Carrier Volume and Nozzle Effect on 2,4-D and Glufosinate Performances in Hazelnut Sucker Control

Larissa Larocca de Souza and Marcelo L. Moretti

Department of Horticulture, Oregon State University, 4017 Agriculture and Life Sciences Building, Corvallis, OR 97331

Additional index words. spray technology, *Corylus avellana*, basal sprout, filbert

Abstract. Hazelnut (*Corylus avellana* L.) basal sprouts, or suckers, are removed to train trees as a single trunk, facilitating mechanization. Suckers are routinely controlled with herbicides, often by using nozzles that generate fine droplets and spray volumes as high as 934 L·ha⁻¹, making spray drift a concern. Spray nozzle type and carrier volume can impact herbicide efficacy and drift. Field studies compared the efficacy of 2,4-D and glufosinate in controlling suckers when applied with a flat-fan nozzle, producing fine droplets, to a TeeJet air-induction nozzle, producing ultra-coarse droplets. These nozzles were evaluated at 187 and 374 L·ha⁻¹. Nozzle and carrier volume did not affect the efficacy of 2,4-D based on control, sucker height, or dry weight. The efficacy of glufosinate was unaffected by nozzle type or spray volume in most evaluations. These results indicate that hazelnut suckers can be effectively controlled using drift-reduction nozzles with lower carrier volumes (187 L·ha⁻¹). Drift-reduction nozzles, coupled with lower spray volume, can maintain herbicide efficacy, minimize drift risk, and reduce cost.

The application of herbicides is the most common practice for the control of suckers in Oregon hazelnut production (de Souza and Moretti, 2020). Hazelnut naturally grows as a multistem bush but is trained as a single trunk by pruning suckers to benefit mechanization of harvest and increase yield (Mehlenbacher and Smith, 1992). The vigorous growth of suckers requires four or more herbicide applications during the growing season (de Souza and Moretti, 2020; Olsen and Peachey, 2013). 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 with abiotic aspects of environment and spray equipment (Kudsk, 2002). Carrier volume and droplet size are spray quality parameters that can interfere with herbicide efficacy. It is well established that spray coverage improves with increasing spray volume—to a

point. In broad terms, spray volumes increasing up to 100 L·ha⁻¹ improve herbicide efficacy, while a decrease in efficacy is observed when volumes are increased to 400 L·ha⁻¹ (Knoche, 1994). Coverage is arguably more critical for the efficacy of contact herbicides. Droplet size also impacts spray coverage; smaller droplets increase coverage compared with larger droplets at a constant volume (Knoche, 1994). Herbicide efficacy is often greater with fine droplets compared with coarse droplets (Butts et al., 2018), while other studies have shown that changes in droplet size may increase or have no effect on the efficacy of systemic herbicides (Creech et al., 2016; Etheridge et al., 2001; Feng et al., 2003). Although the effect of droplet size on efficacy is herbicide-specific, there is a clear reduction in drift potential with increasing droplet size (Butts et al., 2018; Hewitt, 1997; Johnson et al., 2006). Economic and environmental concerns prioritize the reduction of spray drift and application volume while maintaining herbicide efficacy (Etheridge et al., 2001).

Recommendations for sucker control by herbicide have not changed for many years. The hazelnut industry perceives that high carrier volumes are required for efficacy. That perception may be based on work developed for spot treatments using up to 935 L·ha⁻¹ (Reich, 1970). Growers commonly use between 233 to 467 L·ha⁻¹ for sucker control regardless of herbicide choice (Moretti, personal observation). Two herbicides widely used for sucker control are 2,4-D and glufosinate, a systemic and a contact herbicide, respectively. Carrier volumes greater than 94 L·ha⁻¹ have been recommended for best performance with 2,4-D. According to Creech

et al. (2015), droplet size did not influence efficacy, while Creech et al. (2016) found very coarse droplets to be beneficial. Glufosinate efficacy was reportedly optimized between 140 and 281 L·ha⁻¹ with medium to coarse droplet sizes compared across several plant species (Creech et al., 2016). Spray droplet size is, in part, determined by spray nozzles. Drift-reduction nozzles are an effective option for producing larger droplets (Etheridge et al., 1999). Nozzles mostly used in hazelnut orchards are flat-fan nozzles that generate fine droplets. The objective of this study was to compare the use of drift-reduction nozzles with flat-fan nozzles for control of hazelnut suckers, and its interaction with carrier volume and herbicide.

Materials and Methods

Two experiments were designed to compare the effect of the spray nozzle and carrier volume on hazelnut sucker control. A season-long study was designed to compare treatments after four applications following available recommendations (Olsen and Peachey, 2013). A short-term study followed a similar treatment structure but was concluded 28 d after treatment.

