Title
Evaluation of Weed Control Efficacy and Crop Safety of the PPO-inhibiting Herbicide Tiafenacil in California Orchard Cropping Systems

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Evaluation of Weed Control Efficacy and Crop Safety of the PPO-inhibiting Herbicide Tiafenacil in California Orchard Cropping Systems

By

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Abstract

Tiafenacil is a protoporphyrinogen oxidase (PPO) inhibitor that blocks chlorophyll biosynthesis and causes protoporphyrin accumulation, a highly photodynamic intermediate. The lipid peroxidation and cell membrane destruction caused by tiafenacil leads to plant death. Glufosinate inhibits glutamine synthetase (GS), a key enzyme for amino acid metabolism and photorespiration. Glufosinate leads to plant death by a massive accumulation of reactive oxygen species (ROS). Herbicide mixtures are commonly used in agriculture to increase weed control spectrum and reduce selection pressure for herbicide resistance. Tiafenacil is registered in the US for preplant use on annual crops such as corn and soybean, but not in orchard crops. Glufosinate is commonly used in orchards with a rate range of 650 to 998 g ai ha^{-1}. Field studies were conducted to determine the crop safety of tiafenacil on young almond, walnut, prune, and pistachio trees, as well as the weed control efficacy on broadleaf and grass weeds relevant to California orchard crops. To evaluate crop safety, tiafenacil was applied at 74 and 148 g ai ha^{-1} three times per year at the base of prune, walnut, and pistachio trees that were less than one-year-old at the time of the first application. A similar almond experiment also included a 222 g ai ha^{-1} rate of tiafenacil in the protocol. In all four tree crop experiments, treatments were applied once in the spring of 2020, then reapplied three times during early 2021 and early 2022 so that plots were treated a total of 7 times during a three-year period. There was no visual injury on any of the young trees between 30 and 700 days after initial treatment. Similarly, there were no treatment effects on tree diameter even at the highest rate of tiafenacil. Although no yield measurement was taken because of the age of the trees, the relatively few fruits that formed appeared to be normal. In a separate study on weed control efficacy, tiafenacil at 12 g ai ha^{-1} performed statistically similarly with tiafenacil plus glufosinate in most instances, but control of both broadleaf and grass weeds numerically improved when tiafenacil was applied in mixture with glufosinate. In a greenhouse study, tiafenacil at 12 g ha^{-1} alone provided 98-100% control of barnyardgrass and 95-98% control of junglerice. There was no significant difference between tiafenacil alone or tiafenacil plus glufosinate; although in some instances, control of junglerice and barnyardgrass was numerically higher with the tankmix than with glufosinate alone. Most postemergence PPO inhibiting herbicides registered in tree crops have activity only on broadleaf weeds; however, these results indicate that tiafenacil has good activity on broadleaf and grass weeds relevant to California orchard crops and that crop safety was acceptable at up to 2- or 3-fold the expected use rate in tree crops. Although tiafenacil has some activity on grass weeds, mixing tiafenacil with glufosinate may be needed for the most reliable control of both broadleaf and grass weeds.

Nomenclature: glufosinate; saflufenacil; tiafenacil; junglerice, *Echinochloa colona*; barnyardgrass, *Echinochloa crus-galli*; filaree, *Erodium spp*; hairy fleabane, *Erigeron bonariensis*; Italian ryegrass, *Lolium multiflorum* L; annual bluegrass, *Poa annua*; walnut, *Juglans regia* L; pistachio, *Pistacia vera* L; almond, *Prunus dulcis* L; prune, *Prunus domestica* L

Keywords: PPO-inhibitor herbicide; tree nuts; broadleaf weeds; grass weeds; crop safety

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Dedications

This thesis is dedicated in loving memory to my father, Edner Laguerre who is not here to celebrate with me but would be very proud. Additionally, to both my mothers Jacqueline Antoine and Lynne Shelton for turning me into the person I am today, with the grace of God.

