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Season-long weed control with sequential herbicide programs in California tree nut crops

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Research Article

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Abstract

Weed control in tree nut orchards is a year-round challenge for growers that is particularly intense during winter through summer as a result of competition and interference with management and harvest operations. A common weed control program consists of an application of a winter PRE and POST herbicide mixture, followed by a desiccation treatment in early spring and before harvest. Because most spring and summer treatments depend on a limited number of foliar-applied herbicides, summer-germinating species and/or herbicide-resistant biotypes become troublesome. Previous research has established effective PRE herbicide programs targeting winter glyphosate-resistant weeds. However, more recently, growers have reported difficulties in controlling several summer-germinating grass weeds with documented or suspected resistance to the spring and summer POST herbicide programs. In this context, research was conducted to evaluate a sequential PRE approach to control winter- and summer-germinating orchard weeds. Eight field experiments were conducted in tree nut orchards to evaluate the efficacy of common winter herbicide programs and a sequential herbicide program for control of a key summer grass weed species. In the sequential-application strategy, three foundational herbicide programs applied in the winter were either mixed with pendimethalin, followed with pendimethalin in March, or applied as a split application of pendimethalin in both winter and spring. Results indicate that the addition of pendimethalin enhanced summer grass weed control throughout the crop growing season by up to 31%. Applying all or part of the pendimethalin in the spring improved control of the summer grass weed junglerice by up to 49%. The lower rate of pendimethalin applied in the spring performed as well as the high rate in the winter, suggesting opportunities for reducing herbicide inputs. Tailoring sequential herbicide programs to address specific weed challenges can be a viable strategy for improving orchard weed control without increasing herbicide use in some situations.

Introduction

Orchard crops are grown on over 1.3 million hectares in California, with the tree nuts almond [*Prunus dulcis* (Mill.) D.A. Webb], walnut (*Juglans regia* L.), pistachio (*Pistacia vera* L.), and pecan [*Carya illinoinensis* (Wangenh.) K. Koch] accounting for nearly half of this hectarage and a 2017 farm gate value of $8 billion (CDFA 2018). Tree nuts are primarily produced in the 700-km-long Central Valley of California, where average annual rainfall ranges from 960 mm yr^{-1} in the north to 180 mm yr^{-1} in the south (CIMIS 2020). Because of the Mediterranean climate, most of this precipitation occurs outside the summer growing season, and significant irrigation inputs are required to maintain crop quality and productivity.

Weeds are controlled in these intensely managed cropping systems to reduce direct competition with the crop for water and other inputs, both during orchard establishment and throughout the duration of the several-decade lifespan of the orchard. Poorly controlled orchard weeds can interfere with cultural practices, operation of irrigation equipment, or the accurate placement of water, fertilizers, and other pesticides (Belding et al. 2004). In some early-flowering tree crops, understory vegetation management is also important for reducing risk of frost damage during critical periods in the spring, as solar radiation energy stored in the soil during the day is reradiated at night. Almonds, walnuts, and pecans are mechanically shaken from the tree, swept into windrows, and picked up from the orchard floor after several days of drying; in these crops, a weed-free and smooth orchard floor is critical to the efficiency of these harvest operations (Company and Gradziel 2017; Micke 1996).

In the mild climate of this region, characterized by winter rainfall and summer irrigation, weed control is a year-round management concern. Because of operational efficiencies, labor costs, and impacts of dust on crop performance and air quality, weed control in most California tree nut orchards utilizes some combination of PRE and POST herbicides. A common chemical weed control program in tree nuts begins with a PRE herbicide applied ahead of the onset of winter rains for incorporation, and this application is often made in "strips" centered on the tree row and may cover around 30% to 50% of the orchard floor (Hanson et al. 2014). In spring, the strips are commonly retreated with a POST herbicide program if needed, whereas the area between the sprayed strips is managed with several mowing operations. In summer, shortly before harvest, the entire orchard floor is commonly treated with a POST herbicide program and also closely mowed to minimize plants and debris that can interfere with harvest operations.

Glyphosate is a key component of many orchard herbicide programs. Intense selection pressure led to reports of glyphosate resistance in several key weeds during the late 1990s and 2000s. Such weeds as Italian ryegrass [*Lolium perenne* L. spp. *multiflorum* (Lam.) Husnot; (Jasieniuk et al. 2008; Simarmata et al. 2003)], horseweed [*Erigeron canadensis* L. (Hanson et al. 2009)], and hairy fleabane [*Erigeron bonariensis* L. (Moretti et al. 2016; Shrestha et al. 2007)] showed glyphosate resistance. Evaluation of existing and newly registered herbicide programs for control of these glyphosate-resistant (GR) fall- and winter-germinating weeds largely focused on rates, mixtures, and application timing of PRE herbicides (Brunharo and Hanson 2016; Shrestha et al. 2007), or supplementation with other POST mechanisms of action (Moretti et al. 2013, 2015). Based on university and private-sector research and grower experience, several herbicide programs are now commonly used in the tree nut system to provide acceptable control of these winter species.

The extended duration of required weed control remains a challenge in this cropping system. PRE herbicide programs for control of Italian ryegrass, hairy fleabane, and horseweed are most effective when applied relatively early in winter. However, these compounds often do not have sufficient residual activity to last through harvest because of the length of the season, soil temperature, and moisture conditions during the hot, irrigated portion of the spring and summer season. In an effort to extend residual weed control into the spring, many growers use high labeled rates and complex mixtures in their winter programs; such practices are costly and can occasionally lead to crop safety problems. However, even the most effective winter PRE programs usually must be supplemented with applications of glyphosate or other POST herbicides in spring plus the pre-harvest orchard floor treatment to achieve satisfactory control of summer-germinating species.