Season-long study. The season-long study was conducted in 2017 and 2018 in a mature hazelnut orchard located in Amity, OR. The site is a well-drained Woodburn silt loam soil (Soil Survey Staff, 2020). The orchard was a 10-year-old Jefferson cultivar planted at 6 × 6 m. Irrigation was applied using a single drip line per tree row. Suckers were located up to 0.5 m around the main trunk, and all trees had 15 suckers on average at the initiation of the experiments. The first application was made at an average sucker height of 14 ± 5 cm. Treatments were applied using a CO₂ pressurized backpack sprayer equipped with a three-nozzle boom. An application consisted of one pass to each side of the tree row. The sprayer was calibrated before each application to ensure the carrier volume was delivered within ± 5% of the targeted volume. Variable travel speed and different spray nozzles were used to achieve desired volumes. Four consecutive applications were performed 4 weeks apart between May and August of each year. In 2018, the experiment was repeated in a different section of the same orchard.

The treatments compared were the systemic herbicide 2,4-D (Saber; Loveland Products, Loveland CO) at 1060 g·ha⁻¹ acid equivalent (a.e.), and the contact herbicide glufosinate (Rely 280; BASF, Durham, NC) at 1150 g·ha⁻¹ a.i. Treatments included ammonium sulfate at a rate equivalent to 10 g·L⁻¹. A non-ionic surfactant was included in the 2,4-D treatment at 0.25% v/v (Rainier EA, Wilbur Ellis, Aurora, CO). Herbicides were applied at 187 or 374 L·ha⁻¹ at 275 kPa of pressure. We tested the extended range (XR) flat-fan nozzle (TeeJet Technologies, Glendale Heights, IL) XR11002 at 187 L·ha⁻¹ and XR11004 for 374 L·ha⁻¹; these nozzles generate fine and medium droplets (based on

Received for publication 16 July 2020. Accepted for publication 15 Sept. 2020.

Published online 19 October 2020.

The Oregon Hazelnut Commission supported this work.

We thank Hazelwood Orchards and Birkemeier Farms & Nursery for field study collaborations. We acknowledge the assistance of undergraduate students and staff in data collection.

L.L.d.S. is a Graduate Student.

M.L.M. is an Assistant Professor.

M.L.M. is the corresponding author. E-mail: marcelo.moretti@oregonstate.edu.

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Table 1. Hazelnut sucker control (%) and height (cm) 28 d after treatment in a ‘Jefferson’ hazelnut orchard located in Amity, OR in 2017 and 2018 (season-long control).

			Control				Ht			
			First	Second	Third	Fourth	First	Second	Third	Fourth
Treatment ^z	Volume (L.ha ⁻¹)	Nozzle	(%)				(cm)			
Manual removal	—	—	79	83	70	96	28	30	36	15
2,4-D ^{y,x}	187	Flat fan	57	78	90	94	34	37	41	45
		TTI	58	76	85	94	36	41	46	48
	364	Flat fan	58	76	89	93	32	37	39	42
		TTI	53	75	82	94	33	41	46	49
Glufosinate	187	Flat fan	58	62	78	92	32	41	48	51
		TTI	54	67	84	94	33	39	43	44
	364	Flat fan	58	64	76	93	28	41	50	53
		TTI	51	61	74	90	33	43	50	54
Orthogonal contrasts										
2,4-D	187 vs. 374 L.ha ⁻¹		57 vs. 56	77 vs. 76	87 vs. 85	94 vs. 94	35 vs. 33	39 vs. 39	43 vs. 42	47 vs. 46
	Flat fan vs. TTI		58 vs. 55	77 vs. 75	90 vs. 83*	93 vs. 94	33 vs. 35	37 vs. 41	40 vs. 46*	44 vs. 49
Glufosinate	187 vs. 374 L.ha ⁻¹		56 vs. 54	64 vs. 62	81 vs. 75**	93 vs. 92	33 vs. 30	40 vs. 42	45 vs. 50	48 vs. 53
	Flat fan vs. TTI		58 vs. 53	63 vs. 64	77 vs. 79	92 vs. 92	30 vs. 33	41 vs. 41	49 vs. 46	52 vs. 49

^zAll treatments included ammonium sulfate source at 1% vol/vol (Bronc Max, Wilbur-Ellis); 2,4-D was applied at 1060 g·ha⁻¹ a.i. and glufosinate at 1150 g·ha⁻¹ a.i. Herbicide rate is expressed as the active ingredient (a.i.) or acid equivalent (a.e.), as appropriate.

