Pre-emergent and Post-emergent Herbicide Performance
on *E. tristachya* in California Orchards

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Abstract

E. tristachya (threespike goosegrass) is related to the more widely distributed *Eleusine indica* (goosegrass). While *E. indica* is a large stature and erect annual, *E. tristachya* is a tufted, low growing, perennial (or semi-perennial) grass of growing concern in California's Central Valley orchard production systems. In response to reports from almond growers regarding difficult-to-control grasses, including *E. tristachya*, field and greenhouse research was conducted to address industry needs. In 2016-19, field studies were conducted in a walnut orchard in Chico, California, an almond orchard in Livingston, California and in a prune orchard in Orland, California to evaluate the efficacy of several pre-emergent (PRE) and post-emergent (POST) herbicide control options for *E. tristachya*. Orchard floor management programs generally utilize a winter PRE program to manage *E. tristachya* seedlings. In these experiments, single application treatments were compared to a sequential herbicide program composed of a winter application of indaziflam followed by a spring application of pendimethalin in order to target the phenology of *E. tristachya.* In separate experiments, POST treatments were made to evaluate control options for established *E. tristachya* stands. In 2018, greenhouse experiments were conducted to evaluate the efficacy of several POST herbicides on *E. tristachya* at two different growth stages.

The trial design for field experiments was a randomized complete block with four replications. Winter PRE treatments were applied in January each year and the spring applications of pendimethalin, for the sequential herbicide program, were applied in March. Visual assessments for the PRE treatments were conducted at monthly intervals, starting one month after the January applications, and carried through to June. POST treatments were applied in May and control assessments were conducted at weekly intervals, starting one week after application, for five weeks. In both PRE and POST experiments, control of *E. tristachya* was estimated using a 0 to 100 scale, where 0 means no control and 100 means plants were completely controlled.

The most efficacious control in the PRE experiments was obtained through sequential herbicide applications (SHA) of indaziflam followed by pendimethalin, which provided 88% control, five months after the initial treatment (MAT), across all three years at each site. The highest level of POST control was obtained with sethoxydim, clethodim, and fluazifop, which all controlled tillered *E. tristachya* greater than 73%, five weeks after treatment (WAT) at all sites. Glyphosate applied at a common field rate or twice that rate proved to be the least efficacious, with less than 51% control five WAT across all four years. The results from this study indicate that a properly timed and applied SHA, along with the use of POST graminicides, provides the greatest control of *E. tristachya*, while glyphosate provides poor management of this species.

Key Words: *Eleusine tristachya*, threespike goosegrass, herbicide mixture, perennial crops, postemergence, preemergence, split herbicide application.

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Introduction

California is colloquially known as the breadbasket of the world, and it is aptly the nation's top exporter of many crops. Almonds (*Prunus dulcis* L.) and walnuts (*Juglans regia* L.) are among the top ten commodities in California, with a combined cultivated area of more than 568,000 hectares and a total farm gate crop value of over 7.38 billion US dollars (CDFA, 2019). Given this, the timely and effective control of weeds is an important task for California orchard managers to maintain the quality and competitiveness of the California orchard cropping industry.

Almonds are California's largest tree nut crop in total dollar value and acreage. They rank as the top agricultural export of the state of California, and the largest US specialty crop export. California's almond acreage has expanded rapidly in recent decades, from 283,000 hectares in 2005 to just over 441,000 hectares in 2018, with a total farm gate value of 6.09 billion US dollars in 2018 (CDFA, 2019). This jump is in part due to the increasing demand for almonds in domestic and international markets. California produces approximately 80% of the world's almonds and 100% of the U.S. commercial almond production. Walnuts, while still a widely grown crop, account for approximately 127,000 harvested hectares and a 1.29 billion US dollar farm gate value (United States Department of Agriculture, 2019). One of the main challenges that orchard managers deal with, in terms of meeting the world's demand for these two crops, is appropriate, timely, and cost-effective weed management.

Weeds can affect cropping systems by competing for water, light, and nutrients (Zimdahl, 2018); however, in tree nut cropping systems the effects vary depending on the age of the orchard. In newly planted tree nut orchards, weed competition for resources can severely impede the growth of young trees (Jarvis-Shean *et al*., 2018). In established orchards, weeds usually have less of a direct effect on tree health or nut production, due to their limited ability to compete with the largestatured crops. Instead, weeds in established orchards indirectly affect production by interfering with operations, such as mechanical harvest, and can serve as a host for pests and diseases that can influence the quality and quantity of the crop, as well as the health of the tree (Wisler and Norris, 2005).

The conventional harvesting of both almonds and walnuts is carried out through four operational phases: (1) initiation of orchard floor preparation in order to create suitable harvesting conditions, including leveling the ground and eradicating weeds; (2) detaching the mature nuts from trees through the use of mechanical shakers; (3) sweeping the product on the orchard floor into windrows where it dries for seven to ten days; (4) and picking up the windrowed nuts using a harvester (Kelly, 1967). Weeds present on the orchard floor at the time of harvest interfere with the last two operational phases, sweeping and nut pick up, potentially reducing harvest efficiency and grower profits.

Orchard floor management in most California tree nut production systems uses a combination of (PRE) and post-emergent (POST) herbicides for year-round weed control in the orchard. Depending on the age of the orchard, five to 10 foot "strips" are centered down the tree row to prevent weeds from directly competing with trees (Brunharo *et al.*, 2020). PRE herbicides, applied ahead of winter rains to the strips, incorporate into the top layer of soil where weed seeds germinate. Orchard middles, on the other hand, are usually managed via no-till practices, such as mowing to improve orchard access throughout the rainy winter and spring months (Connell *et al.*, 2001). As the season progresses, the tree row strips often are retreated with POST herbicides to control seedlings that emerged after residual control from PRE treatment begins to fail. In summer, at the onset of harvest operations, the entire orchard floor is usually treated with POST herbicides to eliminate vegetation that might interfere with nut pick up during harvest (Brunharo *et al.*, 2020).

E. tristachya (Figures 1 and 2) is native to South America; however, this species is now established in North America, Australia, Africa and Europe (Phillips, 1972; Wet *et al.*, 1984; Hilu and Johnson, 1997). According to the Consortium of California*, E. tristachya* was first reported in the state in 1967 (Smith, 2019). Since then, this species has become a significant concern in tree nut and other orchard cropping systems throughout the California Central Valley.

E. tristachya is a perennial. It matures and flowers during the summer and then goes deciduous in the winter. It only resumes growth from established plants or from newly germinating seeds once soil temperatures reach 15-20 °C, for three consecutive days in the spring (Calflora, 2021). This growth cycle means that *E. tristachya* achieves its maximum growth and reproductive stage concurrently with orchard harvest operations creating a potential challenge for orchard managers; therefore, timely and effective control of this species is needed to help maintain the viability and profitability of California's tree nut cropping industries.

In recent decades, cultivation has become less common in many orchard crops due to speed of operations and concerns about dust impacts on the crop and regional air quality (Faulkner *et.al.* 2009). Under these conditions, germination and emergence of small seeded grasses such as *E. tristachya*, is favored (Teasdale *et al.*, 1991). Growers are concerned because *E. tristachya* is a prolific seed producer and can rapidly colonize orchard middles and tree rows and is difficult to eliminate once established.

The use of conventional herbicide programs is currently being threatened by the increasing number of herbicide-resistant weeds (Duke and Powles, 2008; Perotti *et al.*, 2020). California currently has 30 confirmed unique cases of herbicide resistance (Heap, 2021). Twenty-four of those cases are to a single site of action. The most common forms of resistance have been to the ALS and EPSPS synthase inhibitors, accounting for 14 cases, which is nearly half the total of all reported cases. Additionally, there are five warm season weed species with documented resistance to four herbicide sites of action, all of which included resistance to EPSP synthase inhibitors, the mode of action of glyphosate. To date, no cases of herbicide resistance have been reported for *E. tristachya*, though a closely related species *E. indica* exhibits resistance to glyphosate (Zhang *et al.*, 2015; Chen *et al.*, 2017) and ACCase (McCullough *et al.*, 2016) in numerous populations. This illustrates a growing concern for many orchard managers, the rise of herbicide-resistant and -tolerant weeds. Previous glyphosate dose-response work conducted on *E. tristachya* at the University of California, Davis showed that plants treated at the 2-tiller stage survived up to a 2x rate and when treated a few weeks later, at the 15-tiller stage, they survived up to a 16x rate (Hanson, 2013). This clearly highlights a potential concern for orchard managers.

Very little information on the control and management of *E. tristachya* in orchard crops is available. The objective of this study was to evaluate *E. tristachya* control with existing and newly registered herbicides and explore a sequential PRE treatment program. Previous research on another grass weed, junglerice (*Echinochloa colona*), in orchard crops suggests that a sequential PRE herbicide program may improve summer weed control compared to the traditional treatment timing (Brunharo *et al*. 2020). Overall, the results of this study may help California orchard managers develop effective management strategies for the growing number of species that are resistant to POST herbicides (Shrestha *et al.*, 2007; Brunharo *et al.*, 2020). Additionally, the sequential PRE treatment program, unlike current PRE emergent programs, targets the emergence of warm season species, will allow California orchard managers to rely less on POST herbicides for summer weed control.

Materials and Methods

The herbicides used in both the greenhouse and field trials were based on PRE and POST herbicides registered for use in almond, walnut, and prune (Table 1).

Greenhouse Experiment Description

The experiment was conducted once on August 15, 2018, in a greenhouse at the University of California, Davis (38.543584681889165, -121.76361385781553). *E. tristachya* seeds, which were greenhouse-grown progeny from plants originally collected in an almond orchard near Delhi, CA, were sown approximately 1-2 mm below the soil surface of commercial potting media (Sun Gro Horticulture Canada Ltd., Vancouver, BC) in flat plastic trays on July 18 and 25, 2018. At the first leaf stage, individual seedlings were transplanted into 10.2 x 10.2 cm square pots filled with the same potting media. Plants were maintained in a greenhouse with day/night temperature of 30/15 C with no supplemental lighting and were irrigated as needed. Prior to treatment, plants were grouped into size classes to allow treatment to 2-3 tiller and 5-6 tiller plants.

All herbicide treatments were applied using a moving-nozzle, cabinet sprayer (Technical Machinery Incorporated, Sacramento, CA, USA) calibrated to deliver 140 L/ha at 207 kPa using an 8002E flat-fan nozzle (Tee Jet Technologies, 106 Wheaton, IL, USA). Nozzle height was 45 cm above the plants during treatment. The herbicides included in this study were: glyphosate, sethoxydim, clethodim, fluazifop, rimsulfuron, glufosinate, and oxyfluorfen and each herbicide was applied with manufacturer-recommended adjuvants (Table 2).

The experimental design was a two by 15 factorial randomized complete block with the two growth stages (2-3 tiller and 5-6 tiller) and 15 herbicide treatments, including a nontreated control, as factors. There were eighteen replicates for each growth stage by treatment combination. Treatment efficacy was visually assessed on a weekly basis using a 0 to 100 scale, where 0 means no control and 100 means plants were completely killed. At five WAT, aboveground biomass was cut at the surface of the soil, placed in separate paper bags, dried to a constant weight in a convection oven at 60 °C. Plant biomass data were analyzed using a generalized linear model in R version 3.5.1 (The R Foundation for Statistical Computing) with experimental runs and replicates as random effects and treatment combinations as fixed effects at a significance level of 0.05. Untransformed data were analyzed using multcomp package in R. Treatment means were compared with Tukey's test with an alpha level of 0.05.

Field Experiment Description

Field trials were conducted to evaluate the performance of several PRE and POST herbicides on *E. tristachya*. The trial design was a randomized complete block with four replications. Herbicide treatments were applied with a CO_2 pressurized backpack sprayer, calibrated to deliver 280 L/ha at 241 kPa through three TeeJet XR11003 flat fan nozzles. A discharge calibration was performed before treatment and a metronome was used to maintain travel speed. The herbicide treatments were applied in a 1.5 m band on both sides of the tree row.

In 2016 and 2017, trials were conducted in a prune orchard located in Orland, CA (39°40'29.5"N 122°08'44.1"W). The soil at this site mapped as an Arbuckle gravelly loam, with a 0 to 2 percent slope; plots at this location were 3 by 4.5 m, with a single tree per plot. In 2017, 2018, and 2019 trials were conducted in walnut and almond orchards. The walnut orchard was located at the Chico State University Farm in Chico, CA (39°41'06.9"N 121°49'57.6"W) with soil classified as an Almendra loam, with a 0 to 1 percent slope; plots at this site were 3 by 6 m and had one tree per plot. The almond orchard was located near Livingston, CA (37°23'12.2"N 120°46'14.3"W) with Pachappa fine sandy loam, slightly saline-alkali soils, a 0 to 1 percent slope; plots at this site were 3 by 4.5 m with one tree per plot.

Data collection consisted of visual assessments at monthly intervals for PRE herbicides, starting one month after treatments that were sprayed in January, for five months. A follow up PRE herbicide was applied in March as part of a SHA. POST assessments were conducted on weekly intervals, starting one week after treatments that were started in May, and conducted for approximately one month. *E. tristachya* control was estimated using a 0 to 100 scale, where 0 means no control and 100 means plants were completely killed. All data collected from the field trials were analyzed using a generalized linear model in R version 3.5.1 (The R Foundation for Statistical Computing) with experimental runs and block as random effects and treatment combinations as fixed effects at a significance level of 0.05. Untransformed data were analyzed using a multcomp package in R. Treatment means were compared with Tukey's test at an alpha value of 0.05.

Results

Greenhouse Efficacy Study

Results from the greenhouse screening of POST herbicides indicate that graminicides such as fluazifop, clethodim, and sethoxydim provided the most effective control of *E. tristachya* at both the 2-3 (Table 2) and 5-6 tiller (Table 3) growth stages.

2-3 tiller growth stage

At the 2-3 tiller growth stage, fluazifop provided the greatest level of control with a biomass reduction of 90% at the 210 g ai/ha rate and a 79% reduction at the 105 g ai/ha rate (Table 2). Clethodim at the 102 g ai/ha rate reduced biomass accumulation by 83% and 67% at 51 g ai/ha. Sethoxydim provided a 77% reduction at 315 g ai/ha and 58% reduction at the 158 g ai/ha rate.

All other treatments provided inadequate control of *E. tristachya* at the 2-3 tiller growth stage with biomass reductions at or below 50%. Of these treatments, glufosinate provided a reduction of 50% at the 1680 g ai/ha rate and 38% reduction at 840 g ai/ha. Oxyfluorfen provided a biomass reduction of 40% at the 1400 g ai/ha rate and 32% at the 700 g ai/ha rate. The two treatments with the lowest reduction in biomass were glyphosate and rimsulfuron. Rimsulfuron treatments only provided a reduction of 27% at the 70 g ai/ha rate and just 13% at the halved rate. Glyphosate treatments provided poor control of this species; the 1140 g ae/ha treatment had a biomass weight equivalent to the untreated control treatments. Plants in the 2280 g ae/ha glyphosate treatments ended up weighing 28 mg more than the untreated control plants (Table 2).