The first example of a GR summer weed in California orchards was junglerice, identified in the northern Central Valley (Alarcón-Reverte et al. 2013). Several GR junglerice biotypes were subsequently identified from multiple orchard production regions of the state (Alarcon-Reverte et al. 2015; Morran et al. 2018). Other summer grass weed species are also occasionally reported as creating problems in the tree nut production system in the Central Valley of California. Common examples are feather fingergrass (*Chloris virgata* Sw.), witchgrass (*Panicum capillare* L.), bearded sprangletop [*Leptochloa fusca* (L.) P. Beauv. ex Roem. & Schult. spp. *fascicularis* (Lam.) P. M. Peterson & N. Snow], and threespike goosegrass [*Eleusine tristachya* (Lam.) Lam.]. Junglerice and the other summer grasses germinate (or in some cases resume growing) when the soil temperatures start to rise in the spring, develop during the summer, and complete their life cycle in the fall. With this life cycle, summer grass weed species reach their maximum biomass accumulation in late summer through early fall—coincidentally when harvest operations are taking place—if previous weed management approaches were insufficient.

To address both winter- and summer-germinating GR weeds, several winter PRE mixture programs were evaluated to achieve sufficient duration of control, and typically the highest label rates were used. Integrated pest management approaches often stress the importance of understanding pest biology and designing control strategies accordingly (Norris et al. 2003). Shifting a portion of the PRE herbicide program from winter to spring may provide a simple yet viable approach for extended control of summer weed species. In this sequential approach, a second PRE herbicide application is made as part of the spring POST program prior to germination of the summer species rather than trying to achieve summer weed control with high rates of PRE herbicides applied in the winter. This approach specifically targets summer-emerging species and may, at the same time, improve crop safety and provide economic and environmental benefits by reducing overtreatment.

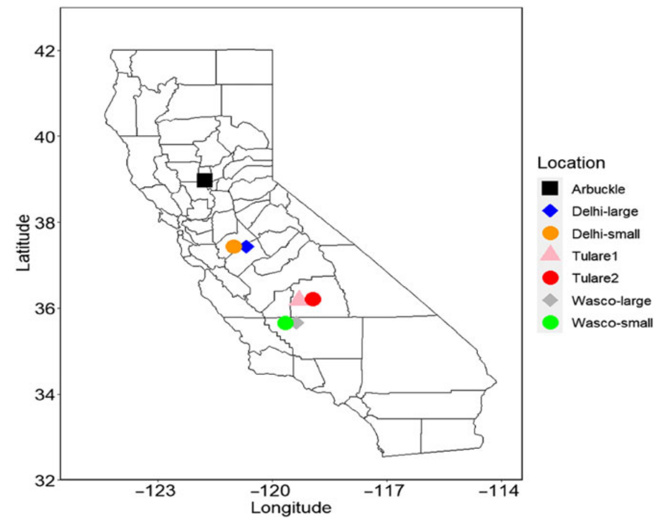

Figure 1. California map with field experiment locations. Data points are slightly shifted to avoid stacking for clarity of presentation.

The overall objective of this research was to evaluate herbicide programs that included PRE herbicide application mixtures with pendimethalin in the winter, followed by various sequential-application programs. Management strategies were designed to target summer grass weed species and to achieve season-long weed control as well as to reduce the overall herbicide application amounts during the growing season.

Materials and Methods

During the period 2012 to 2015, several field experiments were conducted in grower almond orchards to compare performance of winter herbicide mixtures to a split-treatment program. Figure 1 depicts field experiment locations across the Central Valley of California (Khale and Wickham 2013). In 2017–2018, two field experiments were conducted in grower walnut orchards to address the sequential program more thoroughly at a location dominated by GR junglerice.

Winter PRE Herbicide Mixtures

Two sets of experiments were conducted to evaluate winter PRE herbicide programs that are commonly adopted by nut growers in California (herbicide sources are listed in Table 1). For clarity, the first set of experiments will be denominated as large-plot experiments, and the second set as small-plot experiments. The large-plot experiments comprised four field trials focused on mixtures of oxyfluorfen + oryzalin, pendimethalin + flumioxazin,

Table 1. Sources of herbicides used in the orchard weed control experiments.

Herbicide	Trade name	Manufacturer, city and state	Manufacturer website
Flumioxazin	Chateau	Valent U.S.A. Corp., Walnut Creek, CA	www.valent.com
Flumioxazin	Tuscany	Nufarm Americas Inc., Alsip, IL	www2.nufarm.com
Glufosinate	Rely 280	Bayer CropScience, Research Triangle Park, NC	www.cropscience.bayer.us
Glyphosate	Roundup PowerMAX	Bayer CropScience, Research Triangle Park, NC	www.cropscience.bayer.us
Indaziflam	Alion	Bayer CropScience, Research Triangle Park, NC	www.cropscience.bayer.us
Isoxaben	Trellis	Corteva Agriscience, Indianapolis, IN	www.corteva.com
Oxyfluorfen	Goal 2XL	Corteva Agriscience, Indianapolis, IN	www.corteva.com
Oryzalin	Surflan A.S.	United Phosphorus Limited, King of Prussia, PA	www.upl-ltd.com
Pendimethalin	Prowl H2O	BASF Corp., Florham Park, NJ	www.basf.com
Rimsulfuron	Matrix SG	Corteva Agriscience, Indianapolis, IN	www.corteva.com
Penoxsulam/oxyfluorfen	Pindar GT	Corteva Agriscience, Indianapolis, IN	www.corteva.com

Table 2. Winter herbicide programs for *Erigeron bonariensis* (ERIBO) and *Echinochloa colona* (ECHCO) control in California almond orchard large-plot experiments.