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Introduction

Orchard crops, particularly tree nuts, are an important agricultural crop sector in California. Almonds (*Prunus dulcis* L.), walnuts (*Juglans regia* L.), and pistachios (*Pistacia vera* L.) have a combined cultivated area of 730,053 hectares in California and provide over 8.5 billion dollars to the US economy (CDFA, 2019; United States Department of Agriculture NASS, 2020).

Trees need nutrients to support the growth of vegetative tissue, such as trunk, roots, branches, and leaves and reproductive tissue like nuts and fruits etc. (Jarvis-Shean et al., 2018). Weeds can interfere with young tree growth by competing for resources such as light, water, and nutrients that would otherwise be available for trees and this can have both short-term and long-term impacts on orchard productivity (Jarvis-Shean et al., 2018; Zimdahl, 2018). In addition, weeds can interfere with cultural operations such as irrigation, pruning, harvesting, and application of fertilizers and pesticides (Jarvis-Shean et al., 2018; Osipitan et al., 2020). Almonds and walnuts are mechanically shaken from the tree, then swept into windrows, and picked up from the orchard floor after several days of drying; so, for these crops, a weed-free orchard floor is critical to the efficiency of harvest operations (Gradziel, 2017; Micke, 1996). Weeds can increase problems with other pests such as pathogens which can reduce efficiency of the cropping system (Hanson et al., 2017). One of the main challenges that orchard managers deal with is appropriate and cost-effective weed management. Therefore, research on additional weed management tools or practices in orchards can be beneficial for California orchard managers.

There are several troublesome key weedy grasses in California orchards because of their known resistance to some commonly used herbicides. Junglerice (*Echinochloa colona*) is a tropical annual grass weed that is present in the major agricultural system of over 60 countries and is rated among the world’s worst weeds (Holm et al., 1977). Junglerice is becoming a primary weed because of its abundance and herbicide resistance in some tree nut and vineyard production regions in California. Tree nut and vineyard crops are heavily relying on post-emergence glyphosate for weed control, therefore, the presence of glyphosate-resistant weeds is a challenge in these cropping systems (Morran et al., 2018). Barnyardgrass (*Echinochloa crus-galli (L.)* is another troublesome grass weed that is also present in tree nut orchards and vineyards and can be challenging to manage due to resistance to postemergence herbicides. It is considered a problematic weed in at least 42 countries and 36 crops around the world (Holm, 1979; Holm et al., 1977). Italian ryegrass (*Lolium multiflorum*) is commonly found in crop fields, pastures, vineyards, and orchards. It has the highest number of seeds per spikelet and is the tallest among ryegrass species (Bararpour et al., 2017). Italian ryegrass has been listed as the top weed with resistance to 15 sites of action in the United States (Heap, 2016). It is important to manage Italian ryegrass before it reaches the flowering stage in order to get adequate control because it can become a problematic weed due to herbicide resistance in orchards (Avila-Garcia & Mallory-Smith, 2011; Moretti, 2021; Perez-Jones et al., 2005). According to recent surveys in Oregon orchards, 88% of the 75 tested Italian ryegrass populations were herbicide-resistant (Moretti, 2021) and among the resistant populations, three-quarters displayed resistance to more than one herbicide (Bobadilla et al., 2021).

Weeds possess many characteristics that can make them very difficult to manage. Little mallow (*Malva parviflora)* is a biennial or short-lived perennial weed. Large little mallow can decrease crop yield and if left uncontrolled can interfere with machinery that are used for harvesting crops (Wilen, 2019). Hare barley (*Hordeum murinum ssp. leporinum*) is a cool season annual grass that invades pastures and range areas around the world and can grow 15 to 60 cm tall (Haavisto, 2011). Annual bluegrass (*Poa annua*) is native to Europe but is distributed worldwide. It is one of the most well-studied weeds of cool-season grass (Beard et al., 1978). Annual bluegrass is tolerant to low mowing heights and is also well adapted to orchard systems. Lastly, hairy fleabane (*Erigeron bonariensis*) is well adapted to tree nut and vineyard crops. In recent decades, hairy fleabane has become one of the most problematic weeds in California cropping systems because of its resistance to glyphosate (Moretti et al., 2015; Shrestha et al., 2008).

