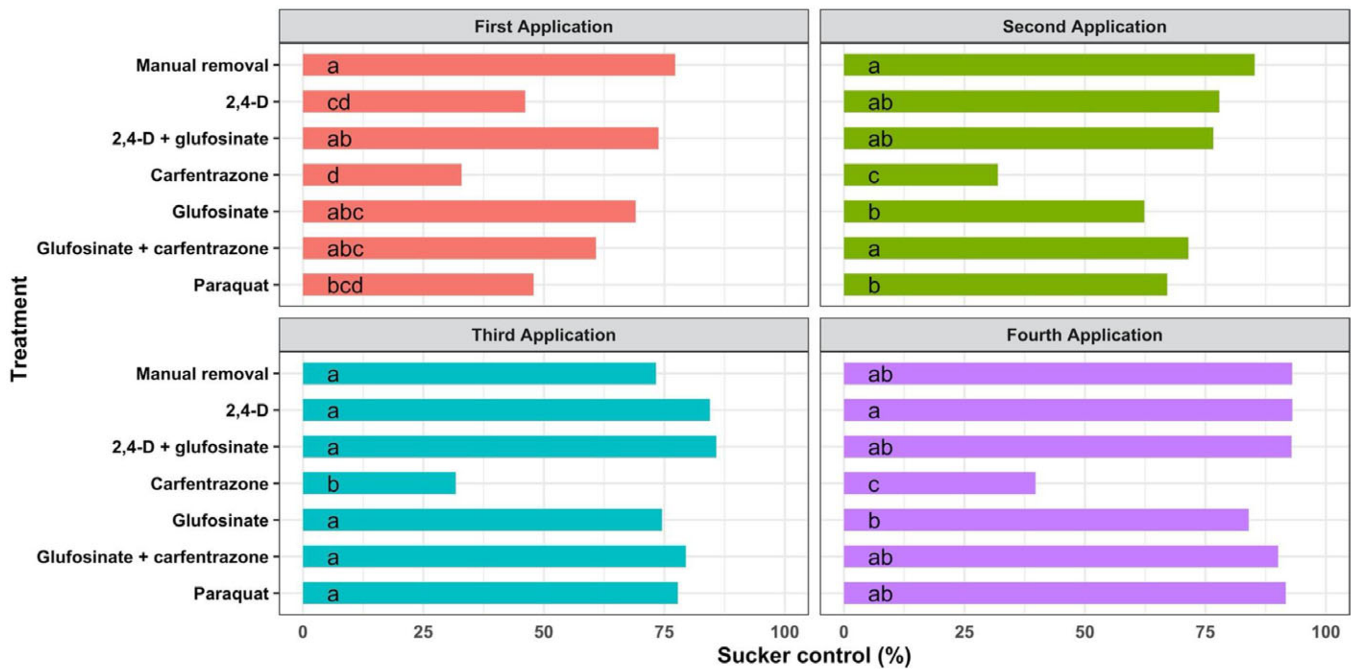


**Figure 1.** Hazelnut sucker control 28 d after treatment for each application period in a season-long sucker control program. The first (red bars), second (green bars), third (blue bars), and fourth (purple bars) evaluations were made in May, June, July, and August of each year, respectively. Data presented are means ($n = 8$) and standard errors of two combined experiments conducted in 2017 and 2018 in Amity, OR. Bars followed by the same letter within an application period are not statistically different based on Tukey's HSD test ($P < 0.05$).

mixed effects (Douma and Weedon 2019). The sucker height and the cross-sectional area were analyzed using the MASS package (Venables and Ripley 2002) using a GLMM with a Penalized Quasi-Likelihood estimation method to account for data overdispersion and normality issues (Bolker 2017). Means were compared using Tukey's HSD test, with a 95% confidence interval using the Multcomp or Eemeans package as appropriate (Hothorn et al. 2014; Lenth 2019).

### Short-Term Control of Hazelnut Suckers

The experiments were arranged in a randomized complete block design with four replicates composed of two trees per plot. Each tree was treated as a subsample, as described for the long-term study. The statistics procedures were conducted similarly to those in the long-term study. Experimental location and application timing was considered random in the GLMM and herbicide treatment as a fixed factor.