			ERIBO[a]				ECHCO[a]	
Treatments		Rate	Delhi-large	Arbuckle	Wasco-13-large	Wasco-14-large	Wasco-13-large	Wasco-14-large
		g ai ha^{-1}	%					
1	Nontreated	–	0 b	0 c	0 b	0 b	0 c	0 c
2	Oxyfluorfen + oryzalin	1,401 + 4,483	67 a	100 a	97 a	82 a	100 a	95 ab
3	Oxyfluorfen/penoxsulam	17/826	64 a	100 a	100 a	90 a	100 a	71 ab
4	Pendimethalin	4,260	61 a	95 b	100 a	60 ab	100 a	97 ab
5	Flumioxazin	357	54 ab	100 a	99 a	70 a	85 a	89 ab
6	Pendimethalin + flumioxazin	4,260 + 357	44 ab	100 a	100 a	80 a	100 a	99 a
7	Pendimethalin + rimsulfuron	4,260 + 70	94 a	99 a	100 a	97 a	100 a	95 ab
8	Indaziflam[b]	51 or 73	47 ab	98 ab	100 a	72 a	92 a	98 ab
9	Isoxaben	1,118	47 ab	97 ab	100 a	85 a	55 b	60 b
10	Pendimethalin fb[c] pendimethalin	3,195 fb 2,130	97 a	100 a	100 a	37 ab	100 a	100 a
11	Oxyfluorfen/penoxsulam fb pendimethalin	17/826 fb 2,130	100 a	100 a	100 a	75 a	100 a	100 a

[a]Evaluation dates differed among experimental sites and weed species. Delhi-large in April 2013; Arbuckle in April 2013; Wasco-13-large in April 2013 for ERIBO; Wasco-13-large in May for ECHCO; Wasco-14-large in March 2014 for ERIBO; and Wasco-14-large in May for ECHCO.
[b]Indaziflam rates were 73 and 51 g ai ha^{-1} in 2013 and 2014, respectively.
[c]Abbreviation: fb, followed by.

pendimethalin + rimsulfuron, and pre-mixes of oxyfluorfen/penoxsulam, as well as pendimethalin, flumioxazin, indaziflam, and isoxaben applied alone (Table 2). Sequential applications of pendimethalin and of oxyfluorfen/penoxsulam followed by (fb) pendimethalin were also included in these experiments. The soil mapped to the Delhi series sand at the Delhi-large site (37.43°N, 120.71°W), as an Arbuckle series sandy loam at the Arbuckle site (38.96°N, 122.06°W), and as a Garces series silt loam at the Wasco-large site (35.65°N, 119.43°W). The experiment at the Wasco-large site was conducted twice (Wasco-13-large in 2013 and Wasco-14-large in 2014). The small-plot experiments included two field trials that were focused on different rates and application timings of rimsulfuron, indaziflam, and the pre-mix penoxsulam/oxyfluorfen (Table 3). The small-plot experiments were conducted in different blocks of the same orchards used for the Delhi-large and Wasco-13-large experiments, and were named Delhi-small and Wasco-small, respectively, and had similar soil characterization.

In the large-plot experiments, winter and spring herbicide applications were performed as follows: the Delhi-large site was treated on January 14 and March 25, 2013; the Arbuckle site on November 27, 2012 and March 27, 2013; the Wasco-13-large site on February 6 and March 12, 2013; and the Wasco-14-large site on January 16 and March 18, 2014. For the small-plot experiments, the winter and spring treatments were performed as follows: the Delhi-small site was treated on February 1 and March 25, 2013; and the Wasco-13-small site was treated on February 6 and March 12, 2013. A CO_2-pressurized backpack sprayer was used to perform the treatments, calibrated to deliver 187 L ha^{-1} through three 8002 flat-fan extended-range nozzles spaced 0.5 m apart, treating 1.5 m on each side of the trees. The large-plot experiments involved three replications of plots 168 m in length and an effective plot size of 252 m^2, whereas the small-plot experiments had four replications of plots 10 m in length and an effective plot size of 30 m^2. A randomized complete block design was adopted for all experiments. Weed control was assessed visually, approximately 30, 60, and 90 d after the winter treatment, on a scale that ranged from 0 to 100%, where 0 represented absence of control, and 100% represented complete weed control. Unless precluded by the grower's preharvest preparations, an evaluation was also conducted 120 d after the winter treatment (see Tables 2 and 3 for evaluation dates). The predominant weed species varied among locations but generally consisted of common orchard species such as little mallow (*Malva parviflora* L.), common groundsel (*Senecio vulgaris* L.), shepherd's-purse [*Capsella bursa-pastoris* (L.) Medik], Italian ryegrass, and hairy fleabane during the February, March, and April evaluations, and junglerice, yellow nutsedge (*Cyperus esculentus* L.), threespike goosegrass, common lambsquarters (*Chenopodium album* L.), and field bindweed (*Convolvulus arvensis* L.) at the May evaluations.