Tiafenacil was recently developed by FarmHannong Co., Ltd., South Korea (Anonymous, 2020a & 2020b; Park et al., 2018) and is a protoporphyrinogen IX oxidase (PPO) inhibiting, nonselective, contact herbicide from the pyrimidinedione chemical class. PPO inhibitors prevent the production of chlorophyll and heme by binding to the protoporphyrinogen-oxidase enzyme (protox). This leads to an accumulation of protoporphyrin IX (PPIX) which leak out of the chloroplast and accumulate in the cytoplasm. In the cytoplasm, PPIX reacts with light and oxygen to create oxygen radicals (singlet oxygen) that cause lipid peroxidation and cell membrane destruction, which ultimately leads to plant death (Shaner, 2014). Tiafenacil is registered in the United States for preplant use in soybean and corn at a maximum rate of 75 g ai ha^{-1} (Anonymous, 2020b) and is a useful tool for herbicide resistance management. Tiafenacil provides an alternative for controlling glyphosate-resistant (GR) Palmer amaranth (*Amaranthus pameri*) in cotton, suppressing glyphosate-resistant horseweed (*Erigeron canadensis*) in corn and soybeans, and controlling common waterhemp (*Amaranthus tuberculatus)* in corn and soybean (Health Canada, 2018; U.S Environmental Protection Agency, 2020). Tiafenacil has the potential to control most broadleaf and grass weeds; however, there is currently little data available on the efficacy of tiafenacil on common weeds in California orchards. Tolpyralate is a new pyrazolone-type HPPD-inhibiting herbicide that has recently been registered in the United States and Canada for use in corn (US Environmental Protection Agency 2018; Health Canada 2018). Tolpyralate has relatively low water solubility (26.5 mg L^{-1}) and low potential for volatilization and has not been found to pose a significant risk to humans or the environment (Anonymous, 2019; Health Canada, 2017). POST applications of tolpyralate at 30 to 40 g ai ha^{-1} alone have been reported to control a range of annual grass and broadleaf weed species (Kikugawa et al., 2015). Currently, there is limited information in the published literature on the use of tolpyralate in North America and globally.

Glufosinate is a nonselective, foliar-applied herbicide used for control of annual and perennial grasses and broadleaf weeds and is registered in many specialty crops. The recommended label rate of glufosinate in tree, vine, and berry crops is in the range of 650 to 998 g ai ha^{-1} (Anonymous, 2020c). Saflufenacil, a uracil-based herbicide, is a PPO inhibitor (Grossmann et al., 2010). Saflufenacil is a selective herbicide developed for the control of broadleaf weeds (Anonymous, 2009).

Herbicide mixtures are commonly used in agriculture to improve efficacy, increase the spectrum of weed control, and mitigate herbicide resistance (Busi & Beckie, 2021; Zhang et al., 2013). Tank-mixing herbicides with different modes of action can be used to address specific weed challenges and can be a viable strategy for improving orchard weed control without increasing herbicide use in some situations (Moretti et al., 2015). For example, previous research has shown that when a PPO inhibitor herbicide is tank-mixed with glufosinate, there is enhanced herbicidal activity, compared to when glufosinate or a PPO inhibitor herbicide is applied individually (Takano et al., 2020).

The objective of this research was 1) to evaluate weed control efficacy of various rates of tiafenacil alone and tank-mixed with glufosinate on annual and perennial weeds relevant to California orchards and 2) to evaluate the crop safety of tiafenacil in young fruit and nut trees.