5-6 tiller growth stage

Fluazifop provided the greatest level of control with a biomass reduction of 83% at the 210 g ai/ha rate and a 71% reduction at 105 g ai/ha rate (Table 3). Clethodim at 102 g ai/ha reduced biomass accumulation by 69% and 60% at 12 g ai/ha. Sethoxydim provided a 62% reduction at the 315 g ai/ha and 49% reduction at 158 g ai/ha.

All other POST treatments applied to *E. tristachya* at the 5-6 tiller growth stage provided biomass reductions at or below 46%. Of these treatments, glufosinate provided a reduction of 46% at the 1680 g ai/ha rate and 35% reduction at 840 g ai/ha. Oxyfluorfen provided a biomass reduction of 38% at the 1400 g ai/ha rate and 29% at 700 g ai/ha. As was found at the 2-3 tiller growth stage, glyphosate and rimsulfuron provided the lowest reduction in biomass. Rimsulfuron only provided a reduction of 21% at the 70 g ai/ha rate and just 3% at the 35 g ai/ha rate. Similar to the results found at the 2-3 tiller growth stage, both glyphosate treatments applied at the 5-6 tiller growth stage provided poor control of this species. The 2280 g ae/ha rate of glyphosate resulted in a 65 mg increase in biomass but remained statistically similar to the non-treated. On the other hand, the 1140 g ae/ha rate of glyphosate resulted in a 141 mg increase of biomass, a statistically greater biomass than the non-treated plants (Table 3).

Field Experiments

Growers that operate in orchard production systems require year-round control of weeds, particularly when dealing with clumping perennial grasses that can interfere with harvest operations. Results from the series of field experiments conducted from 2016-2019 in commercial orchards indicate that optimal control of *E. tristachya* can be obtained through a season-long program, which integrates a sound pre-emergent program that targets the phenology of this warm season perennial grass, along with selective POST treatments of graminicides. Across all four years and at every field site, the most effective pre-emergent treatment applied to *E. tristachya* was the SHA of indaziflam followed by pendimethalin, providing greater than 89% control, five months after the initial treatment (Table 4). All other treatments varied depending on site or year. The most effective POST treatments for the control of *E. tristachya*, across all four years and at every field site, consistently included treatments of the graminicides fluazifop, clethodim, or sethoxydim (Table 5). Treatments of glyphosate and rimsulfuron tended to provide the poorest POST control at five WAT.

Pre-emergent

The SHA treatment, which provided 91% control at five MAT during both the 2016 and 2017 field trials (Tables 6 and 7), yielded the greatest control of *E. tristachya* for the field experiments conducted in the commercial prune orchard located in Orland, CA. In 2016, single product treatments of pendimethalin, indaziflam, and penoxsulam/oxyfluorfen provided similar levels of control, ranging from 69% to 71% at five MAT. The tank mix combinations of indaziflam plus rimsulfuron, flumioxazin plus pendimethalin, and oxyfluorfen plus oryzalin performed similarly with control ranging from 59% to 61% at five MAT. In 2017, treatments of indaziflam, pendimethalin, and penoxsulam/oxyfluorfen all performed statistically similar with residual control ranging from 67% to 69% at five MAT. The tank mix treatment of indaziflam plus rimsulfuron provided slightly less control, 63% at five MAT. All remaining treatments, flumioxazin plus pendimethalin, oxyfluorfen plus oryzalin, flazasulfuron, rimsulfuron, and oryzalin on its own all provided the least residual control of *E. tristachya*, ranging from 50% to 58% at five MAT.

For field experiments conducted in the commercial almond orchard located in Livingston, CA, the SHA provided greater than 90% control across all three years (Tables 8, 9, and 10). All other treatments statistically fell into roughly three tiers across all three years; however, the order within each tier by which these treatments ranked varied from year to year. The first tier included treatments of pendimethalin, penoxsulam/oxyfluorfen (34/1652 g ai/ha), and indaziflam (73 g ai/ha). In 2017, these treatments provided 73% to 76% control five MAT (Table 8), 72% to 75% in 2018 (Table 9), and 68% to 72% control in 2019 (Table 10). There were no statistical differences among these treatments when comparing within the individual experimental years. The next tier included treatments of indaziflam (51 g ai/ha), penoxsulam/oxyfluorfen (22/1101 g ai/ha), flumioxazin plus pendimethalin, oxyfluorfen plus oryzalin, and indaziflam plus rimsulfuron. In 2017, these treatments provided between 60% to 65% control at five MAT with minor statistical variance (Table 8). In 2018 and 2019, control ranged from 59% to 65% and 56% to 61% (Tables 9 and 10) showing no statistical difference among treatments. The last tier included single product treatments of oryzalin, rimsulfuron, and flazasulfuron. Control provided by treatments in this last tier provided less than 53% control across all three years with no statistical difference among treatments when looking at individual years (Tables 8, 9, and 10).

For field experiments conducted in the commercial walnut orchard located in Chico, CA, the SHA of indaziflam followed by pendimethalin, continued to perform statistically better than all other treatments, providing great than 90% control five MAT across all three years (Table 4). In 2017, the remaining treatments resulted in similar control at five MAT, with some statistical variation when comparing treatment means (Table 11). The sulfonylurea herbicides, flazasulfuron and rimsulfuron, performed the poorest with less than 50% control of *E. tristachya* at five MAT. Results from the 2018 and 2019 field experiments continued to illustrate that all other treatments performed similarly at five MAT (Tables 12 and 13). Treatments of oryzalin and the sulfonylurea herbicides performed the poorest with less than 54% control in 2018 and 2019.

Post-emergent

For the field experiments conducted in the commercial prune orchard in Orland, CA, the graminicide treatments of clethodim performed similarly to fluazifop, providing greater than 81% control in 2016 (Table 14) and greater than 79% in 2017 (Table 15) five WAT. Sethoxydim, on the other hand, was comparable to just clethodim in both 2016 at 80% (Table 14) and 2017 at 73% (Table 15). The tank mix combinations of glyphosate plus glufosinate at 60% control and glyphosate plus oxyfluorfen at 59% control were statistically similar at five WAT, in 2016. Treatments of glyphosate at the 2280 g ae/ha and the tank mix of glyphosate plus rimsulfuron were statistically similar, providing 48% and 50% control, respectively, five WAT. The poorest control came from the glyphosate treatment at the 1140 g ae/ha rate with only 35% control five WAT. In 2017, all treatments other than the graminicides provided less than 62% control with some statistical variation when comparing treatment means. The poorest POST control of *E. tristachya* continued to be that of glyphosate plus rimsulfuron and glyphosate at the 1140 g ae/ha rate, providing less than 33% control five WAT (Table 15).

For the field experiments conducted in the commercial almond orchard located in Livingston, CA, the treatment of fluazifop provided greater than 90% control five WAT, across all three years (Tables 16, 17, and 18). In 2017, treatments of fluazifop and clethodim were statistically similar, providing 90% and 81% control respectively five WAT. Treatments of sethoxydim provided 73% control, which was comparable to that of clethodim. The tank mix treatment of glufosinate plus glyphosate, which provided 69% control was statistically similar to the tank mix treatment of oxyfluorfen plus glyphosate which provided 61%, and was statistically similar to that of glufosinate and glyphosate. Treatments of glyphosate at both the 2280 g ae/ha and the 1140 g ae/ha rate, along with treatments of glyphosate plus rimsulfuron, all performed statistically similar with less than 49% control five WAT (Table 16). In 2018, the three graminicides performed statistically similar with greater than 80% control at five WAT. The tank mix treatments of glufosinate plus glyphosate at 64% control, and oxyfluorfen plus glyphosate at 61% control provided statistically similar results. Rimsulfuron plus glyphosate provided 50% control, which was statistically similar to the glyphosate treatment at 2280 g ae/ha at 45% control. Glyphosate at the 1140 g ae/ha provided the poorest control at 34%, five WAT (Table 17). In 2019, fluazifop provided 90% control and clethodim 80% control, which were statistically similar results. Treatments of sethoxydim provided 79% control, which was statistically similar to that of clethodim. Tank mix treatments of glyphosate plus glufosinate provided 64% control and oxyfluorfen plus glyphosate provided 59% control, which were statistically similar. Both glyphosate treatments and that of rimsulfuron plus glyphosate provided the poorest control with less than 44% control five WAT (Table 18).

Results from the field experiments conducted in the commercial walnut orchard located in Chico, CA were similar to those obtained in Livingston, CA. In 2017, fluazifop provided the greatest level of control at 89% five WAT. The two other graminicides performed statistically similar, with clethodim providing 79% control and sethoxydim 76% control. Tank mix treatments of glyphosate plus glufosinate at 60% control and glyphosate plus oxyfluorfen at 55% control showed no statistical difference. The glyphosate treatment at 2280 g ae/ha, at 46% control was statistically similar to glyphosate plus oxyfluorfen. The glyphosate plus rimsulfuron at 36% control and glyphosate treatment at 1140 g ae/ha, at 39% control, performed the poorest at five WAT (Table 19). In 2018, the three graminicides provided statistically similar levels of control, all greater than 83% at five WAT. Tank mix treatments of glyphosate plus glufosinate and glyphosate plus oxyfluorfen provided statistically similar control at 61% and 60% control, respectively, at five WAT. The poorest performance, once again, came from the glyphosate treatment at 2280 g ae/ha at 46% control and the glyphosate treatment at 1140 g ae/ha, at 36% control, five WAT. Similar to the glyphosate treatment at 2280 g ae/ha, the tank mix of rimsulfuron plus glyphosate provided 48% control five WAT (Tables 20). In 2019, fluazifop provided the greatest level of control at 91% five WAT. The other two graminicides, clethodim which provided 78% control, and sethoxydim, which provided 73% control, were statistically similar five WAT. Glyphosate plus glufosinate, at 60% control, glyphosate plus oxyfluorfen at 55% control, and the glyphosate treatment at 2280 g ae/ha were all also statistically similar. Glyphosate plus rimsulfuron at 38% control was similar to the glyphosate treatment at 2280 g ae/ha, while the glyphosate treatment at 1140 g ae/ha, at 43% control at five WAT, performed the poorest.

Discussion

Greenhouse Efficacy Study

Results from the greenhouse efficacy studies conducted in 2018 agree with those of previous dose response studies conducted by Hanson et al. in 2013, which illustrated that *E. tristachya* is relatively tolerant to glyphosate. In this study, the growth stage of this weed species appears to have little influence on glyphosate treatments and the associated low efficacy (Tables 2 and 3). When treatments were made at the 2-3 tiller growth stage, all plants were in the vegetive phase of growth; no seed production was taking place. Treatments of glyphosate initially stunted the treated plants for approximately the first two weeks but resulted in little to no necrosis. This resulted in a dry biomass that was equal to that of the untreated control for treatment at the 2284 g ae/ha rate and a dry biomass weight that was greater than that of the untreated control for treatment of glyphosate that was applied at the 1140 g ae/ha rate (Table 2). For treatments that were applied at the 5-6 tiller stage, plants were already in the reproductive phase. Plants responded with the same initial stunting, but quickly responded with rapid tillering. This resulted in a dry biomass that was greater than the untreated control for plants that were treated at both the 2284 g ae/ha and 1140 g ae/ha rates (Table 3). Although the mechanisms of tolerance to glyphosate in *E. tristachya* was not addressed in this research, common mechanisms in weedy grasses include altered target sites (Gressel, 2018), reduced uptake or translocation (Hennigh *et al*, 2005) increased copies of the target enzyme, or enhanced metabolisms (Baucom, 2009).

This type of stimulated growth pattern relative to the untreated control may be explained by hormesis. Hormesis is defined as a biphasic dose response to a toxin, which is characterized by stimulation or a beneficial effect at sublethal doses of a toxin (Mattson, 2008). This study illustrates that sublethal doses of glyphosate may have induced hormesis as indicated by the increased biomass. Because this response was not induced by the graminicides sethoxydim, clethodim, and fluazifop, or by treatments of rimsulfuron, glufosinate, and oxyfluorfen, it is likely related to the specific EPSPS inhibitor site of action as seen in previous hormetic cases (Duke *et al.*, 2006; Brito *et al.*, 2017, 2018).

The results from the other treatments agree with past studies, which reported that the efficacy of an herbicide on a given weed species may be affected by the stage of growth of that weed species. Weed species are generally more susceptible during the early stages of growth rather than at more mature stages (Barros *et al*., 2005; Kudsk, 2007). Graminicide treatments provided the greatest efficacy in this study, with fluazifop providing greater control than both clethodim and sethoxydim at the reproductive 5-6 tiller stage (Tables 3), which is in line with another study that showed that aryloxyphenoxypropionate (FOPs) were more effective than cyclohexanedione (DIMs) on clumping grass species (Friesen *et al*., 1976). It should be noted that efficacy, regardless of treatment, was greater when applied at the 2-3 tiller stage; therefore, it is necessary to encourage the treatment of the recommended doses at the appropriate phenological stages for optimal control.

While the purpose of this greenhouse efficacy study was not to identify resistance to any of the herbicide treatments, this does merit future investigation, particularly due to the fact that populations of the closely related species *E. indica* have been reported to be resistant to several modes of action including EPSPS inhibitors (Lee *et al.*, 2000; Chen *et al.*, 2020), ACCase inhibitors (McCullough *et al.*, 2016), and ALS inhibitors (Vázquez-García *et al.*, 2021).

Field Experiment

Orchard production systems require year-round weed control to minimize the establishment and the successional seedling recruitment of weeds. *E. tristachya* and other warm season weed species pose a problem for current management programs since these species germinate long after the standard winter PRE herbicides are applied and may escape the spring POST program. Warm season annual grasses such as *E. indica* germinate once the soil temperatures reach fluctuating temperatures between 20°C and 35°C (Nishimoto *et al.*, 2016), while warm season perennial grasses such as *Sorghum halepense* begin to germinate, and in this case begin to regrow from a perennialized root system, once temperatures reach approximately 31°C (Krenchinski *et al.*, 2015). These temperatures indicate that *E. tristachya* likely germinates and resumes growth from April through August in the California Central Valley. It may germinate after the spring burndown treatment, developing above and below ground biomass during the summer months. It then enters its reproductive phase before orchard harvest preparations, adding to the soil seed bank and further establishing itself in orchards.