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Table 3. Winter herbicide programs for *Erigeron bonariensis* (ERIBO) and *Echinochloa colona* (ECHCO) control in California almond orchards small-plot experiments at multiple locations and years.

			ERIBO[a]		ECHCO[a]
Treatments		Rate	Delhi-small	Wasco-13-small	Wasco-13-small
		g ai ha^{-1}	%		
1	Nontreated	—	0 b	0 b	0 c
2	Rimsulfuron	70	100 a	100 a	47 bc
3	Indaziflam[b]	73	99 a	100 a	77 ab
4	Rimsulfuron + indaziflam	70 + 73	100 a	100 a	84 ab
5	Rimsulfuron + indaziflam	70 + 36	100 a	100 a	67 ab
6	Rimsulfuron + indaziflam	35 + 73	100 a	100 a	81 ab
7	Rimsulfuron fb[c] indaziflam	70 fb 73	99 a	100 a	94 ab
8	Rimsulfuron fb indaziflam	70 fb 73	100 a	100 a	72 ab
9	Penoxsulam/oxyfluorfen	28/1,376	100 a	100 a	64 ab
10	Penoxsulam/oxyfluorfen	34/1,652	100 a	100 a	100 a

[a]Evaluation dates differed among experimental sites and weed species: Delhi-small in March 2013; Wasco-13-small in April 2013 for ERIBO; and Wasco-13-small in May for ECHCO.
[b]Indaziflam rates were 73 and 51 g ai ha^{-1} in 2013 and 2014, respectively (see text for justification).
[c]Abbreviation: fb, followed by.

Table 4. Sequential treatments, rates, and application timing in walnut orchards in Tulare County, CA.

Treatment[a,b]		Rate	Application timing
		g ai ha^{-1}	
1	Nontreated	–	–
2	Indaziflam	51	Winter
3	Indaziflam	51	Winter
	+ pendimethalin	+ 4,260	Winter
4	Indaziflam	51	Winter
	+ pendimethalin	+ 2,130	Spring
5	Indaziflam	51	Winter
	fb pendimethalin	fb 4,260	Spring
6	Indaziflam	51	Winter
	+ pendimethalin	+ 2,130	Winter
	fb pendimethalin	fb 2,130	Spring
7	Penoxsulam/oxyfluorfen	560	Winter
8	Penoxsulam/oxyfluorfen	560	Winter
	+ pendimethalin	+ 4,260	Winter
9	Penoxsulam/oxyfluorfen	560	Winter
	fb pendimethalin	fb 2,130	Spring
10	Penoxsulam/oxyfluorfen	560	Winter
	fb pendimethalin	fb 4,260	Spring
11	Penoxsulam/oxyfluorfen	560	Winter
	+ pendimethalin	+ 2,130	Winter
	fb pendimethalin	fb 2,130	Spring
12	Flumioxazin	357	Winter
13	Flumioxazin	357	Winter
	+ pendimethalin	+ 4,260	Winter
14	Flumioxazin	357	Winter
	fb pendimethalin	fb 2,130	Spring
15	Flumioxazin	357	Winter
	fb pendimethalin	fb 4,260	Spring
16	Flumioxazin	357	Winter
	+ pendimethalin	+ 2,130	Winter
	fb pendimethalin	fb 2,130	Spring

[a]Glufosinate at 1,680 g ai ha^{-1}, glyphosate at 1,260 g ae ha^{-1}, ammonium sulfate at 1%, and non-ionic surfactant at 0.25% were added to all treatments.
[b]Abbreviations: +, mixture; fb, followed by sequential treatment.

Weed control data were subjected to the Levene's homogeneity test of variance to compare the variance among treatments. Generalized linear models using template model builder from the R package glmTMB (Brooks et al. 2017) and a *beta* distribution with ilink function were fit for each evaluation date for each site (Oliveira et al. 2017), where weed control was the response variable, herbicide treatment as fixed effects, and block as random effects. Estimated marginal means for weed control were produced and treatments compared with the R package *emmeans* (Lenth et al. 2020), including control for overall experiment-wise Type I error rate considering 11 treatments using the Bonferroni correction and $\alpha = 0.05$.

Sequential Herbicide Management Strategy

Two field experiments (referred to as "Tulare 1" and "Tulare 2") were conducted in Tulare County near Visalia, CA (Tulare 1: 36.18°N, 119.16°W; Tulare 2: 36.20°N, 119.15°W), from December 2017 to August 2018, to test the sequential herbicide application strategy for season-long weed control. Soil at both sites mapped to a Flamen series loam; Tulare 1 had 0.65% organic matter and pH = 7.3, and Tulare 2 had 1.18% organic matter and pH = 6.92.

The treatments consisted of an application of one of three common PRE herbicides for nut tree crops (indaziflam, penoxsulam/oxyfluorfen, or flumioxazin) as the foundation winter chemical weed management program. Pendimethalin was the herbicide used to evaluate the potential of sequential herbicide programs to target summer grass weed species (Bhowmik and Bingham 1990). Pendimethalin was applied either as a mixture with the foundation winter PRE herbicide, or as a sequential treatment in spring (Table 4). At both application timings, glyphosate + glufosinate were added to the treatments to ensure that all subsequent evaluations were of new weeds and not from regrowth. Junglerice was the predominant summer weed species at both sites, and its control was evaluated monthly, with aboveground biomass collected in August before trial termination near walnut harvest. Plots were 3 m by 20 m and were arranged in a randomized complete block design with four replications.