## Results and Discussion

### Season-long Control of Hazelnut Suckers

All treatments evaluated in this study had a significant effect on suckers. The effect of herbicide varied by application ($P < 0.001$); therefore, data were analyzed and are presented separately. In the first application, manual removal provided the highest sucker control rating (77%), and it was similar to control levels observed with glufosinate and mixtures of glufosinate with 2,4-D or carfentrazone (Figure 1). The 2,4-D-, carfentrazone-, or paraquat-alone treatments resulted in less than 50% control. The level of control for most treatments increased in the second application period, except carfentrazone. For instance, 2,4-D provided 77% control after the second application compared to 46% on the first application. In contrast, carfentrazone efficacy was 33% and 31% in the first and second applications. Following the third and fourth applications, treatments with 2,4-D, paraquat, and glufosinate resulted in sucker control levels comparable to manual removal ranging from 73% to 86% (Figure 1). Sucker control with carfentrazone was below 40% across all four application periods. No injury to the crop canopy, leaves, or trunks was observed after any sucker control treatment during the course of these trials (data not shown).

The average height of nontreated hazelnut suckers reached 57 cm 28 DAT after the first application (Figure 2). That is a 42-cm increase in growth compared to the initial 15-cm height, an average growth of 1.5 cm $d^{-1}$. All treatments tested reduced sucker height (<34 cm) when compared to the nontreated plots with no differences among treatments in the first evaluation period. After the second application timing, manual removal, 2,4-D, and 2,4-D mixed with glufosinate presented a mean sucker height of 36 cm, whereas other treatments were not different from the nontreated control (Figure 2). After the third application, all the treatments resulted in a sucker height of <49 cm compared to 134 cm in the nontreated plots. Carfentrazone-treated suckers were 76 cm, and the upper part of the sucker could not be treated with subsequent applications because the boom height was kept at 50 cm. As a result, suckers treated with carfentrazone were 105 cm tall on the fourth application, or approximately twice as tall as other treatments; nontreated suckers were 155 cm tall at that time. All other treatments resulted in suckers <51 cm tall (Figure 2).

Among all treatments, those containing 2,4-D, paraquat, and glufosinate resulted in the smallest sucker biomass, with less than 139 g $tree^{-1}$, a reduction of 89% to 96% compared to nontreated biomass (Table 2). Herbicide treatments, except for carfentrazone, were as effective as manual removal of suckers. All treatments also reduced the cross-sectional area of the suckers by 68% to 86%. The