The purpose of the pre-emergent component of field studies conducted from 2016-2019 was to test multiple preemergent herbicides and a split treatment program to see if we could obtain season-long weed control of *E. tristachya*, minimizing the number of plants and the subsequent establishment and seedling recruitment of this species. Multiple herbicides in these trials, such as indaziflam, pendimethalin, and penoxsulam/oxyfluorfen, provided adequate control of *E. tristachya*; however, the greatest control of this warm season perennial was obtained through the sequential treatment program. In this study, indaziflam was applied in January as the first part of the split treatment strategy, followed by a March treatment of pendimethalin, rather than relying on a single winter treatment. Both products in the sequential program provided long residual activity, minimized the risk of leaching, and extended control (Shaner, 2012; Guerra *et al.*, 2016). For example, the biological activity of pendimethalin can range from 135 through 200 days (Hatzinikolaou *et al.*, 2004; Zimdahl, 2018) and the activity of indaziflam lasts approximately five MAT (Guerra *et al.*, 2016). This indicates that the January, initial, treatment of indaziflam likely continued to provide some residual activity in the soil for 90 days, when pendimethalin was applied. The treatment of pendimethalin then provided additional residual control, limiting the number of seedlings through August when pre-harvest burndown treatments were made. While the results from this study suggest that a management plan that utilizes this sequential approach can minimize seedling recruitment of this species, there is still the need to manage the already established stands of this perennial species.

Data collected from the POST field trials from 2016-2019 confirmed that *E. tristachya* is tolerant to glyphosate. Even when glyphosate was applied at 2284 g ae/ha, *E. tristachya* control did not exceed 54% control (Table 3), with many plants producing new shoots and panicles two weeks after treatment (data not shown). Fluazifop, clethodim, and sethoxydim provided the greatest control of *E. tristachya*. It is important to note that fluazifop provided the greatest percentage of control in these studies, even on heavily tillered plants (Figure 3). These larger, more heavily tillered plants generally became less susceptible to both chemical and mechanical control options; therefore, *E. tristachya* can create a uniform mat and establish itself in orchards if not properly managed. It

E. tristachya is prevalent in orchards where sunlight is ample, due to the fact that this species is not shade tolerant (Fynn *et al.*, 2011). For field studies conducted in the walnut orchard, *E. tristachya* stands were most dense in the orchard middles, at the end of tree rows, and where trees had been removed, likely because conventional walnut orchard configuration in California creates an expansive trees canopy structure. This intercepts approximately 80% of all photosynthetically active radiation (Rosati *et al.*, 2004). *E. tristachya* was ubiquitous throughout the prune orchard field site in Orland, California, likely due to the standard orchard configuration, historical constraint of space needed for harvest equipment, and the relatively small canopy structure, which only captures 30-45% of midday light (Milliron *et al.*, 2019). Similarly, because almond orchards require sunlit middles for drying operations, *E. tristachya* advantageously grew as a uniform stand throughout the almond orchard in Livingston, CA. The abundance of *E. tristachya* in orchards is exacerbated by routine orchard maintenance as well. During most of year, minus pre harvest orchard floor cleanup, orchard middles are managed by mowing. Under these conditions, an *E. tristachya* seed bank can become established, which in turn, compromises both the middles and the tree row weed management for years to come. Once the species has become well established through such a manner, pre harvest orchard floor cleanup which is often based on POST treatments with glyphosate and glufosinate, may be insufficient.

As noted, the presence of *E. tristachya* in Californian walnut, almond, and prune orchards combined with the fact that PRE treatments are applied before the species germinates, and it is tolerant to glyphosate-based POST treatments, poses a challenge for California orchard managers. This highlights the need for an orchard floor management program that addresses the issues with current PRE and POST treatments. It should incorporate a PRE emergent program, which targets the phenology of *E. tristachya,* as the SHA did. The benefit of SHA, unlike current PRE programs, is that this approach targets the emergence of warm season species, such as *E. tristachya*. It has the potential to minimize seedling acquisition and limit establishment of the species; thus, it may permit orchard managers to decrease their reliance on POST herbicides. A revised orchard management plan should also include a POST program, which utilizes graminicides, such as fluazifop, clethodim, or sethoxydim. This is especially relevant because after a glyphosate-based POST treatment, tufts of *E. tristachya* are left on the orchard floor and interfere with the subsequent nut pick up. Orchard managers that adopt this type of management program may be better able to control and even prevent the growth of *E. tristachya*.

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Figures

Figure 1. *Eleusine tristachya* inflorescence

Figure 2. Flowering *Eleusine tristachya*

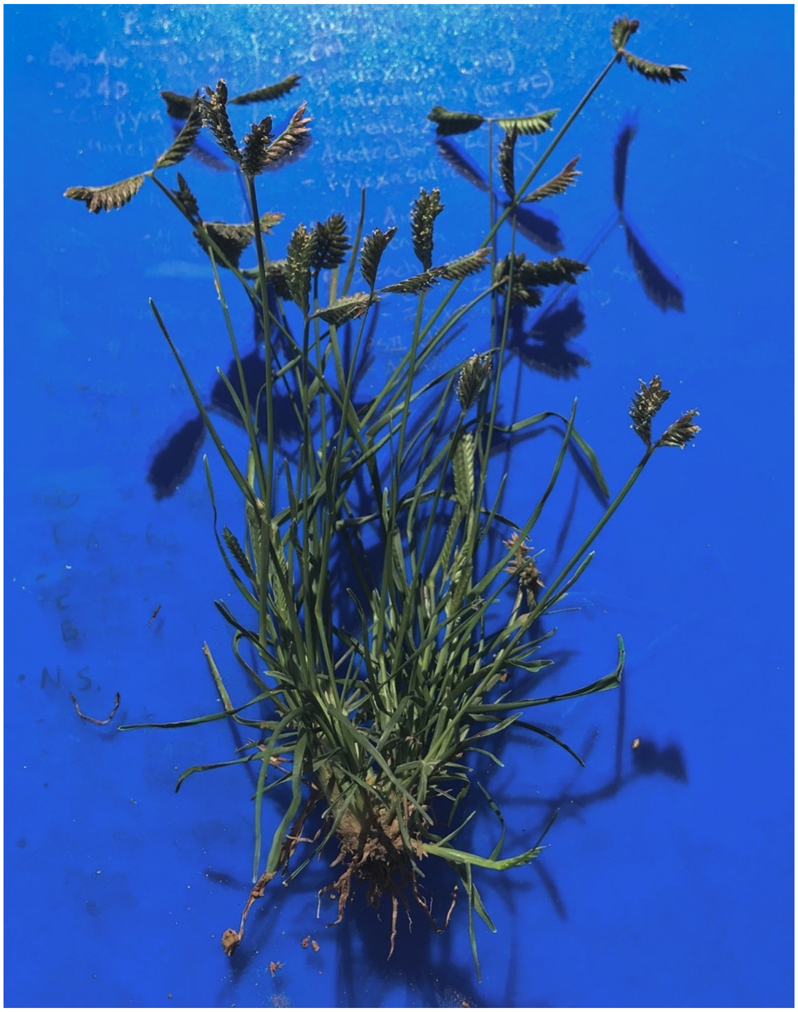

Figure 3. Control of heavily tillered *E. tristachya* at five WAT following fluazifop treatment.

Tables

Table 1. Source of herbicides used in *E. tristachya* greenhouse and field experiments.

Common name	Trade name	Manufacturer	Address
flazasulfuron	Mission®	SummitAgro U.S.A	Durham, NC www.summitagro-usa.com
flumioxazin	Chateau®	Valent U.S.A. Corporation	Walnut Creek, CA www.valentpro.com
fluazifop	Fusilade DX®	Syngenta Crop Protection, LLC	Greensboro, NC www.syngentacropprotection-us.com
clethodim	Select Max®	Valent U.S.A. Corporation	Walnut Creek, CA www.valentpro.com
sethoxydim	Poast®	BASF Ag Products	Research Triangle Park, NC www.agproducts.basf.com
glyphosate	Roundup Weathermax®	Bayer CropScience	Research Triangle Park, NC www.bayercropscienceus.com
glufosinate	Rely 280®	BASF Ag Products	Research Triangle Park, NC www.agproducts.basf.com
indaziflam	Alion®	Bayer CropScience	Research Triangle Park, NC www.bayercropscienceus.com
oryzalin	Surflan A.S.®	United Phosphorus Limited	King of Prussia, PA www.upl-ltd.com
oxyfluorfen	GoalTender®	Corteva Agriscience	Wilmington, DE http://www.corteva.us/
pendimethalin	Prowl H2O®	BASF Ag Products	Research Triangle Park, NC www.agproducts.basf.com
penoxsulam/oxyfluorfen	Pindar GT®	Corteva Agriscience	Wilmington, DE http://www.corteva.us/
rimsulfuron	Matrix SG®	Corteva Agriscience	Wilmington, DE http://www.corteva.us/

Table 2. Greenhouse screening for POST herbicide control of *E. tristachya* at the 2-3 tiller growth stage, conducted in 2018.

	Treatment[a]	Rate	Aboveground Biomass	Standard Deviation	Growth Reduction Relative to Non-treated
		g ai/ha	mg/plant[c]	mg/plant	%[c]
1	glyphosate	2280[b]	3086 l	38.91	+ 1 l
2	glyphosate	1140[b]	3058 l	52.28	0.0 l
3	sethoxydim	315	693 c	37.87	- 77 c
4	sethoxydim	158	1293 e	33.59	- 58 e
5	clethodim	102	514 b	30.84	- 83 b
6	clethodim	51	996 d	46.30	- 67 d
7	fluazifop	210	291 a	22.53	- 90 a
8	fluazifop	105	645 c	50.73	- 79 c
9	rimsulfuron	70	2227 j	71.11	- 27 j
10	rimsulfuron	35	2667 k	73.15	- 13 k
11	glufosinate	1680	1542 f	40.28	- 50 f
12	glufosinate	840	1884 h	55.85	- 38 h
13	oxyfluorfen	1400	1825 g	79.35	- 40 g
14	oxyfluorfen	700	2070 i	40.46	- 32 i
15	non-treated	-	3058 l	63.69	-

[a] Ammonium sulfate at 1% v/v and non-ionic surfactant at 0.25% v/v were added to all treatments.
[b] Grams of acid equivalent per hectare (g ae/ha).
[c] Letters indicate statistical difference at alpha = 0.05 according to Tukey's HSD. Values followed by the same letters are not significantly different. Columns cannot be compared.

Table 3. Greenhouse screening for POST herbicide control of *E. tristachya* at the 5-6 tiller growth stage, conducted in 2018.

	Treatment[a]	Rate	Aboveground Biomass	Standard Deviation	Growth Reduction Relative to Non-treated
		g ai/ha	mg/plant[c]	mg/plant	%[c]
1	glyphosate	2280[b]	5858 mn	62.83	+ 1 mn
2	glyphosate	1140[b]	5934 n	77.12	+ 2 n
3	sethoxydim	315	2182 d	86.95	- 62 d
4	sethoxydim	158	2966 f	109.02	- 49 f
5	clethodim	102	1803 c	35.80	- 69 c
6	clethodim	51	2335 e	135.14	- 60 e
7	fluazifop	210	994 a	89.04	- 83 a
8	fluazifop	105	1669 b	171.56	- 71 b
9	rimsulfuron	70	4561 k	117.15	- 21 k
10	rimsulfuron	35	5600 l	66.42	- 3 l
11	glufosinate	1680	3101 g	59.35	- 46 g
12	glufosinate	840	3744 i	79.84	- 35 i
13	oxyfluorfen	1400	3596 h	99.83	- 38 h
14	oxyfluorfen	700	4101 j	55.99	- 29 j
15	non-treated	-	5793 m	202.37	-

[a] Ammonium sulfate at 1% v/v and non-ionic surfactant at 0.25% v/v were added to all treatments.
[b] Grams of acid equivalent per hectare (g ae/ha).
[c] Letters indicate statistical difference at alpha = 0.05 according to Tukey's HSD. Values followed by the same letters are not significantly different. Columns cannot be compared.

Table 4. Comparison of PRE herbicide treatments for control of *E. tristachya* five MAT in California prune (Orland), almond (Livingston), and walnut (Chico) orchards.

	Treatment[ab]	Rate	Orland, CA		Livingston, CA			Chico, CA		
			2016	2017	2017	2018	2019	2017	2018	2019
		g ai/ha	----------------------	----------------------	-----------	%[c]	-----------	----------------------	----------------------	----------------------
1	indaziflam fb pendimethalin	51 fb 3195	91 e	90 d	90 e	90 e	91 e	90 g	91 e	91 f
2	indaziflam	73	76 d	75 c	75 d	75 d	72 d	69 f	61 cd	65 e
3	penoxsulam/oxyfluorfen	34/1652	73 bcd	71 c	74 d	72 cd	68 d	65 ef	62 d	61 cde
4	pendimethalin	4260	71 cd	69 c	73 d	72 cd	69 d	63 de	59 bcd	57 bcd
5	indaziflam	51	-	-	65 c	65 bc	61 c	57 bc	56 abcd	58 bcd
6	flumioxazin + pendimethalin	357 + 4260	61 abc	58 ab	61 bc	63 b	60 c	62 cde	59 bcd	61 de
7	oxyfluorfen + oryzalin	1401 + 4483	59 ab	56 ab	60 b	61 b	59 c	56 bc	55 abc	56 abcd
8	indaziflam + rimsulfuron	51 + 70	61 abc	63 bc	60 b	59 b	56 bc	57 bc	57 abcd	57 bcd
9	oryzalin	4483	51 a	50 a	53 a	52 a	53 ab	52 ab	52 a	50 a
10	penoxsulam/oxyfluorfen	22/1101	-	-	63 bc	60 b	60 c	59 cd	56 abc	55 abc
11	flazasulfuron	52	53 a	51 a	51 a	49 a	49 a	50 a	54 ab	56 abcd
12	rimsulfuron	70	53 a	50 a	52 a	52 a	49 a	50 a	52 a	54 ab

[a] Glufosinate at 1680 g ai/ha, ammonium sulfate at 1% v/v and non-ionic surfactant at 0.25% v/v were added to all treatments.
[b] "/" indicates products sold as pre-mixes; "+" indicates tank-mix; "fb" indicates "followed by" sequential treatment.
[c] Letters indicate statistical difference at alpha = 0.05 according to Tukey's HSD. Values followed by the same letters are not significantly different. Columns cannot be compared.

Table 5. Comparison of POST herbicide treatments for control of *E. tristachya* five WAT in California prune (Orland), almond (Livingston), and walnut (Chico) orchards.