Weed control and biomass data were subjected to the Levene's homogeneity test of variance before model fitting. Experimental site (Tulare 1 and Tulare 2) and block as random effects, and response variable (either weed control or biomass) as fixed effects were included in the linear model using the R package *lme4* (Bates et al. 2015). Interaction between experimental site and treatments were observed for biomass data; therefore, mean separation was performed separately for each site. In addition, lack of normality of residuals was observed for the biomass data from both experimental sites, and a Box-Cox transformation was performed (Box and Cox 1964; Brunharo and Hanson 2018) based on a

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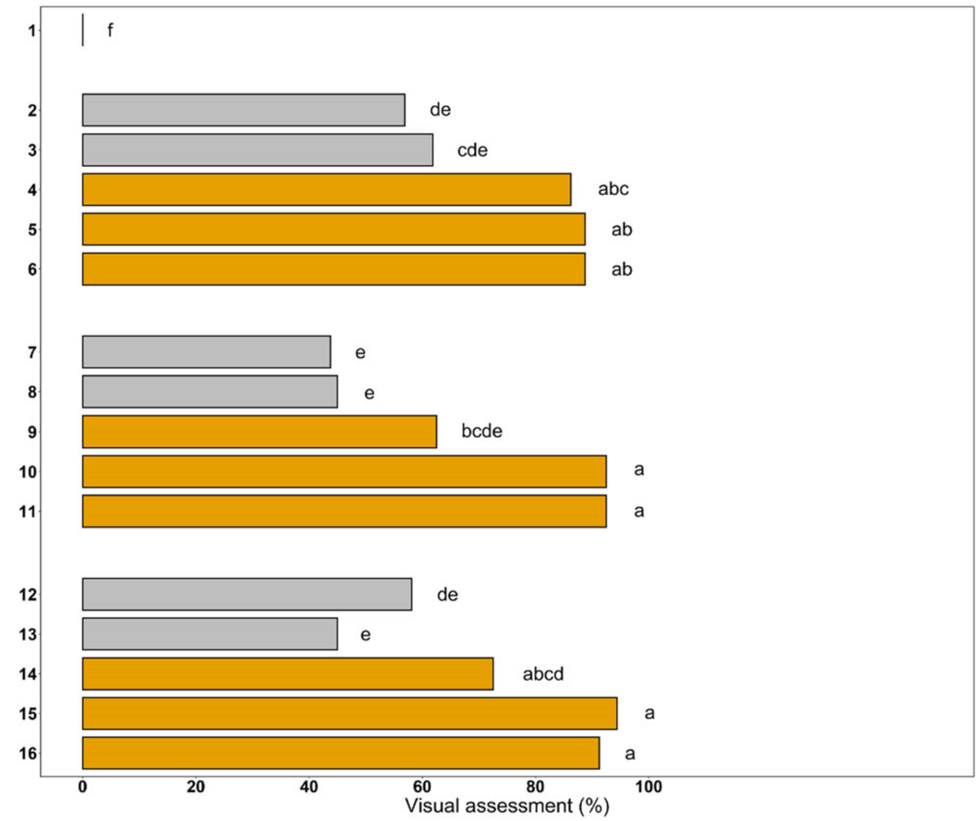

Figure 2. Junglerice control 8 mo after winter herbicide treatments and 5 mo after the spring sequential pendimethalin treatments at Tulare 1 and Tulare 2. Gray bars represent untreated or winter-only treatments, and yellow bars represent sequential programs. Means followed by same letter are not statistically different. Treatments (in g ai ha^{-1}): (1) nontreated; (2) indaziflam 51; (3) indaziflam 51 + pendimethalin 4,260; (4) indaziflam 51 followed by (fb) pendimethalin 2,130; (5) indaziflam 51 fb pendimethalin 4,260; (6) indaziflam 51 + pendimethalin 2,130 fb pendimethalin 2,130, (7) penoxsulam/oxyfluorfen 17/826; (8) penoxsulam/oxyfluorfen 17/826 + pendimethalin 4,260; (9) penoxsulam/oxyfluorfen 17/826 fb pendimethalin 2,130; (10) penoxsulam/oxyfluorfen 17/826 fb pendimethalin 4,260; (11) penoxsulam/oxyfluorfen 17/826 + pendimethalin 2,130 fb pendimethalin 2,130; (12) flumioxazin 357; (13) flumioxazin 357 + pendimethalin 4,260; (14) flumioxazin 357 fb pendimethalin 2,130; (15) flumioxazin 357 fb pendimethalin 4,260; (16) flumioxazin 357 + pendimethalin 2,130 fb pendimethalin 2,130.

log-likelihood function, with $\lambda = 0.3$ and $\lambda = 0.2$ for Tulare 1 and Tulare 2, respectively. Mean separation was performed as previously described in the "Winter PRE herbicide mixture" section, and the effects of the treatments on the response variables weed control and biomass (detransformed) are presented.