^yIncludes non-ionic surfactant at 0.25% vol/vol (Rainier EA, Wilbur-Ellis).

^xThe sequential applications were made in May (first), June (second), July (third), and August (fourth) of each year.

*, **Significant at $P < 0.05$ or 0.01 , respectively.

Table 2. Hazelnut sucker weight (g) and cross-section area (cm²) 28 d after the last treatment in a ‘Jefferson’ hazelnut orchard located in Amity, OR in 2017 and 2018 (season-long).

Treatment ^z	Volume (L·ha ⁻¹)	Nozzle type	Wt (g/plant)	Cross-sectional area (cm ²)
Manual removal	—	—	77	9
2,4-D ^{y,x}	187	Flat fan	106	11
		TTI	132	11
	364	Flat fan	145	13
		TTI	111	13
Glufosinate	187	Flat fan	199	13
		TTI	131	12
	364	Flat fan	147	12
		TTI	139	14
<i>Orthogonal contrast</i>				
2,4-D	187 vs. 374 L·ha ⁻¹		119 vs. 128	11 vs. 13
	Flat fan vs. TTI		125 vs. 122	12 vs. 12
Glufosinate	187 vs. 374 L·ha ⁻¹		165 vs. 143	13 vs. 13
	Flat fan vs. TTI		173 vs. 135	13 vs. 13

^zAll treatments included ammonium sulfate source at 1% vol/vol (Bronc Max, Wilbur-Ellis); 2,4-D was applied at 1060 g·ha⁻¹ a.i. and glufosinate at 1150 g·ha⁻¹ a.i. Herbicide rate is expressed as the active ingredient (a.i.) or acid equivalent (a.e.), as appropriate.

^yIncludes non-ionic surfactant at 0.25% vol/vol (Rainier EA, Wilbur-Ellis).

^xThe sequential applications were made in May (first), June (second), July (third), and August (fourth) of each year.

*, **Significant at $P < 0.05$ or 0.01 , respectively.

manufacturer’s information) (TeeJet Technologies, 2020). We also tested drift-reduction nozzles Turbo TeeJet Induction (TTI) TTI11002 and TTI11004 at 187 L·ha⁻¹ and XR11004 for 374 L·ha⁻¹, respectively. According to the manufacturer, these nozzles have a pre-orifice chamber and air-induction to generate ultra-coarse droplets. Droplet nomenclature is based on the American Society of Agricultural and Biological Engineers (ASABE) standard S-572.1 (ASABE, 2009). Manual pruning was included as a reference, with suckers removed at the same time the herbicide treatments were applied. An experimental unit consisted of eight trees, and each individual tree was treated as a sub-sample. An average assessment was given to each plot.

Assessments. Sucker control was estimated on a scale of 0 to 100, where 0 is no control, and 100 is complete control. The average height of 10 suckers per experimental unit was assessed at 28 d after treatment

(DAT) for each application. Sucker dry weight and cross-sectional area were recorded 28 d after the final treatment. The cross-sectional area was measured by recording the diameter of 20 suckers per experimental unit, using a caliper (Fisherbrand Traceable Digital Calipers; Thermo Fischer Scientific, Waltham, WA). Diameter data were transformed into a cross-sectional area. Crop damage was not observed during the experiment.

Short-term studies. The short-term field studies followed the same experimental design and evaluation as previously described, except that treatments were applied only once, and the experiment was concluded after 28 d. Hazelnut growers treat suckers about every 4 weeks or less. A total of four studies were conducted in 2018. Two studies were in Canby, OR (lat. 45°17′N, long. 122°39′W), on a Latourell loam soil (Soil Survey Staff, 2020). Trees were spaced at 6 × 6 m and were rainfed. The orchard consisted of 12-year-old ‘McDonald’ trees. The first trial was initiated

in May when suckers were 15 cm ± 4 cm in height, and the second study was initiated in June about 4 weeks after the first application of a burndown herbicide by the grower. The suckers were 14 ± 4 cm in height. Two different sections of the same orchard were used for each study.

Two other trials were conducted in Corvallis, OR (lat. 44°29′N, long. 123°13′W) on ‘Jefferson’ hazelnut trees growing in a Chelalis silt loam soil (Soil Survey Staff, 2020). The first trial began in May when suckers had reached 16 ± 5 cm in height. The second study was initiated in June in a different area of the same orchard when suckers were 14 ± 5 cm in height. The site of the second study was treated 4 weeks prior with a burndown herbicide by the grower. Assessments were made as described in the season-long study. Crop damage was not observed during the experiment.