	Treatment[ab]	Rate	Orland, CA		Livingston, CA			Chico, CA		
			2016	2017	2017	2018	2019	2017	2018	2019
		g ai/ha	%[d]							
1	fluazifop	210	89 e	85 f	90 e	91 e	90 d	89 f	90 d	91 e
2	clethodim	102	81 de	79 ef	81 de	80 e	80 cd	79 ef	83 d	78 d
3	sethoxydim	315	80 d	74 e	73 cd	80 e	79 c	76 e	83 d	73 d
4	glyphosate + glufosinate	1140[c] + 1311	60 c	63 d	69 bc	64 d	64 b	60 d	61 c	60 c
5	glyphosate + oxyfluorfen	1140[c] + 280	59 c	55 c	61 b	61 cd	59 b	55 cd	60 c	55 c
6	glyphosate	2280[c]	48 b	41 b	49 a	45 ab	44 a	46 bc	46 ab	51bc
7	glyphosate + rimsulfuron	1140[c] + 35	50 b	33 a	43 a	50 bc	40 a	36 a	48 b	38 ab
8	glyphosate	1140[c]	35 a	33 a	40 a	34 a	36 a	39 ab	36 a	43 a

[a] Ammonium sulfate at 1% v/v and non-ionic surfactant at 0.25% v/v were added to all treatments.
[b] "+" indicates tank-mix.
[c] Grams of acid equivalent per hectare (g ae/ha).
[d] Letters indicate statistical difference at alpha = 0.05 according to Tukey's HSD. Values followed by the same letters are not significantly different. Columns cannot be compared.

Table 6. Visual assessment of residual control of *E. tristachya* following 2016 winter PRE herbicide treatment applications in a commercial prune orchard located in Orland, CA.

	Treatment[ab]	Rate	Treatment Efficacy				
			30 DAT	60 DAT	90 DAT	120 DAT	150 DAT
		g ai/ha	---%[c]---				
1	indaziflam fb pendimethalin	51 fb 3195	100 a	93 c	94 d	94 f	91 e
2	indaziflam	73	100 a	95 c	90 c	84 e	76 d
3	penoxsulam/oxyfluorfen	34/1652	100 a	93 c	84 b	79 d	73 bcd
4	pendimethalin	4260	100 a	95 c	88 bc	84 e	71 cd
5	flumioxazin + pendimethalin	357 + 4260	100 a	93 c	88 bc	76 cd	61 abc
6	oxyfluorfen + oryzalin	1401 + 4483	100 a	91 b	84 b	73 b	59 ab
7	indaziflam + rimsulfuron	51 + 70	100 a	88 ab	81 ab	74 bc	61 abc
8	oryzalin	4483	100 a	88 ab	74 a	64 a	51 a
9	flazasulfuron	52	98 a	88 ab	74 a	63 a	53 a
10	rimsulfuron	70	98 a	84 a	75 a	64 a	53 a

[a] Glufosinate at 1680 g ai/ha, ammonium sulfate at 1% v/v and non-ionic surfactant at 0.25% v/v were added to all treatments.
[b] "/" indicates products sold as pre-mixes; "+" indicates tank-mix; "fb" indicates "followed by" sequential treatment.
[c] Letters indicate statistical difference at alpha = 0.05 according to Tukey's HSD. Values followed by the same letters are not significantly different. Columns cannot be compared.

Table 7. Visual assessment of residual control of *E. tristachya* following 2017 winter PRE herbicide treatment applications in a commercial prune orchard located in Orland, CA.

	Treatment[ab]	Rate	Treatment Efficacy				
			30 DAT	60 DAT	90 DAT	120 DAT	150 DAT
		g ai/ha	%[c]				
1	indaziflam fb pendimethalin	51 fb 3195	100 a	93 c	95 e	91 d	90 d
2	indaziflam	73	100 a	94 c	88 d	81 c	75 c
3	penoxsulam/oxyfluorfen	34/1652	100 a	91 c	83 c	78 bc	71 c
4	pendimethalin	4260	100 a	93 c	85 cd	81 c	69 c
5	flumioxazin + pendimethalin	357 + 4260	99 a	88 bc	83 c	71 b	58 ab
6	oxyfluorfen + oryzalin	1401 + 4483	100 a	86 b	81 bc	71 b	56 ab
7	indaziflam + rimsulfuron	51 + 70	100 a	86 b	78 b	71 b	63 bc
8	oryzalin	4483	100 a	85 b	73 ab	61 a	50 a
9	flazasulfuron	52	98 a	84 ab	70 a	59 a	51 a
10	rimsulfuron	70	99 a	81 a	71 a	60 a	50 a

[a] Glufosinate at 1680 g ai/ha, ammonium sulfate at 1% v/v and non-ionic surfactant at 0.25% v/v were added to all treatments.
[b] "/" indicates products sold as pre-mixes; "+" indicates tank-mix; "fb" indicates "followed by" sequential treatment.
[c] Letters indicate statistical difference at alpha = 0.05 according to Tukey's HSD. Values followed by the same letters are not significantly different. Columns cannot be compared.

Table 8. Visual assessment of residual control on *E. tristachya* following 2017 winter PRE herbicide treatment applications in a commercial almond orchard located in Livingston, CA.

	Treatment[ab]	Rate	Treatment Efficacy				
			30 DAT	60 DAT	90 DAT	120 DAT	150 DAT
		g ai/ha	------%[c]------				
1	indaziflam fb pendimethalin	51 fb 3195	99 bc	89 d	94 h	92 h	90 e
2	indaziflam	73	100 c	96 g	91 g	84 g	75 d
3	penoxsulam/oxyfluorfen	34/1652	99 bc	93 f	87 f	79 f	74 d
4	pendimethalin	4260	100 c	96 g	91 g	82 g	73 d
5	indaziflam	51	99 bc	88 cd	83 e	76 e	65 c
6	flumioxazin + pendimethalin	357 + 4260	97 a	91 e	85 e	78 f	61 bc
7	oxyfluorfen + oryzalin	1401 + 4483	99 bc	91 e	84 de	71 c	60 b
8	indaziflam + rimsulfuron	51 + 70	98 ab	86 b	81 c	73 cd	60 b
9	oryzalin	4483	98 ab	86 b	76 b	65 b	53 a
10	penoxsulam/oxyfluorfen	22/1101	99 bc	88 cd	80 c	74 d	63 bc
11	Flazasulfuron	52	97 a	87 bc	72 a	65 b	51 a
12	rimsulfuron	70	97 a	85 a	76 b	63 a	52 a

[a] Glufosinate at 1680 g ai/ha, ammonium sulfate at 1% v/v and non-ionic surfactant at 0.25% v/v were added to all treatments.
[b] "/" indicates products sold as pre-mixes; "+" indicates tank-mix; "fb" indicates "followed by" sequential treatment.
[c] Letters indicate statistical difference at alpha = 0.05 according to Tukey's HSD. Values followed by the same letters are not significantly different. Columns cannot be compared.

Table 9. Visual assessment of residual control on *E. tristachya* following 2018 winter PRE herbicide treatment applications in a commercial almond orchard located in Livingston, CA.

	Treatment[ab]	Rate	Treatment Efficacy				
			30 DAT	60 DAT	90 DAT	120 DAT	150 DAT
		g ai/ha	----------------------	----------------------	%[c]	----------------------	----------------------
1	indaziflam fb pendimethalin	51 fb 3195	100 a	93 e	94 f	91 i	90 e
2	indaziflam	73	100 a	95 f	91 e	84 h	75 d
3	penoxsulam/oxyfluorfen	34/1652	100 a	92 de	87 d	79 f	72 cd
4	pendimethalin	4260	99 a	96 f	88 d	82 g	72 cd
5	indaziflam	51	100 a	89 bc	79 b	76 e	65 bc
6	flumioxazin + pendimethalin	357 + 4260	100 a	91 cd	82 c	78 f	63 b
7	oxyfluorfen + oryzalin	1401 + 4483	100 a	92 de	82 c	71 c	61 b
8	indaziflam + rimsulfuron	51 + 70	100 a	89 ab	79 b	73 d	59 b
9	oryzalin	4483	99 a	89 ab	75 a	65 b	52 a
10	penoxsulam/oxyfluorfen	22/1101	100 a	90 bc	82 c	74 d	60 b
11	flazasulfuron	52	100 a	89 bc	75 a	65 ab	49 a
12	rimsulfuron	70	99 a	88 a	74 a	63 a	52 a

[a] Glufosinate at 1680 g ai/ha, ammonium sulfate at 1% v/v and non-ionic surfactant at 0.25% v/v were added to all treatments.
[b] "/" indicates products sold as pre-mixes; "+" indicates tank-mix; "fb" indicates "followed by" sequential treatment.
[c] Letters indicate statistical difference at alpha = 0.05 according to Tukey's HSD. Values followed by the same letters are not significantly different. Columns cannot be compared.

Table 10. Visual assessment of residual control on *E. tristachya* following 2019 winter PRE herbicide treatment applications in a commercial almond orchard located in Livingston, CA.

	Treatment[ab]	Rate	Treatment Efficacy				
			30 DAT	60 DAT	90 DAT	120 DAT	150 DAT
		g ai/ha	--------------------	----------	%[c]	----------	--------------------
1	indaziflam fb pendimethalin	51 fb 3195	100 a	90 g	97 h	93 f	91 e
2	indaziflam	73	100 a	94 i	86 g	77 e	72 d
3	penoxsulam/oxyfluorfen	34/1652	100 a	92 h	84 f	76 e	68 d
4	pendimethalin	4260	100 a	94 i	82 e	76 e	69 d
5	indaziflam	51	98 b	89 f	77 cd	68 c	61 c
6	flumioxazin + pendimethalin	357 + 4260	100 a	88 ef	82 e	72 d	60 c
7	oxyfluorfen + oryzalin	1401 + 4483	100 a	89 f	83 ef	71 d	59 c
8	indaziflam + rimsulfuron	51 + 70	100 a	83 c	76 c	65 b	56 bc
9	oryzalin	4483	100 a	86 d	73 b	62 a	53 ab
10	penoxsulam/oxyfluorfen	22/1101	99 a	87 de	78 d	69 c	60 c
11	flazasulfuron	52	99 a	80 a	70 a	61 a	49 a
12	rimsulfuron	70	100 a	82 b	71 a	61 a	49 a

[a] Glufosinate at 1680 g ai/ha, ammonium sulfate at 1% v/v and non-ionic surfactant at 0.25% v/v were added to all treatments.
[b] "/" indicates products sold as pre-mixes; "+" indicates tank-mix; "fb" indicates "followed by" sequential treatment.
[c] Letters indicate statistical difference at alpha = 0.05 according to Tukey's HSD. Values followed by the same letters are not significantly different. Columns cannot be compared.

Table 11. Visual assessment of residual control on *E. tristachya* following 2017 winter PRE herbicide treatment applications in a commercial walnut orchard located in Chico, CA.

	Treatment[ab]	Rate	Treatment Efficacy				
			30 DAT	60 DAT	90 DAT	120 DAT	150 DAT
		g ai/ha	---	---	%[c]	---	---
1	indaziflam fb pendimethalin	51 fb 3195	100 a	91 d	94 g	92 h	90 g
2	indaziflam	73	100 a	94 e	86 f	76 g	69 f
3	penoxsulam/oxyfluorfen	34/1652	100 a	90 cd	79 de	71 f	65 ef
4	pendimethalin	4260	99 a	90 cd	79 de	70 ef	63 de
5	indaziflam	51	100 a	87 a	77 cd	66 d	57 bc
6	flumioxazin + pendimethalin	357 + 4260	100 a	91 d	80 e	72 f	62 cde
7	oxyfluorfen + oryzalin	1401 + 4483	100 a	90 cd	79 de	65 cd	56 bc
8	indaziflam + rimsulfuron	51 + 70	100 a	88 bc	78 cde	68 e	57 bc
9	oryzalin	4483	100 a	88 bc	74 ab	62 bc	52 ab
10	penoxsulam/oxyfluorfen	22/1101	100 a	87ab	75 ab	66 d	50 cd
11	flazasulfuron	52	100 a	89 bc	73 a	60 ab	50 a
12	rimsulfuron	70	100 a	89 bc	76 bc	58 a	50 a

[a] Glufosinate at 1680 g ai/ha, ammonium sulfate at 1% v/v and non-ionic surfactant at 0.25% v/v were added to all treatments.
[b] "/" indicates products sold as pre-mixes; "+" indicates tank-mix; "fb" indicates "followed by" sequential treatment.
[c] Letters indicate statistical difference at alpha = 0.05 according to Tukey's HSD. Values followed by the same letters are not significantly different. Columns cannot be compared.

Table 12. Visual assessment of residual control on *E. tristachya* following 2018 winter PRE herbicide treatment applications in a commercial walnut orchard located in Chico, CA.

	Treatment[ab]	Rate	Treatment Efficacy				
			30 DAT	60 DAT	90 DAT	120 DAT	150 DAT
		g ai/ha	%[c]				
1	indaziflam fb pendimethalin	51 fb 3195	100 a	91 c	94 f	93 g	91 e
2	indaziflam	73	100 a	91 c	81	71 f	61 cd
3	penoxsulam/oxyfluorfen	34/1652	100 a	91 c	82 e	71 f	62 d
4	pendimethalin	4260	99 a	91 c	81 de	71 f	59 bcd
5	indaziflam	51	100 a	90 b	79 bc	69 de	56 abcd
6	flumioxazin + pendimethalin	357 + 4260	100 a	89 a	81 de	68 cd	59 bcd
7	oxyfluorfen + oryzalin	1401 + 4483	100 a	89 a	78 ab	66 ab	55 abc
8	indaziflam + rimsulfuron	51 + 70	100 a	91 c	80 cd	70 ef	57 abcd
9	oryzalin	4483	100 a	89 a	77 a	67 bc	52 a
10	penoxsulam/oxyfluorfen	22/1101	100 a	90 b	78 ab	67 bc	56 abc
11	flazasulfuron	52	100 a	89 a	78 ab	67 b	54 ab
12	rimsulfuron	70	100 a	89 a	78 ab	65 a	52 a

[a] Glufosinate at 1680 g ai/ha, ammonium sulfate at 1% v/v and non-ionic surfactant at 0.25% v/v were added to all treatments.
[b] "/" indicates products sold as pre-mixes; "+" indicates tank-mix; "fb" indicates "followed by" sequential treatment.
[c] Letters indicate statistical difference at alpha = 0.05 according to Tukey's HSD. Values followed by the same letters are not significantly different. Columns cannot be compared.

Table 13. Visual assessment of residual control on *E. tristachya* following 2019 winter PRE herbicide treatment applications in a commercial walnut orchard located in Chico, CA.

