# Herbicide Management of Threespike Goosegrass in California Orchards

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Abstract. **Threespike goosegrass (*Eleusine tristachya*) is a difficult-to-control perennial grass of increasing concern for orchard production systems in the Central Valley of California, USA. This grass has a bunch-type growth habit when tillered, which can interfere with orchard operations, particularly nut pickup from the ground at harvest. From 2016 to 2019, herbicide efficacy on threespike goosegrass was evaluated in a walnut (*Juglans regia*) orchard in Chico, CA, USA; an almond (*Prunus dulcis*) orchard in Livingston, CA, USA; and a prune (*Prunus domestica*) orchard in Orland, CA, USA. At each location, two independent experiments were conducted to evaluate 12 preemergent (PRE) herbicide treatments and eight postemergent (POST) treatments over several years, for a total of 16 trials. PRE herbicides were applied in January according to the region's typical winter orchard management practices. One treatment included an additional sequential application in March to extend residual activity later into the warm season when threespike goosegrass germinates or resumes growth. In separate studies, POST control of established stands of threespike goosegrass was evaluated in May and June of each year. Each trial was conducted in a randomized complete block design with four replications. Threespike goosegrass control was visually estimated monthly for 5 months after the PRE treatments or at weekly intervals for 5 weeks following POST treatments. The most effective PRE treatment was a sequential application of indaziflam in January, followed by a March application of pendimethalin, providing 90% or greater control of threespike goosegrass 5 months after treatment across all sites and all years. Of the POST treatments, the three graminicides outperformed the other treatments with 73% to 91% control overall sites and years at 5 weeks after treatment. Fluazifop had the highest control ratings (85% to 91%) among the graminicide herbicides but was not always statistically better than clethodim or sethoxydim (74% to 83% control). Glyphosate alone resulted in unacceptable control (33% to 51%) regardless of rates tested, experimental sites, or years. Together, these results confirm grower reports of poor glyphosate performance on threespike goosegrass but suggest that effective herbicide programs can be developed to manage threespike goosegrass using PRE herbicides and POST graminicides registered in California orchard crops.**

California, USA, is the nation's top producer and exporter of many tree fruit and nut crops. Deciduous tree fruit and nut crops are cultivated on ~2.2 million acres in California, with a combined value of $10.8 billion in 2020 [California Department of Food and Agriculture (CDFA) 2021]. Almond (*Prunus dulcis*) and walnut (*Juglans regia*) account for more than 1.6 million acres of this crop sector (CDFA 2021).

Weed management is a critical challenge for orchard growers, although the impact of weeds can vary depending on the age of the orchard. In newly planted orchards, weed competition for resources can impede the growth of small trees (Jarvis-Shean et al. 2018). In established orchards, weeds affect production by interfering with irrigation and mechanical harvest operations. Orchard floor vegetation also can serve as a host for diseases or insect and vertebrate pests that may reduce the long-term health of the trees (Wisler and Norris 2005). In addition, weeds on the orchard floor during harvest can interfere with sweeping, drying, and nut pickup in tree nut crops, potentially reducing harvest efficiency (Connell et al. 2001).

Most California orchard floors are managed with a combination of preemergent (PRE) and postemergent (POST) herbicides and mechanical weed control. Intense herbicide programs are often used in the tree row, ~25% to 50% of the orchard floor, to prevent weeds from directly competing with trees (Hanson et al. 2014). PRE herbicides are typically applied to the tree row strips ahead of winter rains. As the season progresses, this area may be retreated with POST herbicides to control weed seedlings that emerge after residual control fails. The area between tree rows, on the other hand, usually is managed in wetter areas of the Central Valley using mowing to maintain a low vegetation cover during winter and spring; this improves access to the orchard during the wet season (Connell et al. 2001). At one time, soil cultivation was widely used to maintain orchard middles; however, this practice has become less common because it is slower than mowing and contributes to dust load on the crop and reduces regional air quality (Faulkner et al. 2009). In tree nuts that are harvested from the orchard floor, the entire orchard floor is usually treated with an additional application of a broad-spectrum POST herbicide such as glyphosate, glufosinate, or paraquat before harvest to eliminate vegetation that might interfere with