Statistical analysis. The long-term experiment was a four-factor factorial study

Fig. 1. Hazelnut sucker response to herbicides applied with different nozzle types and carrier volume 4 weeks after treatment. Glufosinate (1150 g·ha⁻¹ a.i.) and 2,4-D (1060 g·ha⁻¹ a.e.) were applied at 187 or 384 L·ha⁻¹ using a flat-fan (FF) or a Turbo TeeJet Induction (TTI) nozzle. Manual removal was included for comparison. Means and 95% confidence interval (n = 16) were calculated across four short-term experiments conducted in Canby, OR and Corvallis, OR in 2018. Treatments were not statistically different according to Tukey's test ($P < 0.05$).

Table 3. The response of hazelnut sucker control (%), height (cm), dry weight (g), and cross-sectional area (cm²) based on pre-defined comparisons using orthogonal contrasts for the short-term study.

Contrast ^z		Group means	Control (%)	Ht (cm)	Wt (g/plant)	Cross-section (cm ²)
2,4-D ^y	Carrier volume	187 vs. 374 L·ha ⁻¹	86 vs. 86	24 vs. 26	14 vs. 17	5 vs. 5
	Nozzle type	Flat fan vs. TTI	85 vs. 83	22 vs. 26	11 vs. 18	4 vs. 6
Glufosinate	Carrier volume	187 vs. 374 L·ha ⁻¹	86 vs. 86	21 vs. 21	8 vs. 8	4 vs. 4
	Nozzle type	Flat fan vs. TTI	86 vs. 80*	21 vs. 27 **	8 vs. 14	4 vs. 4

²All treatments included ammonium sulfate source at 1% vol/vol (Bronc Max, Wilbur-Ellis); 2,4-D was applied at 1060 g·ha⁻¹ a.e. and glufosinate at 1150 g·ha⁻¹ a.i. Herbicide rate is expressed as the active ingredient (a.i.) or acid equivalent (a.e.), as appropriate.

³Includes non-ionic surfactant at 0.25% vol/vol (Rainier EA, Wilbur-Ellis).

*, **Significant at $P < 0.05$ or 0.01, respectively.

organized as a randomized complete block design with four replicates. The factors were application timing, herbicide, nozzle type, and carrier volume. Data were submitted to a generalized linear mixed model using RStudio (RStudio Team, 2020). Random factors included experimental year, block, and their interactions, because the focus of the study was to infer across years. The data were analyzed using the package glmmTMB version 1.01 (Brooks et al., 2017). Control data were analyzed with beta distribution, a suitable distribution for proportions, and percentages of continuous data (Douma and Weedon, 2019). Height, weight, and cross-sectional area were analyzed using a Gaussian distribution. Means were compared using Tukey's honestly significant difference test. Orthogonal tests were designed for specific comparisons of the effects of carrier volume and nozzle type for each herbicide. We observed a significant effect of application timing and treatment. Data were analyzed by the application event.

The short-term studies were analyzed as a three-factor factorial study organized as a

randomized complete block design with four replicates. The factors were herbicide, nozzle type, and carrier volume. The experiment was repeated in four locations. Random factors included experimental location, block, and their interactions. Data analysis was like that described for the long-term study.

Results

Season-long study. In the first application, sucker control ranged from 51%, with glufosinate sprayed at 364 L·ha⁻¹ using TTI nozzle, to 79% with manual removal; but there were no differences among treatments (Table 1). Performance of glufosinate and 2,4-D were comparable and unaffected by carrier volume or nozzle type. The level of control increased with the number of applications to 61% to 83% following the second application, 74% to 90% with the third, and 90% to 96% with the fourth. The 2,4-D and glufosinate control were equivalent to manual removal (96%). For the same period, all treatments presented at least 90% of sucker control (Table 1).

Sucker height was similar to sucker control, indicating no effect of carrier volume or nozzle type used. We observed no differences in sucker height with 2,4-D or glufosinate treatment across all application events, but suckers continued to grow during the season despite four consecutive treatments. At the end of the experiment, sucker height ranged from 15 cm (manual removal) to 54 cm. Orthogonal contrasts also indicate that carrier volume did not affect 2,4-D efficacy in any of the applications when averaged across nozzle types. When comparing nozzle type, we observed no differences for 2,4-D except at the third application event, when flat-fan nozzles provided 90% control compared with 83% with TTI nozzles. We noticed a similar difference with sucker height at that time; but in both cases, the difference was not significant for management impact. Comparisons among glufosinate treatments indicate no differences in control or sucker height for carrier volume or nozzle type. The only instance of a significant effect of carrier volume was observed in the third application. That difference was not observed for sucker

height nor after the fourth application. Evaluation of sucker weight and the cross-sectional area also showed no effect of carrier volume or nozzle type. Among all treatments, sucker weight ranged from 77 to 199 g/plant, and the cross-sectional area ranged from 9 to 14 cm² (Table 2). Orthogonal contrasts indicated no differences between treatments for herbicides, nozzles, or carrier volumes.