	Treatment[ab]	Rate	Treatment Efficacy				
			30 DAT	60 DAT	90 DAT	120 DAT	150 DAT
		g ai/ha	---%[c]---				
1	indaziflam fb pendimethalin	51 fb 3195	100 a	91 cd	94 f	93 e	91 f
2	indaziflam	73	100 a	91 cd	83 d	74 d	65 e
3	penoxsulam/oxyfluorfen	34/1652	100 a	91 cd	81 c	72 c	61 cde
4	pendimethalin	4260	100 a	91 cd	85 e	74 d	57 bcd
5	indaziflam	51	100 a	91 cd	81 c	70 b	58 bcd
6	flumioxazin + pendimethalin	357 + 4260	100 a	89 a	81 c	70 b	61 de
7	oxyfluorfen + oryzalin	1401 + 4483	100 a	90 ab	80 bc	68 a	56 abcd
8	indaziflam + rimsulfuron	51 + 70	100 a	92 d	83 d	69 ab	57 bcd
9	oryzalin	4483	99 a	89 a	78 a	68 a	50 a
10	penoxsulam/oxyfluorfen	22/1101	100 a	90 bc	81 c	70 b	55 abc
11	flazasulfuron	52	99 a	91 bc	80 bc	68 a	56 abcd
12	rimsulfuron	70	100 a	89 a	79 ab	68 a	54 ab

[a] Glufosinate at 1680 g ai/ha, ammonium sulfate at 1% v/v and non-ionic surfactant at 0.25% v/v were added to all treatments.
[b] "/" indicates products sold as pre-mixes; "+" indicates tank-mix; "fb" indicates "followed by" sequential treatment.
[c] Letters indicate statistical difference at alpha = 0.05 according to Tukey's HSD. Values followed by the same letters are not significantly different. Columns cannot be compared.

Table 14. Visual assessment of *E. tristachya* control following 2016 POST herbicide treatment applications in a commercial prune orchard located in Orland, CA.

	Treatment[ab]	Rate	Treatment Efficacy				
			1 WAT	2 WAT	3 WAT	4 WAT	5 WAT
		g ai/ha	%[d]				
1	fluazifop	210	31 c	48 d	63 e	83 e	89 e
2	clethodim	102	33 c	39 b	55 d	69 d	81 de
3	sethoxydim	315	33 c	41 bc	55 d	68 d	80 d
4	glyphosate + glufosinate	1140[c] + 1311	34 cd	43 c	51 cd	54 c	60 c
5	glyphosate + oxyfluorfen	1140[c] + 280	36 d	44 c	50 c	54 c	59 c
6	glyphosate	2280[c]	29 b	40 b	50 c	52 bc	48 b
7	glyphosate + rimsulfuron	1140[c] + 35	30 bc	39 b	44 b	50 b	50 b
8	glyphosate	1140[c]	18 a	29 a	38 a	40 a	35 a

[a] Ammonium sulfate at 1% v/v, non-ionic surfactant at 0.25% v/v, and/or MSO at 1% v/v were added to all treatments according to label recommendations.
[b] "+" indicates tank-mix.
[c] Grams of acid equivalent per hectare (g ae/ha).
[d] Letters indicate statistical difference at alpha = 0.05 according to Tukey's HSD. Values followed by the same letters are not significantly different. Columns cannot be compared.

Table 15. Visual assessment of *E. tristachya* control following 2017 POST herbicide treatment applications in a commercial prune orchard located in Orland, CA.

	Treatment[ab]	Rate	Treatment Efficacy				
			1 WAT	2 WAT	3 WAT	4 WAT	5 WAT
		g ai/ha	%[d]				
1	fluazifop	210	28 c	48 e	61 e	79 f	85 f
2	clethodim	102	28 c	36 bc	53 d	66 e	79 ef
3	sethoxydim	315	30 c	40 d	51 d	58 d	73 e
4	glyphosate + glufosinate	1140[c] + 1311	28 c	41 d	44 c	50 cd	63 d
5	glyphosate + oxyfluorfen	1140[c] + 280	38 d	38 c	43 bc	48 bc	55 c
6	glyphosate	2280[c]	25 b	39 cd	51 d	44 b	41 b
7	glyphosate + rimsulfuron	1140[c] + 35	28 c	33 b	35 a	38 a	33 a
8	glyphosate	1140[c]	15 a	29 a	40 ab	38 a	31 a

[a] Ammonium sulfate at 1% v/v and non-ionic surfactant at 0.25% v/v, and/or MSO at 1% v/v were added to all treatments according to label recommendations.
[b] "+" indicates tank-mix.
[c] Grams of acid equivalent per hectare (g ae/ha).
[d] Letters indicate statistical difference at alpha = 0.05 according to Tukey's HSD. Values followed by the same letters are not significantly different. Columns cannot be compared.

Table 16. Visual assessment of *E. tristachya* control following 2017 POST herbicide treatment applications in a commercial almond orchard located in Livingston, CA.

	Treatment[ab]	Rate	Treatment Efficacy				
			1 WAT	2 WAT	3 WAT	4 WAT	5 WAT
		g ai/ha	---%[d]---				
1	fluazifop	210	29 b	50 d	65 d	80 e	90 e
2	clethodim	102	25 ab	40 c	53 c	67 d	81 de
3	sethoxydim	315	29 b	43 cd	56 cd	59 cd	73 cd
4	glyphosate + glufosinate	1140[c] + 1311	29 b	36 bc	43 b	54 bc	69 bc
5	glyphosate + oxyfluorfen	1140[c] + 280	40 c	41 c	46 b	53 bc	61 b
6	glyphosate	2280[c]	25 ab	41 c	56 cd	51 b	49 a
7	glyphosate + rimsulfuron	1140[c] + 35	29 b	34 b	39 a	40 a	43 a
8	glyphosate	1140[c]	18 a	29 a	44 b	43 a	40 a

[a] Ammonium sulfate at 1% v/v and non-ionic surfactant at 0.25%, and/or MSO at 1% v/v were added to all treatments according to label recommendations.
[b] "+" indicates tank-mix.
[c] Grams of acid equivalent per hectare (g ae/ha).
[d] Letters indicate statistical difference at alpha = 0.05 according to Tukey's HSD. Values followed by the same letters are not significantly different. Columns cannot be compared.

Table 17. Visual assessment of *E. tristachya* control following 2018 POST herbicide treatment applications in a commercial almond orchard located in Livingston, CA.

	Treatment[ab]	Rate	Treatment Efficacy				
			1 WAT	2 WAT	3 WAT	4 WAT	5 WAT
		g ai/ha	---%[d]---				
1	fluazifop	210	25 bc	53 e	68 e	81 e	91 e
2	clethodim	102	25 bc	39 b	50 b	68 d	80 e
3	sethoxydim	315	29 c	48 d	58 d	70 d	80 e
4	glyphosate + glufosinate	1140[c] + 1311	33 d	43 c	50 b	58 c	64 d
5	glyphosate + oxyfluorfen	1140[c] + 280	38 e	45 cd	53 bc	58 c	61 cd
6	glyphosate	2280[c]	30 cd	45 cd	56 cd	48 b	45 ab
7	glyphosate + rimsulfuron	1140[c] + 35	21 b	36 a	40 a	48 b	50 bc
8	glyphosate	1140[c]	19 a	34 a	46 a	40 a	34 a

[a] Ammonium sulfate at 1% v/v and non-ionic surfactant at 0.25% v/v , and/or MSO at 1% v/v were added to all treatments according to label recommendations.
[b] "+" indicates tank-mix.
[c] Grams of acid equivalent per hectare (g ae/ha).
[d] Letters indicate statistical difference at alpha = 0.05 according to Tukey's HSD. Values followed by the same letters are not significantly different. Columns cannot be compared.

Table 18. Visual assessment of *E. tristachya* control following 2019 POST herbicide treatment applications in a commercial almond orchard located in Livingston, CA.

	Treatment[ab]	Rate	Treatment Efficacy				
			1 WAT	2 WAT	3 WAT	4 WAT	5 WAT
		g ai/ha	-------------------- %[d] --------------------				
1	fluazifop	210	28 bcd	46 c	71 d	81f	90 d
2	clethodim	102	25 b	39 b	54 c	63 d	80 cd
3	sethoxydim	315	25 b	40 b	58 c	71 e	79 c
4	glyphosate + glufosinate	1140[c] + 1311	31 d	38 b	51 bc	55 c	64 b
5	glyphosate + oxyfluorfen	1140[c] + 280	29 cd	39 b	50 b	58 cd	59 b
6	glyphosate	2280[c]	28 bcd	46 c	58 c	51 bc	44 a
7	glyphosate + rimsulfuron	1140[c] + 35	24 b	33 a	43 a	49 b	40 a
8	glyphosate	1140[c]	20 a	31 a	45 a	40 a	36 a

[a] Ammonium sulfate at 1% v/v and non-ionic surfactant at 0.25% v/v, and/or MSO at 1% v/v were added to all treatments according to label recommendations.
[b] "+" indicates tank-mix.
[c] Grams of acid equivalent per hectare (g ae/ha).
[d] Letters indicate statistical difference at alpha = 0.05 according to Tukey's HSD. Values followed by the same letters are not significantly different. Columns cannot be compared.

Table 19. Visual assessment of *E. tristachya* control following 2017 POST herbicide treatment applications in a commercial walnut orchard located in Chico, CA.

	Treatment[ab]	Rate	Treatment Efficacy				
			1 WAT	2 WAT	3 WAT	4 WAT	5 WAT
		g ai/ha	--------------------------%[d]--------------------------				
1	fluazifop	210	26 b	50 e	65 d	76 f	89 f
2	clethodim	102	28 bc	41 d	53 c	64 ef	79 ef
3	sethoxydim	315	30 de	43 de	54 cd	61 e	76 e
4	glyphosate + glufosinate	1140[c] + 1311	28 cd	38 bc	45 b	54 d	60 d
5	glyphosate + oxyfluorfen	1140[c] + 280	33 e	41 d	48 b	51 cd	55 cd
6	glyphosate	2280[c]	28 cd	46 d	55 c	50 c	46 bc
7	glyphosate + rimsulfuron	1140[c] + 35	30 de	35 ab	38 a	39 a	36 a
8	glyphosate	1140[c]	19 a	30 b	45 b	43 b	39 ab

[a] Ammonium sulfate at 1% v/v and non-ionic surfactant at 0.25% v/v, and/or MSO at 1% v/v were added to all treatments according to label recommendations.
[b] "+" indicates tank-mix.
[c] Grams of acid equivalent per hectare (g ae/ha).
[d] Letters indicate statistical difference at alpha = 0.05 according to Tukey's HSD. Values followed by the same letters are not significantly different. Columns cannot be compared.

Table 20. Visual assessment of *E. tristachya* control following 2018 POST herbicide treatment applications in a commercial walnut orchard located in Chico, CA.

	Treatment[ab]	Rate	Treatment Efficacy				
			1 WAT	2 WAT	3 WAT	4 WAT	5 WAT
		g ai/ha	---%[d]---				
1	fluazifop	210	30 c	51 f	70 d	81 f	90 d
2	clethodim	102	26 b	40 bc	59 c	71 e	83 d
3	sethoxydim	315	31 c	46 ef	60 c	73 ef	83 d
4	glyphosate + glufosinate	1140[c] + 1311	31 c	41 bcd	55 bc	61 d	61 c
5	glyphosate + oxyfluorfen	1140[c] + 280	30 c	45 def	56 bc	56 cd	60 c
6	glyphosate	2280[c]	29 bc	44 cde	60 c	54 bc	46 ab
7	glyphosate + rimsulfuron	1140[c] + 35	26 b	39 b	53 ab	51 b	48 b
8	glyphosate	1140[c]	21 a	33 a	50 a	44 a	36 a

[a] Ammonium sulfate at 1% v/v and non-ionic surfactant at 0.25% v/v, and/or MSO at 1% v/v were added to all treatments according to label recommendations.
[b] "+" indicates tank-mix.
[c] Grams of acid equivalent per hectare (g ae/ha).
[d] Letters indicate statistical difference at alpha = 0.05 according to Tukey's HSD. Values followed by the same letters are not significantly different. Columns cannot be compared.

Table 21. Visual assessment of *E. tristachya* control following 2019 POST herbicide treatment applications in a commercial walnut orchard located in Chico, CA.

	Treatment[ab]	Rate	Treatment Efficacy				
			1 WAT	2 WAT	3 WAT	4 WAT	5 WAT
		g ai/ha	%[d]				
1	fluazifop	210	30 c	50 d	65 d	76 e	91 e
2	clethodim	102	29 c	41 c	53 c	64 d	78 d
3	sethoxydim	315	25 b	43 cd	54 c	61 d	73 d
4	glyphosate + glufosinate	1140[c] + 1311	30 c	38 bc	45 b	54 c	60 c
5	glyphosate + oxyfluorfen	1140[c] + 280	38 d	41 c	48 bc	51 bc	55 c
6	glyphosate	2280[c]	30 c	48 d	55 c	50 b	51 bc
7	glyphosate + rimsulfuron	1140[c] + 35	28 bc	35 b	38 a	39 a	38 ab
8	glyphosate	1140[c]	19 a	30 a	46 b	43 a	43 a

[a] Ammonium sulfate at 1% v/v and non-ionic surfactant at 0.25% v/v, and/or MSO at 1% v/v were added to all treatments according to label recommendations.
[b] "+" indicates tank-mix.
[c] Grams of acid equivalent per hectare (g ae/ha).
[d] Letters indicate statistical difference at alpha = 0.05 according to Tukey's HSD. Values followed by the same letters are not significantly different. Columns cannot be compared.