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**Units**

| To convert U.S. to SI, multiply by | U.S. unit | SI unit | To convert SI to U.S., multiply by |
|---|---|---|---|
| 0.4047 | acre(s) | ha | 2.4711 |
| 0.3048 | ft | m | 3.2808 |
| 9.3540 | gal/acre | $L \cdot ha^{-1}$ | 0.1069 |
| 2.54 | inch(es) | cm | 0.3937 |
| 1.1209 | lb/acre | $kg \cdot ha^{-1}$ | 0.8922 |
| 119.8264 | lb/gal | $g \cdot L^{-1}$ | 0.0083 |
| (°F − 32) ÷ 1.8 | °F | °C | (°C × 1.8) + 32 |

sweeping and pickup operations (Martin and Hanson 2022).

Threespike goosegrass, native to South America, is now established in North America, Australia, Africa, and Europe (de Wet et al. 1984; Hilu and Johnson 1997; Phillips 1972). The earliest specimen reported in the Calflora Observations Database (Calflora 2022) was collected in San Joaquin County in 1967. Since then, this species has become a significant concern in tree nut and other orchard cropping systems throughout the northern half of the California Central Valley.

Threespike goosegrass is a warm-season perennial grass that thrives with ample sunlight (Fynn et al. 2011). It can form heavy mats in new orchard plantings, orchards with small-statured trees, or in orchards such as almonds that are managed with sunlit middles to facilitate nut drying during harvest. It is a prolific seed producer, even under regular mowing, and can rapidly colonize orchard middles and tree rows. Threespike goosegrass goes dormant during the winter in California; in spring, once soil temperatures reach 15 to 20 °C, it begins regrowth from dormant crowns or from newly germinating seeds (Calflora 2022). It matures and flowers during summer and reaches maximum size at the time of many orchard harvest operations. The phase-out of cultivation for orchard middles favors small-seeded grasses such as threespike goosegrass (Teasdale et al. 1991), and also means that field operations do not physically remove its perennial crowns. Although threespike goosegrass density tends to be greatest in the less-intensively managed orchard middles, mowing and harvest operations easily spread seed from the middles to the tree row, and the species can be challenging to eliminate in both management zones once established in an orchard.

Application of herbicides is the most common means of managing threespike goosegrass in orchards. However, in California, at least 21 weed species have developed resistance to herbicides, especially POST herbicides (Heap 2022). Several populations of annual goosegrass (*Eleusine indica*), a closely related species, are resistant to glyphosate (Chen et al. 2017; Zhang et al. 2015) and acetyl-CoA carboxylase (ACCase)-inhibiting herbicides (McCullough et al. 2016). California orchard managers have expressed concerns about glyphosate resistance in threespike goosegrass (Hanson BD, unpublished data); however, no cases of resistance have been confirmed in this species (Heap 2022). Brunori and Puricelli (2020) reported a 3- to 6-fold difference in threespike goosegrass sensitivity to glyphosate between the seedling and reproductive growth stages in Argentina. A preliminary dose-response trial with threespike goosegrass from California suggested a similar growth stage effect with an 8-fold difference in glyphosate sensitivity between plants treated at the two- or eight-tiller stage (Hanson BD, unpublished data). This suggests that a program for controlling threespike goosegrass with herbicides should not be based on glyphosate and should be designed to minimize the potential for developing resistance.