Materials and Methods

Crop safety studies. Several field experiments were conducted in a young mixed species orchard in Davis, CA (38°32'19.7"N 121°47'40.3"W) to evaluate the crop safety performance of tiafenacil on young almond, prune, walnut, and pistachio trees. The soil at this site is mapped as a Yolo silt loam with a 0 to 2 percent slope (USDA-NRCS, 2022). The almond cultivar is 'Nonpareil' on 'Empyrean 1' rootstock, prunes are 'Improved French' on 'Krymsk 86' rootstock, walnuts are 'Chandler' on 'clonal RX1' rootstock, and pistachios are 'Kerman' on 'UCB 1' rootstock, and the orchard was planted in March 2020. The orchard uses a single-line drip irrigation system, and all crops were maintained with pruning, mowing, and maintenance pesticides as needed throughout the year. Six or nine herbicide treatments including tiafenacil alone, saflufenacil alone, and tiafenacil tank-mixed with tolpyralate and a nontreated control were used to evaluate the crop safety performance on young orchard crops in California (Tables 2 and 3). Ammonium sulfate (AMS; BroncMax, Wilbur-Ellis, Aurora, CO) and methylated seed oil were included at 1% v/v in all treatments. The plots were 3 by 6 m centered on a single tree and were set up in a randomized complete block design with four replicates. Herbicide treatments were applied using a carbon dioxide pressurized backpack sprayer calibrated to deliver 187 L ha^{-1} at 241 kPa through three XR11002 flat fan nozzles (TeeJet Technologies, 106 Wheaton, IL, USA). A discharge calibration was performed before treatment and a metronome was used to maintain travel speed during application. The first season the young trees received one herbicide application two months after planting and then were treated with three herbicide applications at 21-day intervals in spring 2021 and 2022. Data collection consisted of visual assessments of crop injury using a 0 to 100 scale at monthly intervals starting one month after the first application in May 2020. Trunk diameter 46 cm above the soil surface was measured before the first tiafenacil application in May 2020 and then in each subsequent year between January and March while the trees were dormant.

Orchard efficacy studies. Several field experiments were conducted at the UC Davis Pomology Field Facility in Davis, CA in an 8-year-old ‘Nonpareil’ almond orchard in the winter of 2021 and fall 2021 and subsequently in an 8-year-old ‘Chandler’ walnut orchard in winter 2022 (38.5403776, -121.7849871). An experiment was also initiated on April 12, 2022, at the Wolfskill Experimental Orchard in Winters, CA in a 5-year-old mixed species orchard of ‘Lapins’ cherry and ‘Howard’ walnut (38.5053790, -121.9807380). Twelve herbicide treatments including tiafenacil alone or in various tank-mixes with glufosinate were applied in a small plot research study to evaluate potential additive and synergistic interactions on weed control efficacy. The plots were 3 by 6 m centered on a single tree and were set up in a randomized complete block design with four replicates. Herbicide applications for the three experiments that were conducted at the Davis site were made on February 5, 2021, November 29, 2021, and January 26, 2022, respectively. Herbicide treatments were applied on April 12, 2022 for the experiment at the Wolfskill Experimental Orchard. The weed sizes ranged from 8 to 10 cm at application in all experiments. Treatment efficacy was visually assessed at 7, 14, and 28 days after treatment (DAT) relative to the nontreated control using a 0 to 100 scale, where 0 means no weed control and 100 means complete plant death. The aboveground plant biomass was harvested in a 1-m^{-2} quadrat near the center of each plot and placed in separate paper bags and dried to a constant weight in a convection oven at 50 C for the spring 2022 experiment.

Fallow field efficacy studies. Two field experiments were conducted at the UC Davis Plant Science Field Facility in Davis, CA (38.5387579, -121.7819151) to evaluate the weed control efficacy of tiafenacil alone or tank-mixed with glufosinate in summer and fall 2021. The plots were

3 by 6 m set up in a randomized complete block design with four replicates. Another field experiment was conducted in spring 2022 with tiafenacil alone or tank-mixed with glufosinate and glyphosate (Roundup PowerMax, Bayer Crop Science, Saint Louis, MO). The plots were 2 by 5 m set up in a randomized complete block design with four replicates. Herbicide applications were made on August 9, 2021 for the summer experiment and November 29, 2021 for the fall experiment. Weeds ranged from 8 to 13 cm tall except for common purslane which averaged 15 cm long. Treatment efficacy was visually assessed at 7, 14, and 28 DAT using a 0 to 100 scale. The aboveground plant tissue was harvested in 1-m^{-2} quadrat for each plot, and dried to a constant weight in a convection oven at 50 C, then dry biomass data was collected.