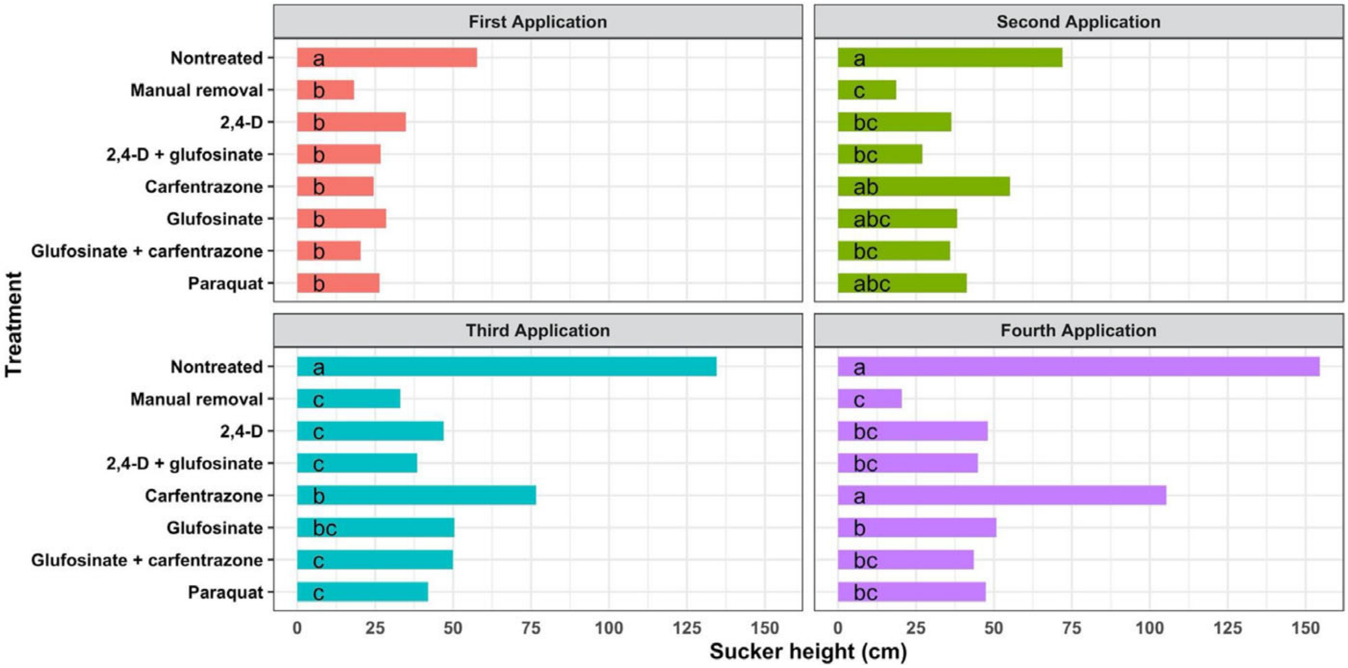


**Figure 2.** Hazelnut sucker height 28 d after treatment for each application period in a season-long sucker control program. The first (red bars), second (green bars), third (blue bars), and fourth (purple bars) evaluations were made in May, June, July, and August of each year, respectively. Data presented are means ($n = 8$) and standard errors of two combined experiments conducted in 2017 and 2018 in Amity, OR. Bars followed by the same letter within an application period are not statistically different based on Tukey's HSD test ($P < 0.05$).

results indicated that 2,4-D, paraquat, and glufosinate are effective options for sucker control. In general, mixtures did not improve the efficacy of sucker control when compared to single products; however, mixtures can be a good option when considering both weed and sucker control.

## Short-Term Control of Hazelnut Suckers

The results of the short-term study indicate that 2,4-D and its mixtures with carfentrazone, glufosinate, or saflufenacil controlled suckers to levels comparable to manual removal (Table 3). 2,4-D plus pyraflufen was less effective than 2,4-D alone or manual removal. The mixture of glufosinate with saflufenacil or carfentrazone with 67% and 73% control, respectively, were as effective as manual removal, but not different from glufosinate alone. Carfentrazone, saflufenacil, and pyraflufen provided less control than glufosinate. Treatments with 2,4-D, glufosinate, and paraquat suppressed sucker growth, with height 28 DAT ranging between 13 and 17 cm, compared to 24 cm in the nontreated plots. Carfentrazone, pyraflufen, and saflufenacil alone resulted in sucker height similar to nontreated. In contrast, all treatments reduced sucker biomass compared to the nontreated control. Treatments with 2,4-D, glufosinate, paraquat, and saflufenacil resulted in biomass between 13 and 36 g plant$^{-1}$ compared to 87 g plant$^{-1}$ of the nontreated. However, none of these treatments reduced the sucker cross-sectional area (Table 3).

The long-term and short-term studies 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 1970 study, 2,4-D and paraquat were mixed at 0.25% v/v in 378 L of water and applied to suckers to the point of run-off rather than on a per-hectare basis. This spray volume 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.

Although the literature on sucker control in hazelnut is limited, chemical control of suckers 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 rootstock 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, but manual removal always resulted in greater reductions in 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 s tree$^{-1}$ in orchards planted at a density of 540 trees ha$^{-1}$ (Franco and Pancino 2008). Removal of larger diameter suckers required more time. A de-suckering operation would cost between \$135 and \$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 (\$6,750 ha$^{-1}$ yr$^{-1}$) (Miller et al. 2013). As the labor wages continue to increase, the current costs are much higher. As for herbicides, multiple applications are also required, but the costs would be between three and nine 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, because of maximum allowable per-season rates. In addition to sucker control, herbicide

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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 influencing spray coverage and penetration. The common recommendation is to apply the herbicides when suckers average 15 cm in height. Because sucker emergence is not uniform, variability in sucker height can be substantial. Further studies evaluating application parameters are required to improve the efficacy of sucker control with herbicides.