Very little information on the management of threespike goosegrass in orchard crops is available. Previous research on another warm-season grass weed, junglerice (*Echinochloa colona*), in orchards suggests that a sequential PRE herbicide program may improve summer weed control compared with the traditional treatment timing (Brunharo et al. 2020). Development of a sequential herbicide program for the management of threespike goosegrass and other warm-season weeds would allow California orchard managers to be less reliant on frequent applications of higher-rate POST herbicides for summer weed control. In turn, this could help manage weed species already resistant to POST herbicides and reduce the selection pressure for threespike goosegrass or other species developing resistance. The objective of this study was to evaluate threespike goosegrass control with established and newly registered herbicides, and to develop herbicide program recommendations for orchard weed managers.

## Materials and methods

Field trials were conducted over several years in three locations in California, USA, to evaluate the performance of PRE and POST herbicides registered for use in almond, walnut, and prune (*Prunus domestica*) on threespike goosegrass (Table 1). In 2016 and 2017, trials were conducted in a prune orchard near Orland, CA, USA (lat. 39.67°N, long. 122.15°W). This site is on Arbuckle gravelly loam with a 0% to 2% slope; plots at this location were 10 ft by 15 ft. In 2017, 2018, and 2019, trials were conducted in walnut and almond orchards. The walnut orchard was at the Chico State University Farm in Chico, CA, USA (lat. 39.69°N, long. 121.83°W), on Almendra loam soil with a 0% to 1% slope; plots at this site were 10 ft by 20 ft. The almond orchard was near Livingston, CA, USA (lat. 37.39°N, long. 120.77°W) on Pachappa fine sandy loam, slightly saline-alkali soils, with a 0% to 1% slope; plots at this site were 10 ft by 15 ft.

Each trial was conducted using a randomized complete block design with four replications. Herbicide treatments were applied with a carbon dioxide–pressurized backpack sprayer delivering 30 gal/acre through three flat fan nozzles (XR11003; TeeJet Spraying Systems, Wheaton, IL, USA) spaced 18 inches apart. Treatments were applied in 5-ft bands on both sides of the tree row. Plots were single-tree plots, so plot length was equivalent to the within-row tree spacing in each orchard.

In January, PRE treatments and a POST-only control treatment (0.59 lb/acre glufosinate + 1.13 lb/acre glyphosate) were applied. Visual assessments of weed control were made relative to the POST-only control at monthly intervals for 5 months after initial treatment (MAIT). In addition to single-product or tank-mix PRE programs applied at typical winter timing, a sequential treatment of indaziflam in January followed by pendimethalin in March (Brunharo et al. 2020) was also evaluated. In separate experiments, POST treatments were applied in May, when threespike goosegrass seedlings were actively growing, and established plants were well-tillered and beginning to flower. POST treatments included three graminicides (ACCase inhibitors) and several treatments with glyphosate, alone or in tank mixes. Threespike goosegrass control from POST treatments was evaluated relative to a nontreated control at weekly intervals for 5 weeks after treatment. All experiments were ended in June ahead of the grower's field preparation for harvest.

At each evaluation, threespike goosegrass control (plant vigor and density) was rated on a 0 to 100 scale (0 = no control, 100 = plants killed or absent) relative to their respective control treatment. Data within a site-year were analyzed using a generalized linear model in R (version 3.5.1; R Foundation for Statistical Computing, Vienna, Austria) with block as a random effect

**Table 1. Herbicides evaluated for control of threespike goosegrass in California, USA, orchard experiments conducted during 2016 to 2019.**