Appendix

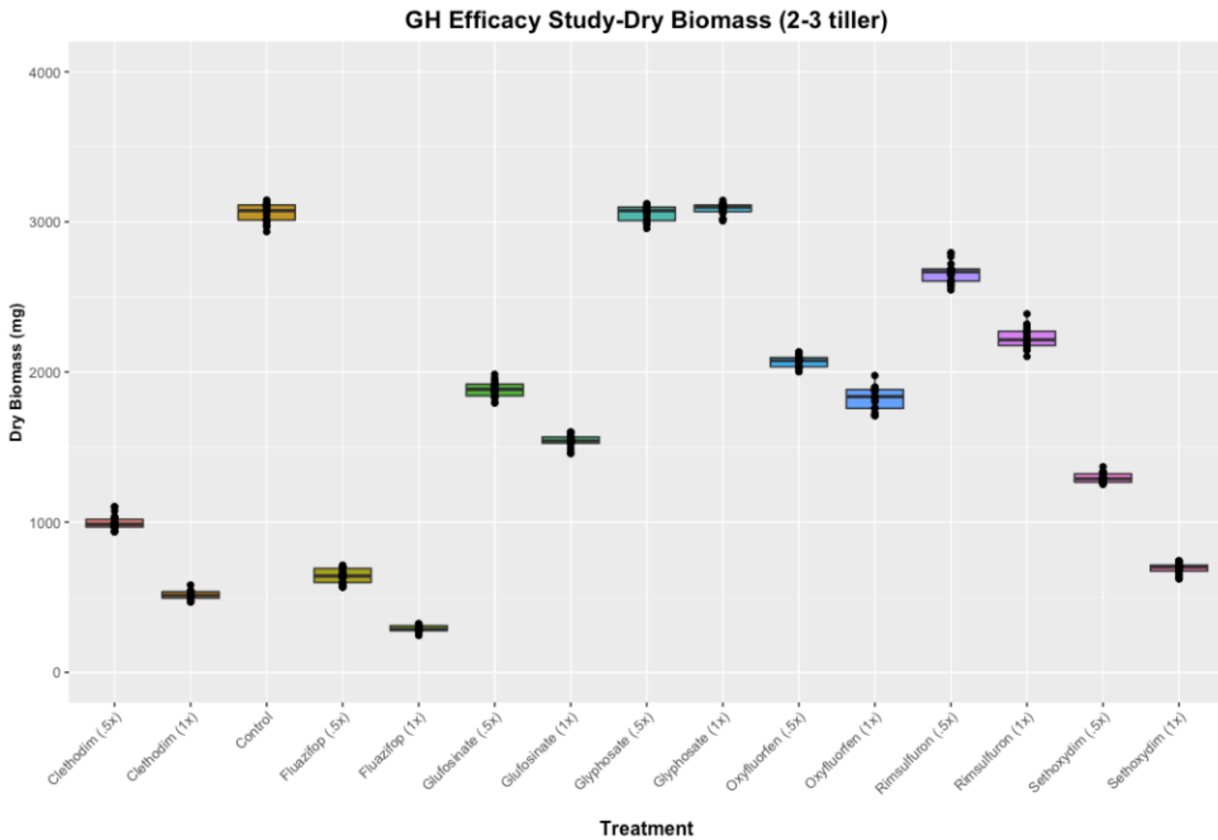

Figure A 1. *E. tristachya* dry biomass, at five WAT, results from 2018 greenhouse (GH) efficacy study conducted on plants at the 2-3 tiller stage. Box plots show the interquartile range (IQR) including the upper and lower quartiles and treatment means. The overlayed scatter plots show the treatment distribution

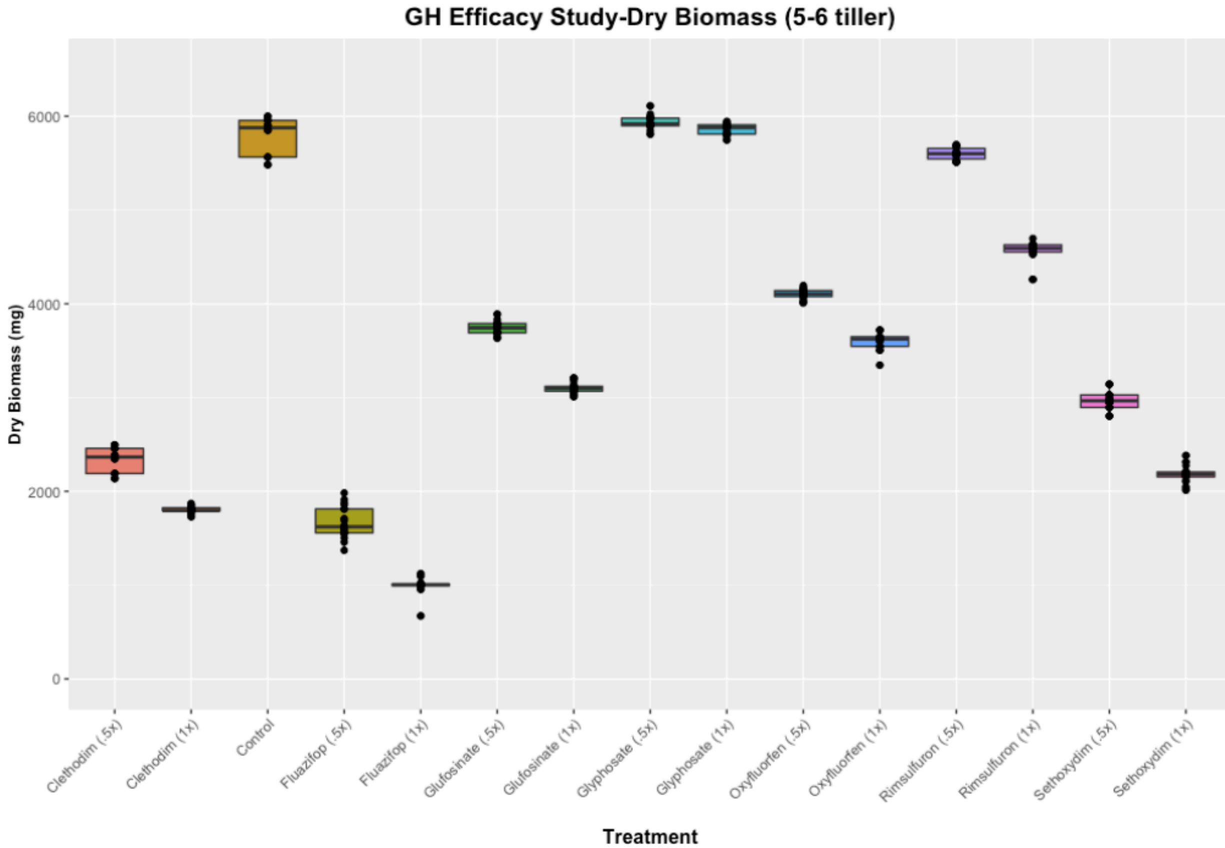

Figure A 2. *E. tristachya* dry biomass five WAT in a 2018 greenhouse (GH) efficacy study conducted on plants at the 5-6 tiller stage. Box plots show the interquartile range (IQR) including the upper and lower quartiles and treatment means. The overlayed scatter plots show the treatment distribution.

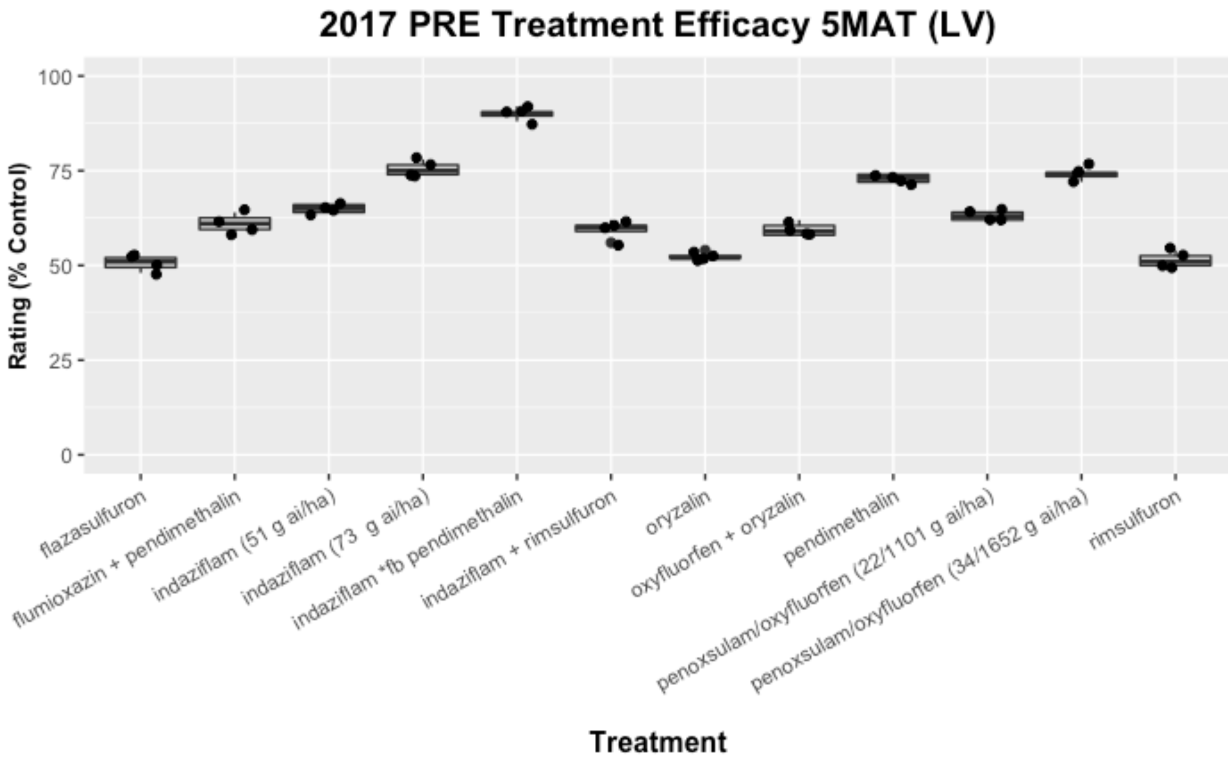

Figure 3. *E. tristachya* control five months after winter preemergence herbicide treatments in a commercial almond orchard near Livingston, CA in 2017. Box plots show the interquartile range (IQR) including the upper and lower quartiles and treatment means. The overlayed scatter plots show the treatment distribution.

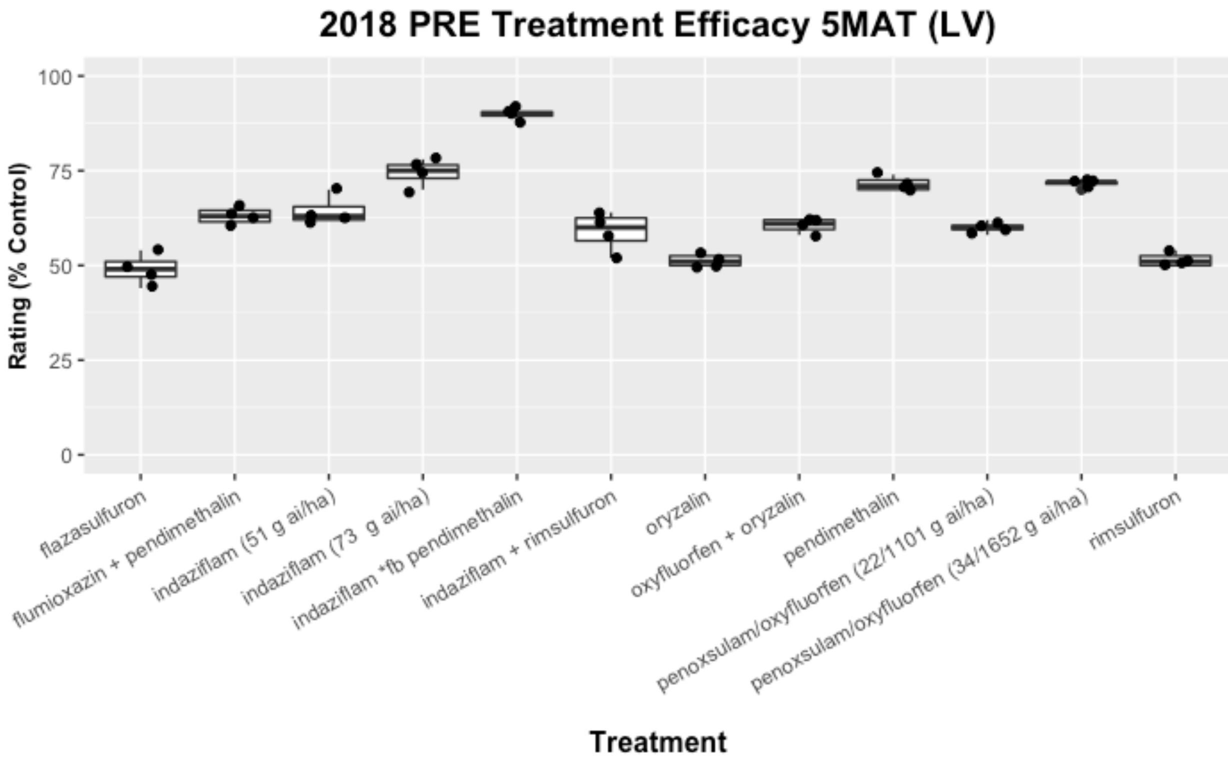

Figure A 4. *E. tristachya* control 5 months after winter preemergence herbicide treatments in a commercial almond orchard near Livingston, CA in 2018. Box plots show the interquartile range (IQR) including the upper and lower quartiles and treatment means. The overlayed scatter plots show the treatment distribution.

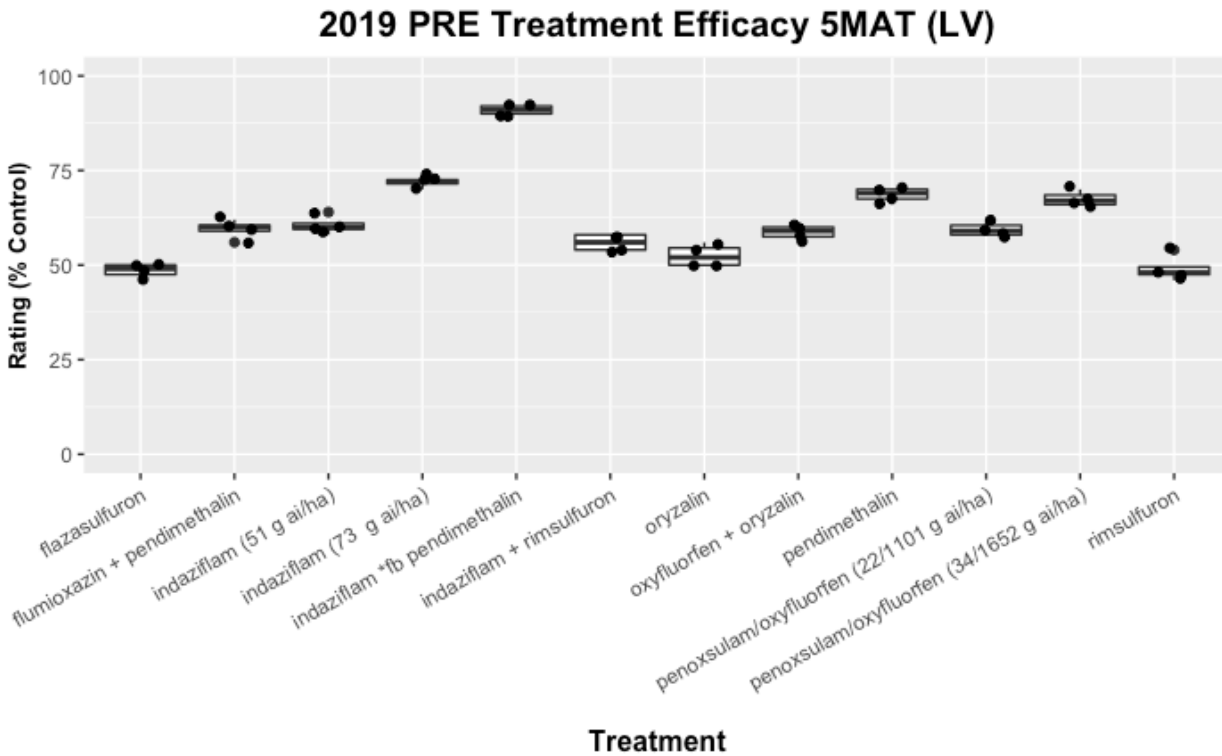

Figure A 5. *E. tristachya* control 5 months after winter preemergence herbicide treatments in a commercial almond orchard near Livingston, CA in 2019. Box plots show the interquartile range (IQR) including the upper and lower quartiles and treatment means. The overlayed scatter plots show the treatment distribution.