A contrast analysis was performed to answer the following specific questions: (a) Does the addition of pendimethalin enhance overall weed control?; (b) Can a sequential application of pendimethalin at 2,130 g ai ha^{-1} in the winter followed by pendimethalin at 2,130 g ha^{-1} in the spring perform as well as a single pendimethalin application with the higher rate (4,260 g ha^{-1}) in the winter?; and (c) Can the lower pendimethalin rate (2,130 g ha^{-1}) in the spring perform as well as the higher pendimethalin rate (4,260 g ha^{-1}) in the winter for control of summer-emerging grasses? To answer these questions, vectors of contrast values were created with linear combinations of factor levels of interest that summed to zero. The residual mean squared error used to estimate the mean differences, and 95% confidence intervals were derived from the mixed-effects model from the previous analysis. A customized script was created to obtain the mean difference between treatment groups and 95% confidence intervals (available at https://github.com/caiobrunharo/sequential_herbicide_programs) in R (R Core Team 2020). Because the contrasts of interest were not orthogonal, a Sidak correction was applied (Aho 2013).

Results and Discussion

Season-long chemical weed management is highly desired by growers, particularly when hard-to-control species and/or weed populations that have evolved herbicide resistance are present in the fields. This research indicates that the winter herbicide programs provide effective winter weed control, including GR hairy fleabane (ERIBO; Tables 2 and 3). However, the overall weed control was less consistent for summer weeds, like junglerice, in the May evaluations for some of the treatments and experimental sites (ECHCO; Tables 2 and 3). For instance, rimsulfuron applied in February provided only 47% junglerice control as observed in May, probably because of the brief residual activity of this molecule (Ashburn-Poppell et al. 2002). Spring-germinating species, such as junglerice, threespike goosegrass, and field bindweed, become harder to control with POST herbicides as they reach more advanced developmental stages (Soltani et al. 2016); therefore, their early control is crucial.

The sequential herbicide application strategy yielded similar results at both sites, and the visual data are presented as a compiled dataset, whereas the biomass data are presented separately for each experimental site. Control of junglerice in August 2018, 8 mo after winter treatments and 5 mo after spring sequential treatments, are shown in Figure 2. The general trend observed is that the addition

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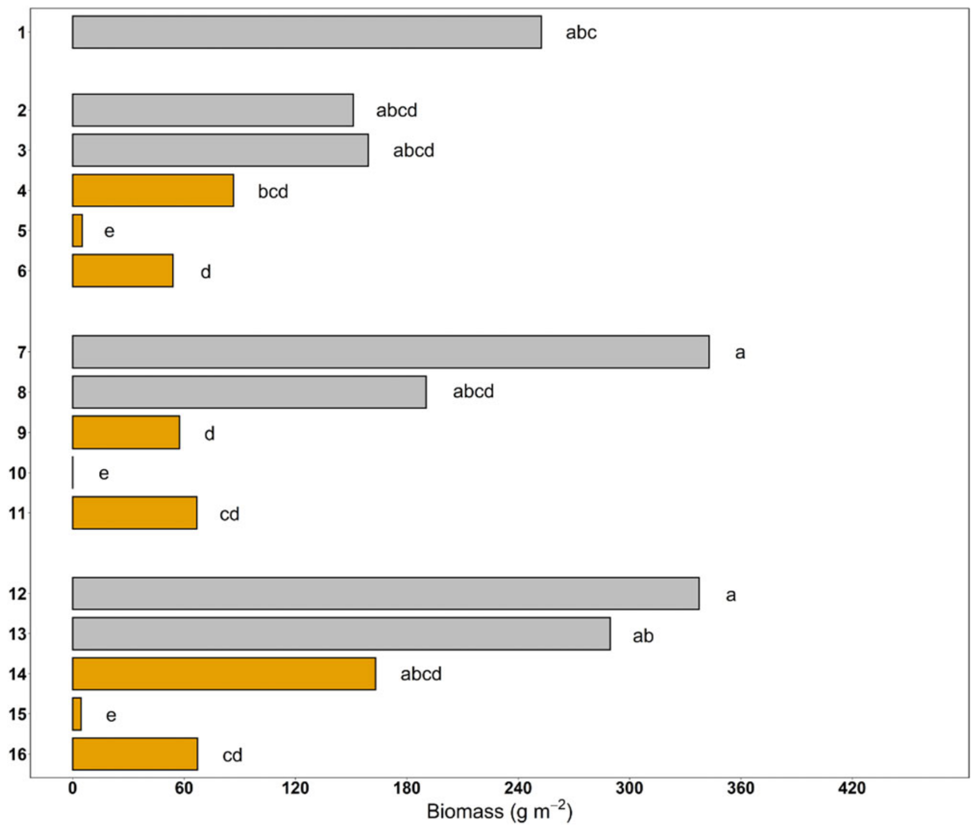

Figure 3. Junglerice biomass 8 mo after the winter herbicide treatments and 5 mo after the spring sequential pendimethalin treatments at Tulare 1. Gray bars represent untreated or winter-only treatments, and yellow bars represent sequential programs. Means followed by same letter are not statistically different. Treatments (in g ai ha^{-1}): (1) Nontreated; (2) indaziflam 51; (3) indaziflam 51 + pendimethalin 4,260; (4) indaziflam 51 followed by (fb) pendimethalin 2,130; (5) indaziflam 51 fb pendimethalin 4,260; (6) indaziflam 51 + pendimethalin 2,130 fb pendimethalin 2,130; (7) penoxsulam/oxyfluorfen 17/826; (8) penoxsulam/oxyfluorfen 17/826 + pendimethalin 4,260; (9) penoxsulam/oxyfluorfen 17/826 fb pendimethalin 2,130; (10) penoxsulam/oxyfluorfen 17/826 fb pendimethalin 4,260; (11) penoxsulam/oxyfluorfen 17/826 + pendimethalin 2,130 fb pendimethalin 2,130; (12) flumioxazin 357; (13) flumioxazin 357 + pendimethalin 4,260; (14) flumioxazin 357 fb pendimethalin 2,130; (15) flumioxazin 357 fb pendimethalin 4,260; (16) flumioxazin 357 + pendimethalin 2,130 fb pendimethalin 2,130.

of pendimethalin enhanced junglerice control throughout the crop growing season. Not surprisingly, junglerice visual control was best with all three winter foundation PRE herbicides followed by a pendimethalin treatment in the spring (treatments 5, 6, 10, 11, 15, and 16; Figure 2). Treatments with the foundation winter PRE treatments alone provided reduced junglerice control levels (treatments 2, 7, and 12; Figure 2).