| Common name | Trade name | Formulation[i] | Manufacturer |
|---|---|---|---|
| Clethodim | Select Max® | 0.97 lb/gal | Valent U.S.A., Walnut Creek, CA, USA |
| Flazasulfuron | Mission® | 25% | Summit Agro USA, Durham, NC, USA |
| Fluazifop | Fusilade DX® | 2.0 lb/gal | Syngenta Crop Protection; Greensboro, NC, USA |
| Flumioxazin | Chateau® | 51% | Valent U.S.A. |
| Glyphosate | Roundup Weathermax® | 4.5 lb/gal | Bayer CropScience, St. Louis, MO, USA |
| Glufosinate | Rely 280® | 2.34 lb/gal | BASF Ag Products, Research Triangle Park, NC, USA |
| Indaziflam | Alion® | 1.67 lb/gal | Bayer CropScience |
| Oryzalin | Surflan A.S.® | 4 lb/gal | United Phosphorus, Inc., King of Prussia, PA, USA |
| Oxyfluorfen | GoalTender® | 4 lb/gal | Corteva Agriscience, Wilmington, DE, USA |
| Sethoxydim | Poast® | 1.5 lb/gal | BASF Ag Products |
| Pendimethalin | Prowl H2O® | 3.8 lb/gal | BASF Ag Products |
| Penoxsulam/Oxyfluorfen | Pindar GT® | 0.083/3.93 lb/gal | Corteva Agriscience |
| Rimsulfuron | Matrix SG® | 25% | Corteva Agriscience |

[i] Liquid herbicide formulations are expressed as pounds a.i. per gallon except for glyphosate, which is expressed as pounds acid equivalent per gallon; 1 lb/gal = 119.8264 g·L$^{-1}$.

and treatments as fixed effects. Treatment means were compared using Tukey's honestly significant difference test at $\alpha = 0.05$. A mean value across all site-years is included for practitioner reference; however, these data were not statistically compared.

## Results

**Preemergent treatments.** Treatments performed consistently across trial sites and years (Table 2). Through 2 MAIT, relatively little threespike goosegrass was observed in all plots, but new growth or emergence was observed in later evaluations (data not shown). By 5 MAIT, treatment efficacy separated into roughly three "tiers". Across all sites and years, the best control was with the sequential treatment of indaziflam in January (0.046 lb/acre) followed by pendimethalin in March (3.8 lb/acre) resulting in 90% to 91% control of threespike goosegrass in all trials. This top tier was significantly better than the second tier of treatments, which gave control of ~65% to 70% (mean over all trials). These treatments included indaziflam alone (0.065 lb/acre), penoxsulam/oxyfluorfen (0.031 + 1.47 lb/acre), and pendimethalin alone (3.8 lb/acre). The following set of treatments resulted in less than 61% control (mean over all trials), including flumioxazin + pendimethalin (0.31 + 3.8 lb/acre), oxyfluorfen + oryzalin (1.25 + 4.0 lb/acre), and lower rates of indaziflam and penoxsulam/oxyfluorfen. Oryzalin, flazasulfuron, and rimsulfuron treatments resulted in 49% to 54% control of threespike goosegrass across site-years.

**Postemergent treatments.** As with preemergent treatments, results from postemergent treatments were consistent across sites and years (Table 3). At 5 WAT, the graminicides tested provided the best results overall (73%

**Table 2. Comparison of preemergent herbicide treatments for control of threespike goosegrass in California, USA, orchards: prune (Orland), almond (Livingston), and walnut (Chico).**