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## References

Anonymous (1996) Saber® herbicide product label. Loveland Publications. No. 34704-803. Greeley, CO. Loveland Products Inc. 21 p

Anonymous (2019) Global hazelnut market––growth, trends, and forecast (2020–2025). http://www.mordorintelligence.com/industry-reports/global-hazelnut-market. Accessed: April 5, 2020

Bolker B (2017) Dealing with quasi-models in R. Compare 1:5.452305

Brooks ME, Kristense K, van Benthem KJ, Magnusson A, Berg CW, Nielsen A, Skaug HJ, Machler M, Bolker BM (2017) glmmTMB balances speed and flexibility among packages for zero-inflated generalized linear mixed modeling. R J 9:378–400

Dolci M, Galeotti F, Curir P, Schellino L, Gay G (2004) New 2-naphthyloxyacetates for trunk sucker growth control on grapevine (*Vitis vinifera* L.). Plant Growth Regul 44:47–52

Dolci M, Schellino L, Radicati L (2000) Control of sucker growth in hazelnut with esters of 1-naphthylacetic acid. Pages 431–436 *in* Mehlenbacher SA, ed, Proceedings of the Vth International Congress on Hazelnut. Corvallis, OR: International Society of Horticultural Sciences

Douma JC, Weedon JT (2019) Analysing continuous proportions in ecology and evolution: A practical introduction to beta and Dirichlet regression. Methods Ecol 10:1412–1430

[FAO] Food and Agriculture Organization of the United Nations (2019) FAOSTAT statistical database. http://www.fao.org/faostat/en/#data/QC. Accessed: April 28, 2020

Franco S, Pancino B (2008) Economic result of organic hazelnut cultivation in the Monti Cimini area. Pages 783–788 *in* Varvaro L, Franco S, eds, Proceedings of the VIIth International Congress on Hazelnut. Viterbo, Italy. Lazio, Italy: International Society of Horticultural Sciences

Hothorn T, Bretz F, Westfall P, Heiberger RM, Schuetzenmeister A, Scheibe S (2014) multcomp: Simultaneous inference in general parametric models. R package version:1.4-12. https://cran.r-project.org/web/packages/multcomp/index.html. Accessed: November 20, 2019

Kang F, Wang H, Pierce FJ, Zhang Q, Wang S (2012) Sucker detection of grapevines for targeted spray using optical sensors. Trans ASABE 55: 2007–2014

Kaya-Altop E, Haghnama K, Sarıaslan D, Phillippo CJ, Mennan H, Zandstra BH (2016) Long-term perennial weed control strategies: economic analyses and yield effect in hazelnut (*Corylus avellana*). Crop Prot 80:7–14

Lenth R (2019) Emmeans package: Estimated Marginal Means, aka Least-Squares Means. R package version 1.3. 5.1. https://CRAN. R-project. org/package= emmeans. Accessed: August 1, 2020

Mehlenbacher SA, Smith DC (1992) Effect of spacing and sucker removal on precocity of hazelnut seedlings. J Am Soc Hort Sci 117:523–526

Mercanligil S, Arslan P, Alasalvar C, Okut E, Akgül E, Pınar A, Geyik PÖ, Tokgözoğlu L, Shahidi F (2007) Effects of hazelnut-enriched diet on plasma cholesterol and lipoprotein profiles in hypercholesterolemic adult men. Eur J Clin Nutr 61:212

Meyers JM, Faucett J, Tejeda DG, Kabashima J, Miles JA, Janowitz I, Duraj V, Smith R, Weber E (2000) High risk tasks for musculoskeletal disorders in agricultural field work. Pages 616–619 *in* Proceedings of the Human Factors and Ergonomics Society Annual Meeting. https://journals.sagepub.com/doi/10.1177/154193120004402232. Accessed: August 1, 2020

Miller M, Seavert CF, Olsen JL (2013) Orchard Economics: The Costs and Returns of Establishing and Producing Hazelnuts in the Willamette Valley. Corvallis, OR: Oregon State University Extension Service, AEB 43. p 29

Molnar TJ, Goffreda JC, Funk CR (2010) Survey of *Corylus* resistance to *Anisogramma anomala* from different geographic locations. HortScience 45:832–836