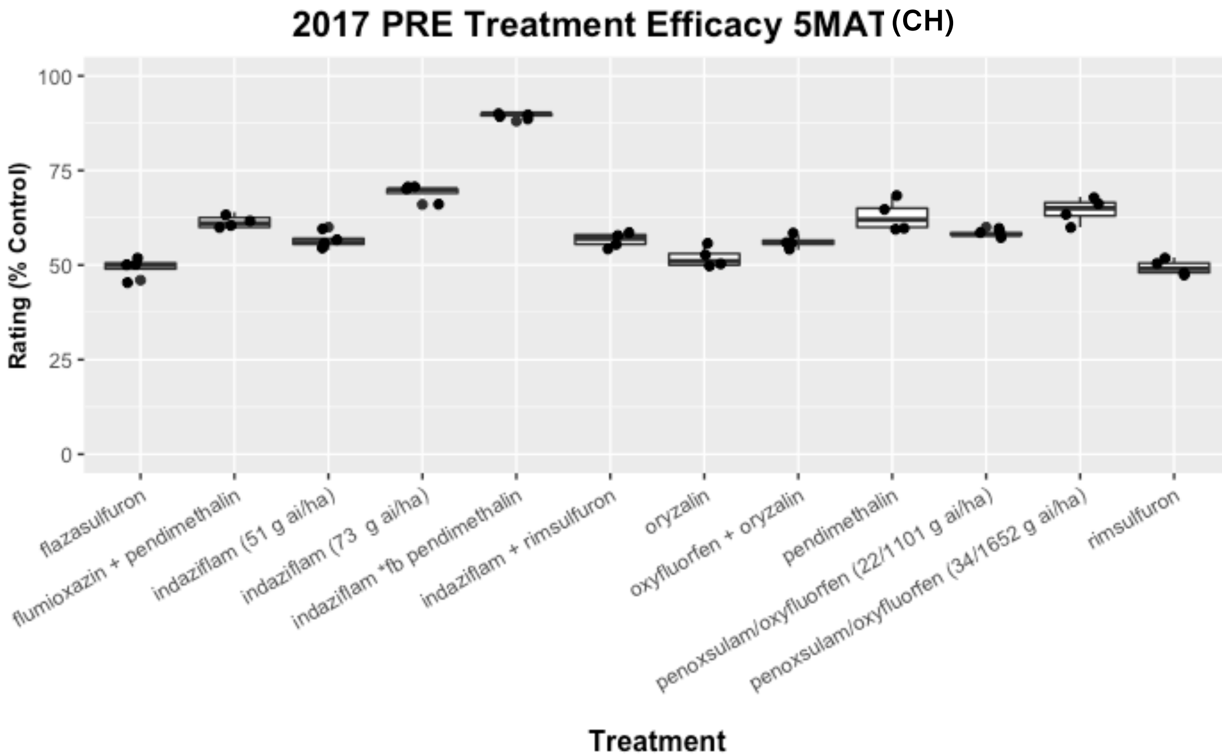

Figure A 6. *E. tristachya* control 5 months after winter preemergence herbicide treatments in a commercial walnut orchard near Chico CA in 2017. Box plots show the interquartile range (IQR) including the upper and lower quartiles and treatment means. The overlayed scatter plots show the treatment distribution.

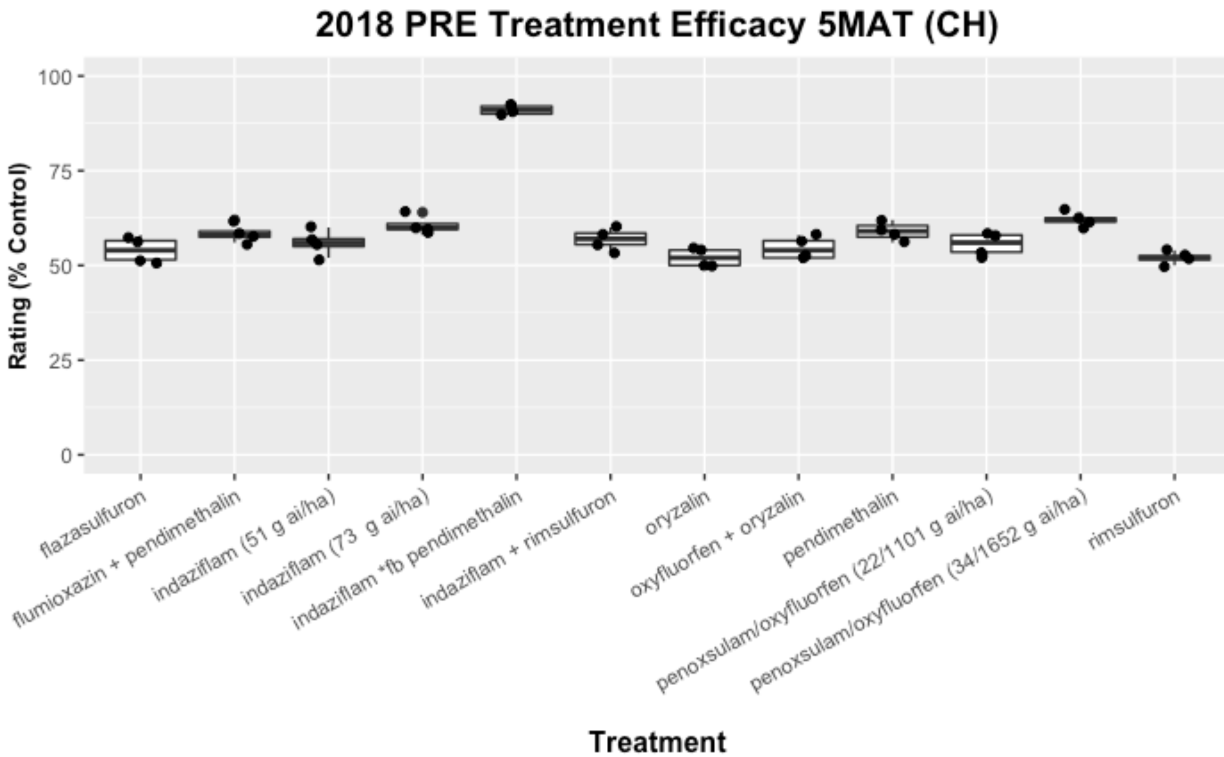

Figure A 7. *E. tristachya* control 5 months after winter preemergence herbicide treatments in a commercial walnut orchard near Chico CA in 2018. Box plots show the interquartile range (IQR) including the upper and lower quartiles and treatment means. The overlayed scatter plots show the treatment distribution.

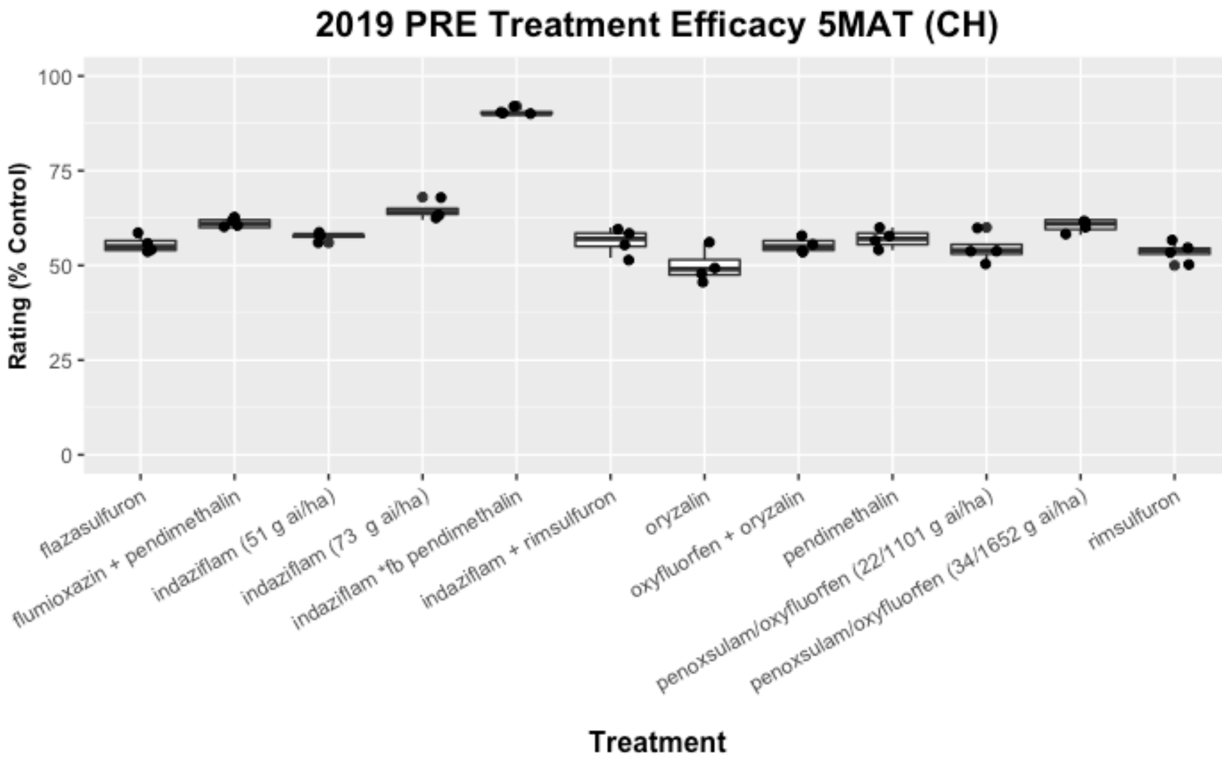

Figure A 8. *E. tristachya* control 5 months after winter preemergence herbicide treatments in a commercial walnut orchard near Chico CA in 2019. Box plots show the interquartile range (IQR) including the upper and lower quartiles and treatment means. The overlayed scatter plots show the treatment distribution.

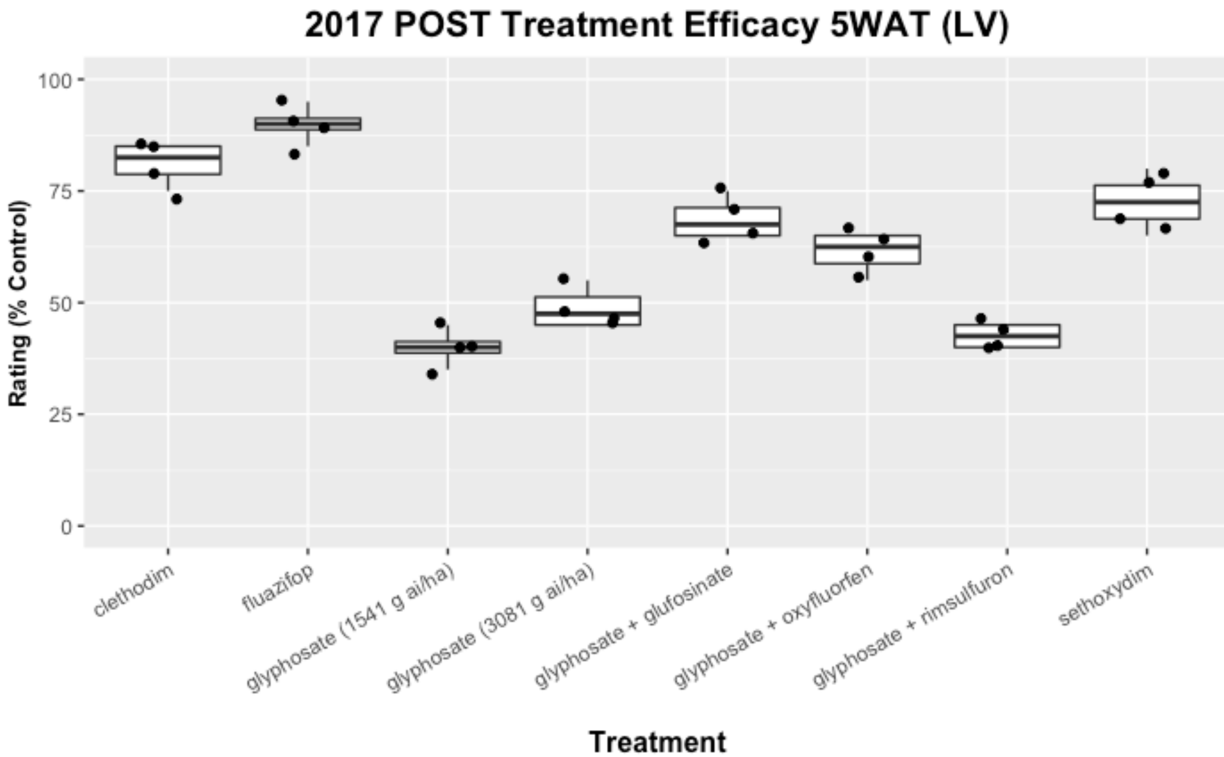

Figure A 9. *E. tristachya* control 5 weeks after postemergence herbicide treatments in a commercial almond orchard near Livingston CA in 2017. Box plots show the interquartile range (IQR) including the upper and lower quartiles and treatment means. The overlayed scatter plots show the treatment distribution.