Biomass data supported the visual control ratings for junglerice for Tulare 1 (Figure 3) and Tulare 2 (Figure 4). The foundation winter treatments alone resulted in junglerice biomass similar to the untreated plots (treatments 2, 7, and 12). Sequential applications of the higher rate of pendimethalin (4,260 g ha^{-1}) in the spring (treatments 5, 10, and 15; Figures 3 and 4) reduced junglerice biomass to levels close to zero, regardless of the foundation winter PRE program. Tank-mixing pendimethalin (4,260 g ha^{-1}) with the winter foundation program (treatments 3, 8, and 13; Figures 3 and 4) did not provide enhanced junglerice control compared to the foundation winter treatments alone (treatments 2, 7, and 12; Figures 3 and 4). Superior junglerice control was observed with spring applications of pendimethalin. Junglerice control was generally better with most treatments at the Tulare 2 site, where weed pressure was lower (data not shown) compared to Tulare 1. At the lower weed pressure site, the sequential application of the lower rate of pendimethalin (2,130 g ha^{-1}) resulted in similar control levels compared to the higher pendimethalin rate (4,260 g ha^{-1}), which underscores the value of field scouting and tailored herbicide programs.

The contrast analysis summarized the overall trends observed in the previous analysis (Table 5). We observed that the addition of pendimethalin to the system (either in winter or spring) enhanced junglerice control, improving weed control by up to 31% and reducing the average biomass by up to 159 g m^{-2} (Table 5, contrast 1). From contrast 2, we observed that a sequential application of lower rates of pendimethalin (2,130 g ha^{-1} in the winter followed by 2,130 g ha^{-1} in the spring) provided better control of junglerice than a single application of the higher rate of pendimethalin (4,260 g ha^{-1}) in the winter. The sequential application enhanced weed control by up to 49% and reduced biomass by up to 154 g m^{-2} (Table 5, contrast 2). Finally, from contrast 3 we observed that the lower rate of pendimethalin (2,130 g ha^{-1}) applied in the spring outperformed the higher rate of pendimethalin (4,260 g ha^{-1}) applied in the winter, where weed control improved by up to 32% and biomass was reduced by up 126 g m^{-2} (Table 5, contrast 3). These results suggest that a strategic management of the pendimethalin application timing may be more important than the total herbicide load in the system for summer grass control.

When considering only the summer annual grass species, the lower rates of pendimethalin (2,130 g ha^{-1}) in the spring generally outperformed the higher rate of pendimethalin (4,260 g ha^{-1})

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Table 5. Contrast analysis of treatment groups.

Contrasts	Research question	Group means	Weed control		Biomass			
					Tulare 1		Tulare 2	
			MD[a]	CI[b]	MD	CI	MD	CI
			—— % ——		——g m^{-2} ——		—— g m^{-2} ——	
Contrast 1	Does the addition of pendimethalin enhance weed control?	"Yes pendimethalin" vs "No pendimethalin"	24	16; 31[c]	−124	−159; −90[c]	−67	−84; −50[c]
Contrast 2	Can a sequential application of pendimethalin at 2,130 g ai ha^{-1} in the winter followed by 2,130 g ha^{-1} in the spring perform as well as a single pendimethalin application with the higher rate (4,260 g ha^{-1}) in the winter?	"Sequential pendimethalin" vs "Single pendimethalin in winter"	40	31; 49[c]	−111	−154; −68[c]	−71	−93; −50[c]
Contrast 3	Can the lower pendimethalin rate (2,130 g ha^{-1}) in the spring perform as well as the higher pendimethalin rate (4,260 g ha^{-1}) in the winter for control of summer-emerging grasses?	"Lower pendimethalin rate in spring" vs "Higher pendimethalin rate in winter"	23	14; 32[c]	−83	−126; −40[c]	−56	−77; −34[c]

[a]MD, Mean difference.
[b]Confidence interval [lower; upper]. Raw data used to create the contrasts is available at https://github.com/caiobrunharo/sequential_herbicide_programs.
[c]$P < 0.001$.