| | | Control of threespike goosegrass 5 mo after initial treatment | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Orland | | Livingston | | | Chico | | | Mean of all sites[iii] |
| Treatment[i] | Rate (lb/acre)[ii] | 2016 | 2017 | 2017 | 2018 | 2019 | 2017 | 2018 | 2019 | |
| | | %[iv] | | | | | | | | |
| Flazasulfuron | 0.044 | 53 a | 51 a | 51 a | 49 a | 49 a | 50 a | 54 ab | 56 a-d | 51.6 |
| Oryzalin | 4.0 | 51 a | 50 a | 53 a | 52 a | 53 ab | 52 ab | 52 a | 50 a | 51.6 |
| Pendimethalin | 3.8 | 71 cd | 69 c | 73 d | 72 cd | 69 d | 63 de | 59 bcd | 57 bcd | 66.6 |
| Rimsulfuron | 0.063 | 53 a | 50 a | 52 a | 52 a | 49 a | 50 a | 52 a | 54 ab | 51.5 |
| Indaziflam | 0.046 | – | – | 65 c | 65 bc | 61 c | 57 bc | 56 a-d | 58 bcd | 60.3 |
| Indaziflam | 0.065 | 76 d | 75 c | 75 d | 75 d | 72 d | 69 f | 61 cd | 65 e | 70.0 |
| Penoxsulam/Oxyfluorfen | 0.020/0.98 | – | – | 63 bc | 60 b | 60 c | 59 cd | 56 abc | 55 abc | 58.8 |
| Penoxsulam/Oxyfluorfen | 0.031/1.47 | 73 bcd | 71 c | 74 d | 72 cd | 68 d | 65 ef | 62 d | 61 cde | 68.3 |
| Flumioxazin + pendimethalin | 0.319 + 3.8 | 61 abc | 58 ab | 61 bc | 63 b | 60 c | 62 cde | 59 bcd | 61 de | 60.6 |
| Indaziflam + pimsulfuron | 0.046 + 0.063 | 61 abc | 63 bc | 60 b | 59 b | 56 bc | 57 bc | 57 a-d | 57 bcd | 58.8 |
| Oxyfluorfen + oryzalin | 1.25 + 4.0 | 59 ab | 56 ab | 60 b | 61 b | 59 c | 56 bc | 55 abc | 56 a-d | 57.8 |
| Indaziflam FB pendimethalin | 0.046 FB 2.85 | 91 e | 90 d | 90 e | 90 e | 91 e | 90 g | 91 e | 91 f | 90.5 |

[i] All treatments were made in January and included glyphosate (1.13 lb/acre), glufosinate (0.59 lb/acre), ammonium sulfate (1% v/v), and nonionic surfactant (0.25% v/v). "FB" indicates followed by sequential treatment; "/" indicates products sold as pre-mixes; "+" indicates tank mix. The low rates of indaziflam and penoxsulam/oxyfluorfen were not included in the Orland site because of space limitations.

[ii] Herbicide rates are expressed as pounds a.i. per acre, except for glyphosate, which is expressed as pounds acid equivalent per acre; 1 lb/acre = 1.1209 kg·ha$^{-1}$.

[iii] Not statistically compared.

[iv] Percent control data are relative to a postemergent-only treatment of glufosinate + glyphosate with no preemergent herbicides. Values followed by the same letter are not significantly different (Tukey's highly significant difference at $\alpha = 0.05$). Columns are not compared.

Table 3. Comparison of postemergent herbicide treatments for control of threespike goosegrass in California, USA orchards: prune (Orland), almond (Livingston), and walnut (Chico).

| | | Control of threespike goosegrass 5 wk after treatment | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Orland | | Livingston | | | Chico | | | Mean of all sites[iii] |
| Treatment[i] | Rate (lb/acre)[ii] | 2016 | 2017 | 2017 | 2018 | 2019 | 2017 | 2018 | 2019 | |
| | | %[iv] | | | | | | | | |
| Glyphosate | 1.13 | 35 a | 33 a | 40 a | 34 a | 36 a | 39 ab | 36 a | 43 a | 37.0 |
| Glyphosate | 2.26 | 48 b | 41 b | 49 a | 45 ab | 44 a | 46 bc | 46 ab | 51 bc | 46.3 |
| Glyphosate + glufosinate | 1.13 + 1.17 | 60 c | 63 d | 69 bc | 64 d | 64 b | 60 d | 61 c | 60 c | 62.6 |
| Glyphosate + oxyfluorfen | 1.13 + 0.25 | 59 c | 55 c | 61 b | 61 cd | 59 b | 55 cd | 60 c | 55 c | 58.1 |
| Glyphosate + rimsulfuron | 1.13 + 0.03 | 50 b | 33 a | 43 a | 50 bc | 40 a | 36 a | 48 b | 38 ab | 42.3 |
| Fluazifop | 0.19 | 89 e | 85 f | 90 e | 91 e | 90 d | 89 f | 90 d | 91 e | 89.4 |
| Clethodim | 0.09 | 81 de | 79 ef | 81 de | 80 e | 80 cd | 79 ef | 83 d | 78 d | 80.1 |
| Sethoxydim | 0.28 | 80 d | 74 e | 73 cd | 80 e | 79 c | 76 e | 83 d | 73 d | 77.3 |