Short-term study. The results of the short-term study support the findings of the long-term study. Manual removal, 2,4-D, and glufosinate treatments provide control ranging from 74% to 86% (Fig. 1). Sucker height (21–27 cm), weight (8–19 g), and cross-sectional area (3–6 cm²) were unaffected by treatment. We observed differences for sucker control and sucker height with nozzle type based on contrast for glufosinate (Table 3); however, differences noticed between flat-fan and TTI nozzles were only 6% of sucker control (80% and 86%) and 6 cm of sucker height (21 and 27 cm) (Table 3). No difference was seen between nozzle types or spray volume for 2,4-D (Fig. 1). Orthogonal contrasts indicated no differences for sucker dry weight or cross-section area parameters for herbicides, carrier volumes, or nozzle types (Table 3).

Discussion

Carrier volume did not affect sucker control with either herbicide. This study is the first report to evaluate the influence of carrier volume in sucker control, but there are several studies on other cropping systems for weed control (Knoche, 1994). A previous study reported improvement in 2,4-D efficacy on several weed species when spray volume was between 94 and 284 L·ha⁻¹ (Creech et al., 2015). However, the authors reported that higher carrier volume could be detrimental to certain weed species such as velvetleaf (*Abutilon theophrasti* Medik). That effect was attributed to spray running off leaves (Creech et al., 2015). Greater 2,4-D efficacy with increasing carrier volume likely is not a result of an increase in spray coverage, as the efficacy of a systemic herbicide's efficacy, such as 2,4-D, is more resilient against change in spray coverage (Ramsdale and Messersmith, 2001a). Changes to carrier volume may influence herbicide uptake. Uptake of 2,4-D increased with greater carrier volume in *Phaseolus vulgaris* seedlings (Knoche and Bukovac, 1999).

Nor did carrier volume affect glufosinate efficacy. This result agrees with previous work reporting no impact of reduced carrier volume on glufosinate efficacy (Butts et al., 2018; Etheridge et al., 2001), nor on other contact herbicides such as paraquat (Ramsdale and Messersmith, 2001a), nor on carfentrazone (Ramsdale and Messersmith, 2001b). The present study compared carrier volume ranging from 187 to 384 L·ha⁻¹, volumes much greater than those in studies of weed control; but these values are 2.5- to 5-fold lower than previous research in sucker control (Reich, 1970). Further, the volumes used

in this study did not reduce sucker control efficacy. Reduction in spray volume to 187 L·ha⁻¹ can significantly increase the acreage covered by sprayers in orchards, increase their efficiency, and reduce costs. It is important to note that the height of suckers at the time of treatment was within the recommended size on the herbicide label. The size of the target or its canopy structure can impact herbicide performance (Legleiter et al., 2018). One might observe different results when larger suckers are treated.

Nozzle type did not affect sucker control in this study. The flat-fan and TTI nozzles tested generated fine to ultra-coarse droplets, respectively. An increase in droplet size is often associated with a reduction in herbicide efficacy (Knoche, 1994). Despite the differences in droplet size, flat-fan and TTI nozzles were equally effective in controlling hazelnut suckers with 2,4-D and glufosinate in this study. Drift-reduction nozzles have provided similar efficacy for weed control. The efficacy of 2,4-D with the TTI nozzle, among other drift-reduction nozzles, was not different from the flat-fan nozzle when weed density and size were low (Legleiter et al., 2018). In this study, equivalent efficacy was likely the result of high carrier volumes. High carrier volumes have been reported to minimize the impact of droplet size on herbicide efficacy (Butts et al., 2018).

These results demonstrate that hazelnut suckers can be effectively controlled with 187 L·ha⁻¹ carrier volume with 2,4-D or glufosinate. The use of TTI, and possibly other drift-reduction nozzles producing coarse droplets, can maintain herbicide efficacy when suckers are within the recommended size range. We must underscore that although the nozzles tested resulted in equivalent efficacy, the potential for drift is greatly reduced with TTI nozzles. Both glufosinate and 2,4-D can be safely used in hazelnuts if they are not sprayed on the canopy or any desired foliage. During sucker control, it is essential to use TTI or other drift-reduction nozzles to minimize off-target herbicide movement and damage.

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