Greenhouse efficacy studies. Two experiments were initiated on May 24, 2022, and October 1, 2022, in a greenhouse (38.5430721, -121.7640843) at the University of California, Davis to evaluate the efficacy of tiafenacil alone and tank-mixed with glufosinate on barnyardgrass and junglerice. Seeds were collected in January 2022, from an orchard site in Davis, CA. Junglerice and barnyardgrass seeds were chemically scarified for 30 minutes in concentrated (90-99%) sulfuric acid followed by rinsing in deionized water (Buhler & Hoffman, 1999). Seeds were treated with a 0.2% w/v captan solution and germinated at room temperature on moist blotter paper in petri dishes. Germinated seeds were then sown into 10 by 10 cm pots at approximately 2 mm below the soil surface of commercial potting media (Sun Gro Horticulture Canada Ltd, Vancouver, BC, Canada). The experimental design was a randomized complete block with 6 treatments, including a nontreated control. There were four replicates for each treatment. The herbicides included in these studies were tiafenacil, glufosinate, and saflufenacil, see table 9 for rates and mixtures. Herbicide treatments were applied using a moving-nozzle, cabinet sprayer (Technical Machinery Incorporated, Sacramento, CA, USA) calibrated to deliver 140 L ha^{-1} at 241 kPa using an 8002E flat-fan TeeJet nozzle. The nozzle was adjusted to 30 cm above the canopy during the application. Plants remained in the greenhouse with day/night temperature of approximately 30 C with no additional lighting and were irrigated as needed. Treatment efficacy was visually assessed at 7 and 14 DAT using a 0 to 100 scale. The experiment was terminated 14 days after treatment and the aboveground plant biomass was cut at the surface of the soil, placed in separate paper bags, and dried to a constant weight in a convection oven at 40 C.

Field location soil sampling. A soil probe was used to obtain soil from all locations at a depth of 15 to 20 cm. Composite soil samples were transferred to a separate bag for each location. All soil samples were dried at 40 C and then stored at room temperature until analysis. Soil samples were sieved through a 2 mm mech screen and sent for analysis at the Analytical Lab at the University of California, Davis.

Data analysis. Weed control data were analyzed using a one-way ANOVA in R version 4.1.2 (The R Development Core Team, 2022), with mean comparisons using Fisher's Protected LSD test with $\alpha = 0.05$. The aboveground biomass data were analyzed using a linear model with *lmer* function in the lme4 package. The emmeans package and the *cld* function with Tukey's test (α=0.05) were used to separate treatment means when appropriate (Kniss & Streibig, 2020; Lengh, 2019). Trunk diameter data were analyzed using a simple linear model to characterize the growth of the orchard crops over 3 yr for the different tiafenacil and tank-mix treatments:

Linear Equation was used:

$$Y = A + BX$$

Where Y is the predicted value, A is the y-intercept; B is the slope of the line, and X is treatment rates in g ai ha^{-1}. All graphs were created using RStudio Team (The R Development Core Team, 2022).

Results and Discussion

Crop safety results. There was no foliar injury observed from any treatments at any rating interval on the young trees (data not shown). Although no fruit yield measurements were taken because the trees were too young for meaningful yield data, visual fruit quality appeared normal in all treated trees. The use of trunk diameter has been widely used as a measure of orchard crop growth (Hernandez-Santana et al., 2017; Martin-Palomo et al., 2019; Moriana et al., 2003). From 2020 to 2022, average trunk diameter increased substantially (Figures 1-4). The rate of prune, walnut, pistachio, and almond trunk growth was not impacted by the herbicide treatments (Tables 2 and 3). Some growers use the highest labeled rates and complex mixtures in their winter programs in an effort to manage difficult weeds, but these practices are costly and can occasionally lead to crop safety problems (Brunharo et al., 2020). Tiafenacil up to 148 g ai ha^{-1}, twice the likely use rate appeared to be safe in young prunes, walnuts, and pistachios. Tiafenacil up to 222 g ai ha^{-1}, a 3x rate, was also safe in young almonds (Figure 4). At the maximum use rate (75 g ai ha^{-1}), tiafenacil would likely have acceptable crop safety in commercial production of these orchard crops.