[i] All treatments were made in May and included ammonium sulfate (1% v/v) and nonionic surfactant (0.25% v/v).
[ii] Herbicide rates are expressed as pounds a.i. per acre, except for glyphosate, which is expressed as pounds acid equivalent per acre; 1 lb/acre = 1.1209 kg·ha$^{-1}$.
[iii] Not statistically compared.
[iv] Percent control data are relative to a nontreated control. Values followed by the same letter are not significantly different (Tukey's highly significant difference at $\alpha = 0.05$). Columns are not compared.

to 91% control). Among the graminicides, fluazifop tended to have the highest control ratings (85% to 91% control), although it was not always statistically better than clethodim or sethoxydim. Glyphosate alone did not result in commercially-acceptable levels of control (33% to 51%) at either rate at any site.

## Discussion

In California nut and fruit orchards, weeds are typically managed with an early-winter application of PRE herbicide followed by spring application of POST herbicides as needed. However, threespike goosegrass and other warm-season orchard weeds tend to germinate in late spring to summer, after the PRE treatment residual activity has diminished and after POST herbicides are commonly applied. Once perennialized, it is no longer susceptible to most PRE treatments; and it is tolerant to glyphosate.

The objective of these field trials was to optimize both PRE and POST herbicide components of orchard weed management targeting threespike goosegrass. In the PRE trials, January applications of indaziflam, pendimethalin, or penoxsulam/oxyfluorfen provided moderate control (~70%) of threespike goosegrass by 5 MAIT. The sequential application of indaziflam in January followed by pendimethalin in March resulted in greater than 90% control at 5 MAIT in all locations. Depending on rate and environmental conditions, these herbicides have residual activity of several months (Guerra et al. 2016; Hatzinikolaou et al. 2004), which often results in a single early-winter PRE application losing activity by the time threespike goosegrass begins to germinate. As in other summer grasses, an early-winter application PRE followed by a supplement PRE herbicide in early spring can extend grass weed control well into summer (Brunharo et al. 2020). However, it should be noted that the early-winter herbicide application remains important for managing weeds that germinate during the cool season as well as any early-germinating threespike goosegrass.

Although these results suggest that sequential applications of PRE herbicides can reduce seedling recruitment of this species, there is still the need to manage established stands. Results from the POST trials confirmed that threespike goosegrass is poorly controlled by glyphosate in California orchards. Even at 2.26 lb/acre, glyphosate control of threespike goosegrass control did not exceed 51% (Table 3), with many plants producing new shoots and panicles 2 weeks after treatment (Wolter 2021). The graminicides fluazifop, clethodim, and sethoxydim were more effective than glyphosate; fluazifop in particular gave consistent ~90% control, even on large, heavily tillered plants.

California orchard managers can use sequential application of PRE herbicides as an option for managing weeds that normally germinate during the warm season, including threespike goosegrass. Depending on the winter weed spectrum in a specific orchard location, there may be other useful sequential combinations in addition to the indaziflam and pendimethalin treatment described in this study. In locations where threespike goosegrass is perennialized, established plants can be controlled using registered graminicides. This preemptive management strategy may also allow orchard managers to decrease their reliance on multiple applications of broad-spectrum POST herbicides, such as glyphosate, glufosinate, and paraquat, which often are used repeatedly to control threespike goosegrass seedlings and established plants before harvest operations.

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