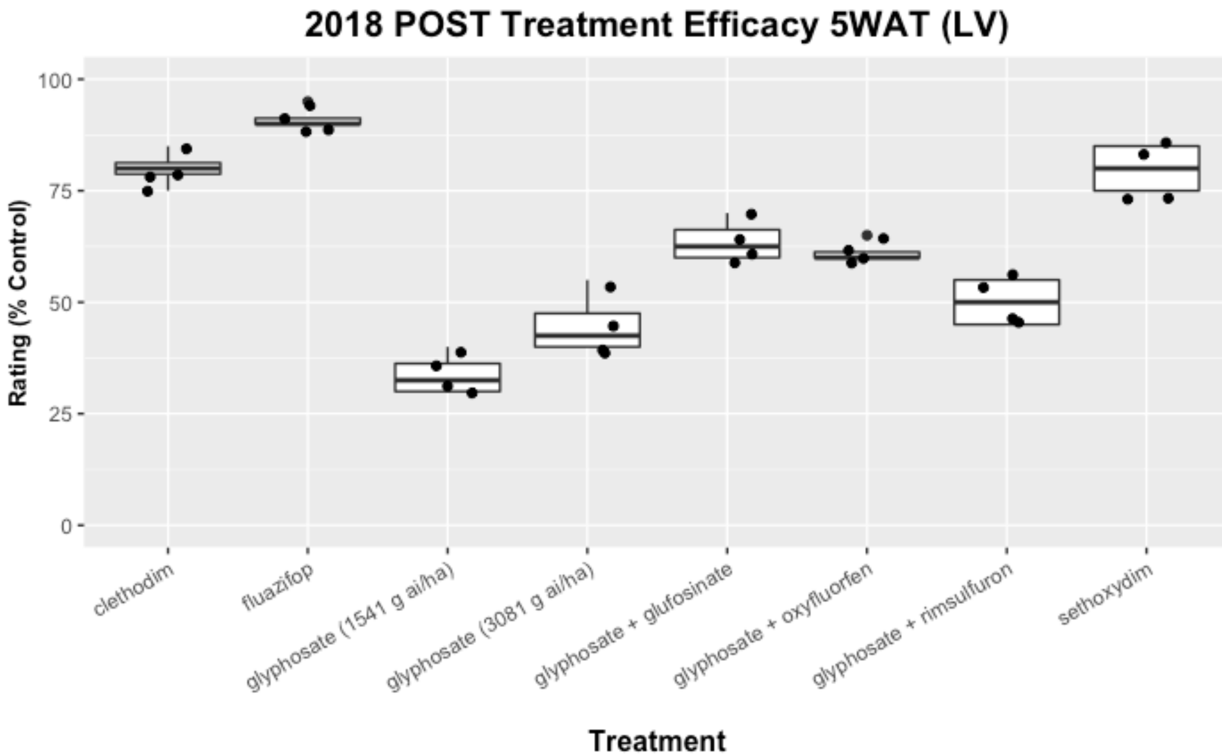

Figure A 10. *E. tristachya* control 5 weeks after postemergence herbicide treatments in a commercial almond orchard near Livingston CA in 2018. Box plots show the interquartile range (IQR) including the upper and lower quartiles and treatment means. The overlayed scatter plots show the treatment distribution.

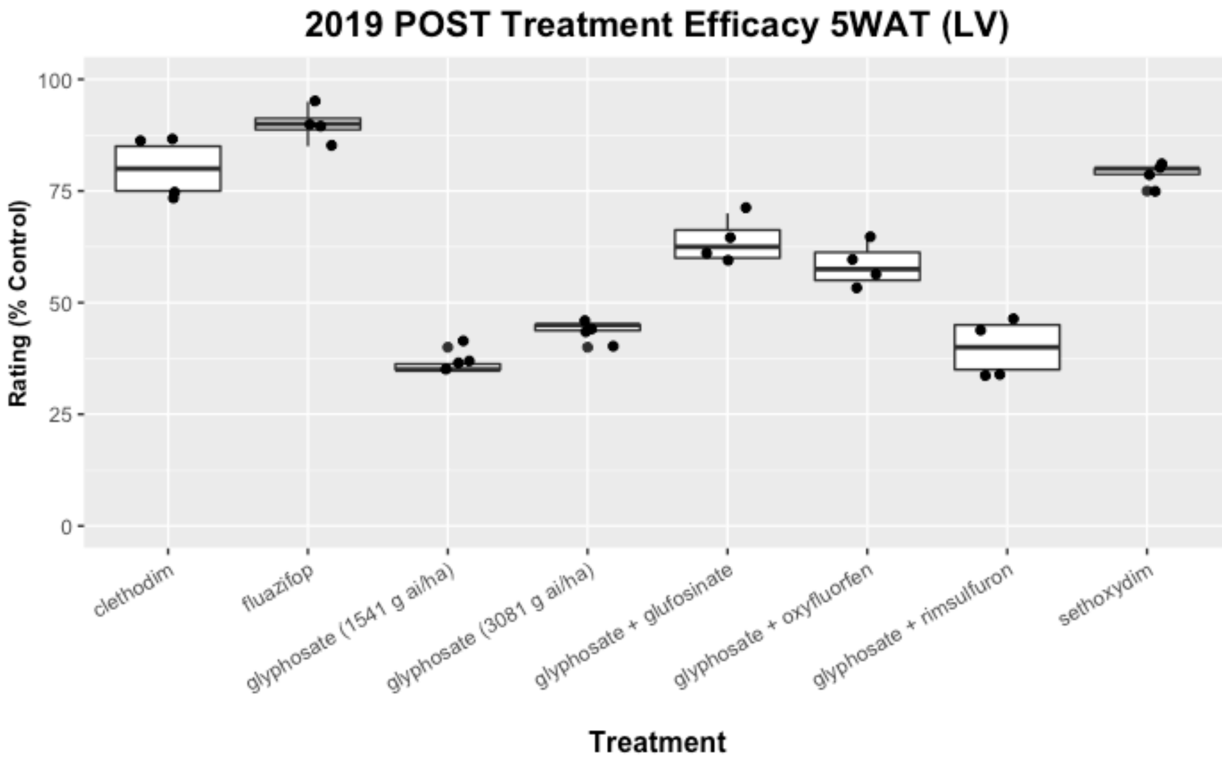

Figure A 11. *E. tristachya* control 5 weeks after postemergence herbicide treatments in a commercial almond orchard near Livingston CA in 2019. Box plots show the interquartile range (IQR) including the upper and lower quartiles and treatment means. The overlayed scatter plots show the treatment distribution.

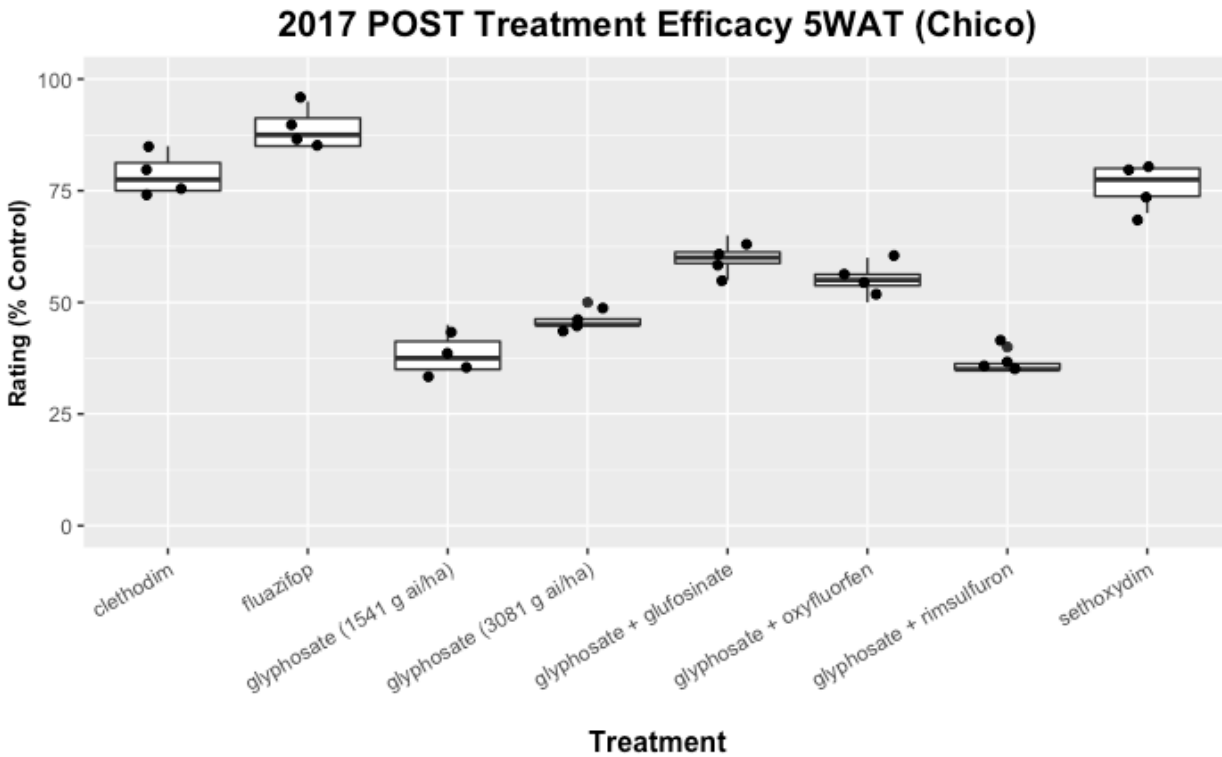

Figure A 12. *E. tristachya* control 5 weeks after postemergence herbicide treatments in a commercial walnut orchard near Chico CA in 2017. Box plots show the interquartile range (IQR) including the upper and lower quartiles and treatment means. The overlayed scatter plots show the treatment distribution.

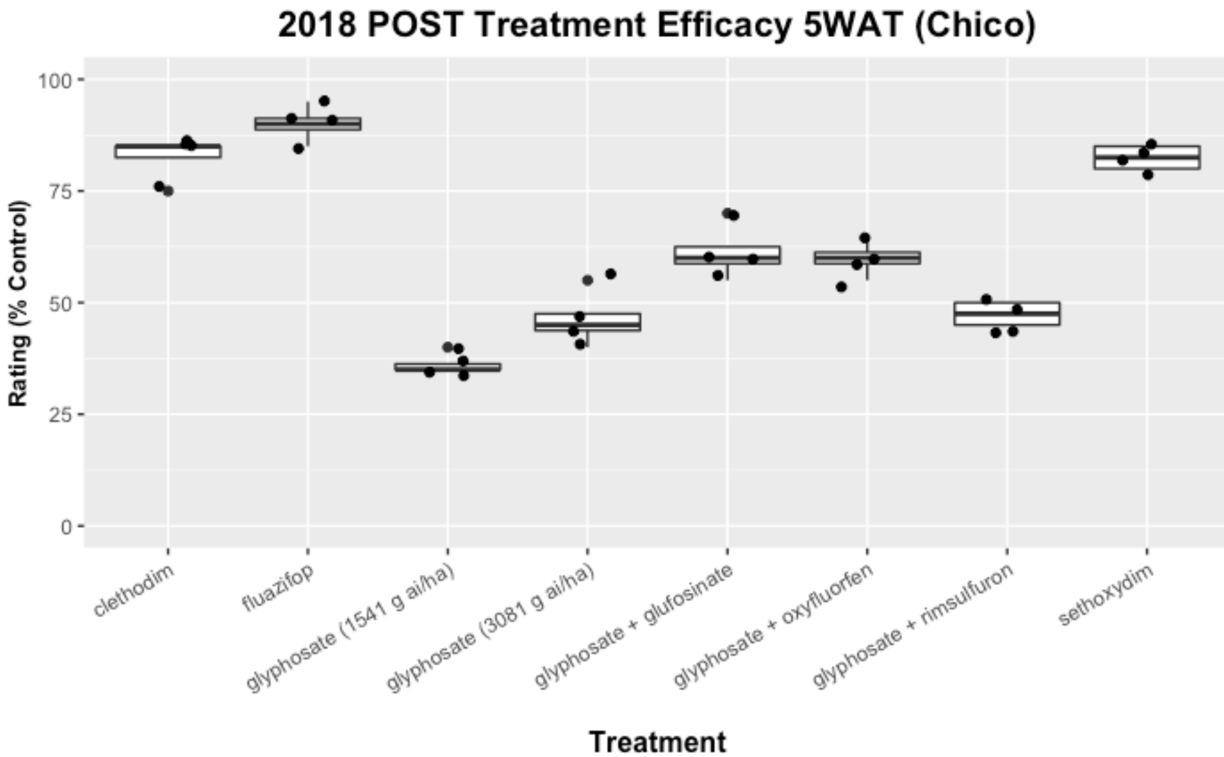

Figure A 13. *E. tristachya* control 5 weeks after postemergence herbicide treatments in a commercial walnut orchard near Chico CA in 2018. Box plots show the interquartile range (IQR) including the upper and lower quartiles and treatment means. The overlayed scatter plots show the treatment distribution.

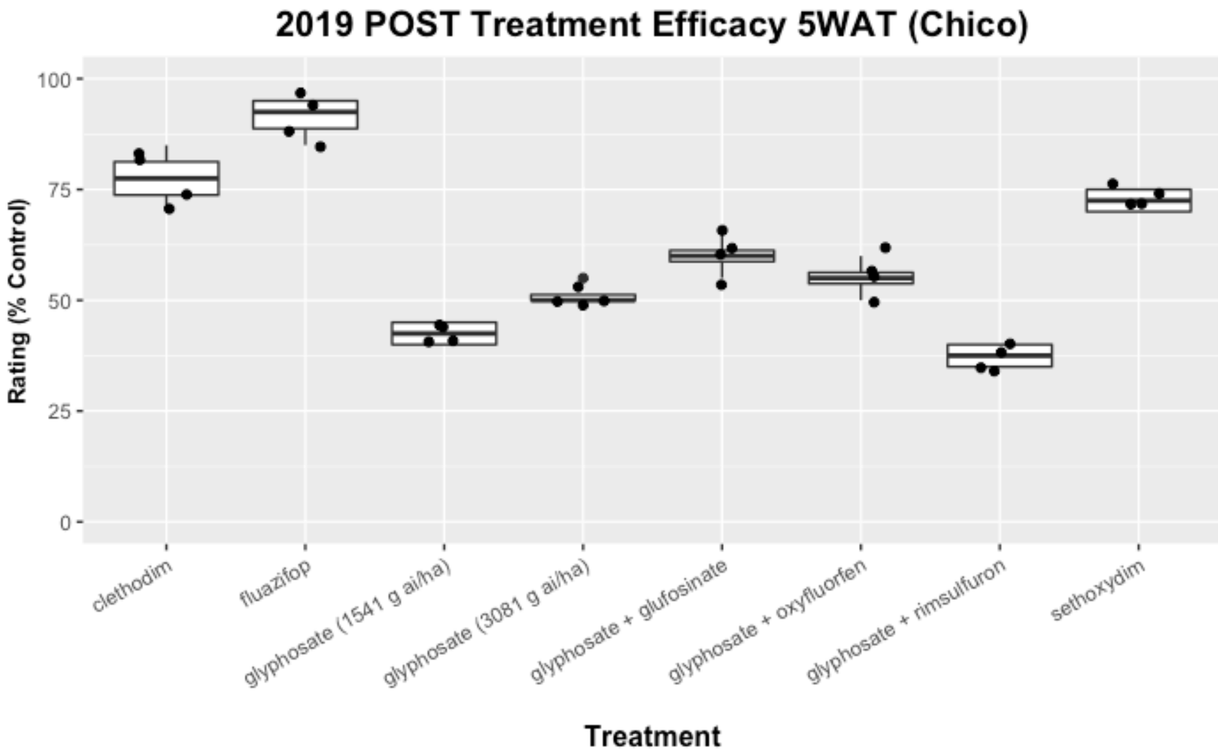

Figure A 14. *E. tristachya* control 5 weeks after postemergence herbicide treatments in a commercial walnut orchard near Chico CA in 2019. Box plots show the interquartile range (IQR) including the upper and lower quartiles and treatment means. The overlayed scatter plots show the treatment distribution