Weed control. In the spring 2022 applications, control of hairy fleabane with tiafenacil at 25 or 50 g ai ha^{-1} ranged from 53 to 58% at 7 DAT (Table 4). Glyphosate at 1037 g ae ha^{-1} provided the lowest control of hairy fleabane (10%) of all treatments. Control of hairy fleabane was improved when glyphosate was tank-mixed with tiafenacil at all rates. Tiafenacil at 25 g ai ha^{-1} + glyphosate at 1037 g ae ha^{-1} + glufosinate at 984 g ai ha^{-1} provided 68% control of hairy fleabane. A similar study reported increased control of glyphosate-resistant horseweed when glyphosate was tank-mixed with tiafenacil (Soltani et al., 2021). Hairy fleabane control with tiafenacil alone at 14 DAT ranged from 65 to 70%. All tank-mix treatments with tiafenacil at 50 g ai ha^{-1} resulted in similar control of hairy fleabane. Glyphosate still provided only 10% control of hairy fleabane, but glyphosate plus glufosinate at 984 g ai ha^{-1} provided 80% control of hairy fleabane. Tiafenacil alone or in tank mixes improved control of hairy fleabane but control did not exceed 60% control by 28 DAT at the tested growth stage (15- 18 cm). All treatments reduced weed biomass relative to the nontreated plots at 28 DAT. Weed biomass from treated plots ranged from 31 to 83 mg per plant.

For the winter 2021 herbicide applications, tiafenacil alone resulted in 48 to 50% control of annual bluegrass, and 43 to 53% of filaree at 7 DAT although these treatments did not differ from tiafenacil tankmixes with glufosinate. Fall 2021 herbicide applications resulted in 40 to 68% control of filaree and 30 to 50% control of annual bluegrass (Table 5). All treatments provided 48 to 60% control of filaree, and 45 to 60% control of annual bluegrass at 14 DAT (Table 6). Filaree control ranged from 50 to 63% control at 28 DAT and 40 to 57% control of annual bluegrass. Tiafenacil alone resulted in 65 to 70% control of filaree, and 63 to 70% control of annual bluegrass at 14 DAT (Table 6). All tank-mixed treatments provided 70 to 80% control of filaree and 73 to 83% control of annual bluegrass at 14 DAT. Filaree control with tiafenacil alone was 45 to 48% and annual bluegrass control was 53% at 28 DAT. Filaree control tended to be lowest with the tiafenacil solo treatments compared to glufosinate tank mixes at 28 DAT, although these differences were not always statistically significant.

In another study conducted in the spring of April 2022, all treatments provided 67 to 90% control of hairy fleabane at 7 DAT (Table 7). Control of hairy fleabane numerically increased in this study because weeds were treated at an earlier growth stage (8-10 cm) compared to the previous study. Tiafenacil at 9 ai g ha^{-1} resulted in the lowest control of hairy fleabane and filaree at 7 DAT (50%) but by 14 DAT, all treatments resulted in 100% control of hairy fleabane. Moretti et al. (2015) found that all treatments including saflufenacil provided

100% control of hairy fleabane. All treatments resulted in 50 to 77% control of filaree. Italian ryegrass control with all treatments ranged from 53 to 80% control at 7 DAT and 40 to 67% at 28 DAT. Control of hairy fleabane was 90% by 28 DAT. All treatments provided 50 to 77% control of filaree at 7 DAT and 50 to 73% control at 14 DAT. Control of filaree was 43% by 28 DAT. There were no significant differences among treatments in weed biomass, but all treatments numerically reduced weed biomass relative to the nontreated control.