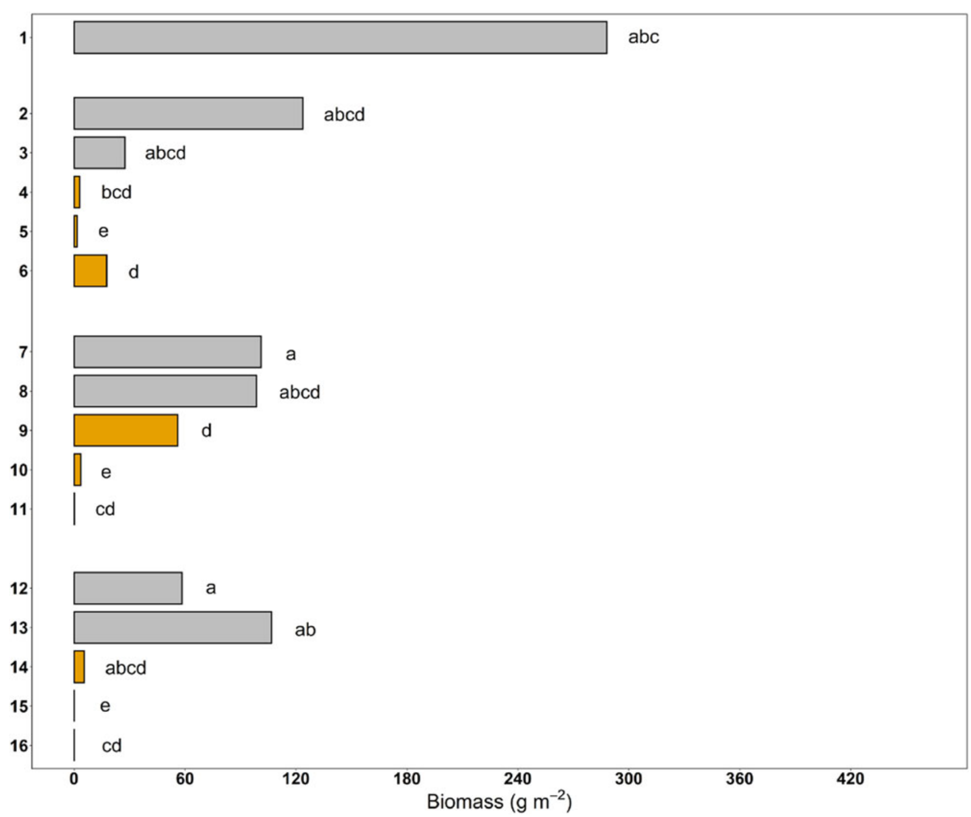

Figure 4. Junglerice biomass 8 mo after winter herbicide treatments and 5 mo after the spring sequential pendimethalin treatments at Tulare 2. Gray bars represent untreated or winter-only treatments, and yellow bars represent sequential programs. Means followed by same letter are not statistically different. Treatments (in g ai ha^{-1}): (1) nontreated; (2) indaziflam 51; (3) indaziflam 51 + pendimethalin 4,260; (4) indaziflam 51 followed by (fb) pendimethalin 2,130; (5) indaziflam 51 fb pendimethalin 4,260; (6) indaziflam 51 + pendimethalin 2,130 fb pendimethalin 2,130; (7) penoxsulam/oxyfluorfen 17/826; (8) penoxsulam/oxyfluorfen 17/826 + pendimethalin 4,260; (9) penoxsulam/oxyfluorfen 17/826 fb pendimethalin 2,130; (10) penoxsulam/oxyfluorfen 17/826 fb pendimethalin 4,260; (11) penoxsulam/oxyfluorfen 17/826 + pendimethalin 2,130 fb pendimethalin 2,130; (12) flumioxazin 357; (13) flumioxazin 357 + pendimethalin 4,260; (14) flumioxazin 357 fb pendimethalin 2,130; (15) flumioxazin 357 fb pendimethalin 4,260; (16) flumioxazin 357 + pendimethalin 2,130 fb pendimethalin 2,130.

applied in the winter but was not always comparable to the sequential treatments. Biologically significant levels of pendimethalin in soils can be found between 135 d (Hatzinikolaou et al. 2004) and 200 d (Zimdahl et al. 1984) after application, with limited mobility in soils (Shaner 2012), which enhances its residual activity compared to other winter PRE herbicides. Because the higher rate of pendimethalin in spring provided excellent control and the lower did not, this is not likely due simply to early-germinating junglerice. Instead, under heavy weed pressure, the spring treatment with the lower rate may not provide sufficient control without the winter component.

The experiments conducted in this research focused primarily on the control of summer grass weed species, and the weed community present in specific fields will determine the adequate herbicide treatment to be adopted. In areas where summer weed species are the major issue, shifting some or all of the pendimethalin component of the herbicide program may significantly improve performance relative to the winter-only PRE approach. However, in areas where winter grass weed species [e.g., annual bluegrass (*Poa annua* L.), Italian ryegrass] are also troublesome, more attention will need to be given to the winter treatments that could be complemented by pendimethalin addition to target these species in a sequential approach. Pendimethalin is a semi-volatile herbicide that requires incorporation, either by irrigation/rainfall or by mechanical techniques; therefore, the sequential application in the spring will require that growers have the means to uniformly incorporate the herbicide in a timely manner. Although this is feasible in sprinkler- and micro sprinkler–irrigated sites, growers whose orchards are irrigated with single- or double-line drip irrigation systems may need to shift the pendimethalin application date early enough to ensure that it is followed by a spring rain event for incorporation.

Results from this research project suggest that, in some instances, it is possible to improve or maintain weed control outcomes in tree nut orchards using less herbicide by carefully considering the biology of the weed, weed control goals, and the weed management tools available. Chemical weed management that emphasizes the winter PRE herbicide application are well established for hard-to-control weed species such as hairy fleabane, but these programs do not always reliably control key summer-annual weed species. Sequential herbicide applications may be a viable option to provide season-long weed control, particularly with the addition of pendimethalin to the management program to target summer annual grass species.

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