Moore KJ, Dixon PM (2015) Analysis of combined experiments revisited. Agron J 107:763–771

Muro J, Luri E (1990) Initial control and subsequent regrowth inhibition of plum suckers in a peach orchard. Page 179–187 *in* Proceedings of la Reunión de la Sociedad Española de Malherbología. Madrid, Spain: Sociedad Española de Malherbología

Murray K, Jepson P (2018) An integrated pest management strategic plan for hazelnuts in Oregon and Washington. Oregon State University Extension Service, AEB EM 9223. https://catalog.extension.oregonstate.edu/sites/catalog/files/project/pdf/em9223.pdf. Accessed: August 1, 2020

Norsworthy JK, Ward SM, Shaw DR, Llewellyn RS, Nichols RL, Webster TM, Bradley KW, Frisvold G, Powles SB, Burgos NR (2012) Reducing the risks of herbicide resistance: best management practices and recommendations. Weed Sci 60 (SP 1):31–62

Olsen J, Peachey E (2013) Growing hazelnuts in the Pacific Northwest: orchard floor management. Oregon State University Extension Service, AEB EM 9079. https://catalog.extension.oregonstate.edu/sites/catalog/files/project/pdf/em9079.pdf. Accessed: August 3, 2020

Reich JE (1970) The use of 2, 4-D, paraquat and dinoseb for control of filbert (*Corylus avellana* L.) suckers. M.S. thesis. Corvallis, OR: Oregon State University. 66 p

R Studio Team (2020) RStudio: Integrated Development R. RStudio, Inc. http://www.rstudio.com. Accessed: February 20, 2020

Serdar U, Akyuz B (2018) Sucker management methods in hazelnut cultivation. Pages 309–314 *in* Tuncer C, Erdoğan V, eds, Proceedings of the IX International Congress on Hazelnut. Atakum, Samsun, Turkey. Leuven, Belgium: International Society of Horticultural Sciences

Smith DC, Erdoğan V (2001) Elimination of hazelnuts suckers by disbudding. Pages 263–268 *in* Mehlenbacher SA, ed, Proceedings of the Vth International Congress on Hazelnut, Corvallis, OR. Leuven, Belgium: International Society of Horticultural Sciences

Stroup WW (2015) Rethinking the analysis of non-normal data in plant and soil science. Agron J 107:811–827

Tomasone R, Colorio G, Cedrola C, Pagano M (2008) Mechanical and physical control of hazelnut suckers. Pages 407–412 *in* Varvaro L, Franco S, eds, Proceedings of the VIIth International Congress on Hazelnut, Viterbo, Italy: International Society of Horticultural Sciences

Tomasone R, Colorio G, Cedrola C, Pagano M (2010) Thermal control of hazelnut suckers. Pages 13–17 *in* Savoie P, Villeneuve J, Morisette R, eds, Proceedings of the XVIIth World Congress of the International Commission of Agricultural Engineering (CIGR). Québec City, Canada: Canadian Society of Bioengineering

Tous J, Girona J, Tasias J (1992) Cultural practices and costs in hazelnut production. Pages 395–418 *in* Me G, Radicati L, eds, Proceedings of the IIIth International Congress on Hazelnut, Alba, Italy. Piedmont, Italy: International Society of Horticultural Sciences

[USDA] United States Department of Agriculture, Natural Resources Conservation Service (2017) Web soil survey. https://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm. Accessed: August 3, 2020

[USDA NASS] United States Department of Agriculture National Agricultural Statistics Service (2019) Noncitrus Fruits and Nuts 2018 summary. Washington, DC. 101 p

Venables W, Ripley B (2002) Random and mixed effects. Pages 271–300 *in* Chambers J, Eddy W, Hardle W, Sheather S, Tierney L, eds, Modern Applied Statistics with S: Statistics and Computing. New York: Springer-Verlag

Weeks WW, Seltmann H (1986) Effect of sucker control on the volatile compounds in flue-cured tobacco. J Agric Food Chem 34: 899–904

Wiman NG, Pscheidt JW, Moretti M (2019) 2019 Hazelnut pest management guide for the Willamette Valley. Oregon State University Extension Service, AEB EM 8328. https://catalog.extension.oregonstate.edu/em8328