In the experiment to evaluate the additive effects of tiafenacil and glufosinate, annual bluegrass control with all treatments ranged from 75 to 100% at 14 DAT (Table 8). Tiafenacil alone resulted in 60 to 100% control of filaree and shepherd's purse at 14 DAT. Tiafenacil at 12 g ai ha^{-1} performed similarly to tank-mixed treatments on all weed species at 14 DAT with the lowest control 55% and the highest 100% control. Tiafenacil at 12 g ai ha^{-1} and all tiafenacil tank-mixed treatments resulted in 100% control of filaree, shepherd's purse, and annual bluegrass at 14 DAT and were better than tiafenacil applied alone at 9 g ha^{-1}. By 28 DAT tiafenacil at 9 g ai ha^{-1} had the lowest weed control of filaree and shepherd's purse at 55% while tiafenacil at 12 g ai ha^{-1} and all tank-mixed treatments provided 100% control of annual bluegrass, shepherd's purse, and filaree.

Greenhouse efficacy. Tiafenacil at 12 g ai ha^{-1} provided 95% control of junglerice and 100% control of barnyardgrass in the summer experiment (Table 9). Mixtures with glufosinate at 180 g ai ha^{-1} had similar control of junglerice as did tiafenacil alone. Saflufenacil at 49 g ai ha^{-1} did not adequately control junglerice and barnyardgrass only reaching 10% control. Tiafenacil plus glufosinate provided 97% control of junglerice, while saflufenacil plus glufosinate provided 93% control of junglerice. Jhala et al. (2013) similarly found that saflufenacil did not affect grass weed control. All treatments resulted in significantly less biomass than the nontreated control.

Barnyardgrass biomass ranged from 325 to 9008 mg, with the numerically lowest biomass from the mixture of tiafenacil and glufosinate. Tiafenacil at 12 g ai ha^{-1} provided 98% control of junglerice and barnyardgrass in the fall greenhouse experiment and was similar to glufosinate alone and the mixture of tiafenacil plus glufosinate (Table 9). Barnyardgrass biomass was significantly lower than the nontreated control in all treatments except for saflufenacil alone. These results agree with previous reports demonstrating the efficacy of glufosinate in controlling barnyardgrass (Lanclos et al., 2002). Overall, tiafenacil alone performed similarly to glufosinate on controlling junglerice and barnyardgrass. Glufosinate applied alone at 180 g ai ha^{-1} resulted in 95% control of junglerice, similarly tiafenacil applied alone resulted in 95% control. Finally, it was determined that saflufenacil applied alone or tank mixing with glufosinate was not as effective as tiafenacil applied alone and tank mixed with glufosinate for grass weed control.

Conclusion

The results of these studies show that tiafenacil has some activity on grass weeds but would likely need to be tank-mixed with an herbicide with grass activity for most effective weed control. Tiafenacil at up to 148 g ai ha^{-1} in young prune, walnut, and pistachio and at up to 222 g ai ha^{-1} in young almond did not result in visible crop injury. If tiafenacil were registered in orchards, 75 g ai ha^{-1} would be sufficient for effective weed control without significant risk of injuring young trees. Tiafenacil can be a new tool that can help managing glyphosate-resistant orchard weeds including hairy fleabane. Overall, in these experiments, increasing the rate of glufosinate did not dramatically increase weed control; thus, with timely applications, relatively lower glufosinate rates plus tiafenacil may be sufficient. Tiafenacil has the potential for registration consideration for use in California tree crops at a much lower rate than 75 g ai ha^{-1} when in mixture with another herbicide.

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Tables

Table 1. Source of herbicides used in field and greenhouse trials.

Active ingredient	Commercial product name	Manufacturer	Address
Tiafenacil	Gamma™	ISK Biosciences Corporation	7470 Auburn Road, Suite A Concord, Ohio 44077
Glufosinate	Rely® 280	BASF Corporation	26 Davis Dr, Research Triangle Park, NC, USA
Tolpyralate	Shieldex®400SC	ISK Biosciences Corporation	7470 Auburn Road, Suite A Concord, Ohio 44077
Saflufenacil	Treevix®	BASF Corporation	26 Davis Dr, Research Triangle Park, NC, USA
Glyphosate	Roundup PowerMax®	Bayer Crop Sciences	800 Lindbergh Blvd, St Louis, MO, USA

Table 2. Regression parameters for trunk diameter increase in almond after 7 tiafenacil and other tank-mixed herbicide applications made during 2020-2023.

Treatment[a]	Rate	A[b] (mm)	B	SE
	g ai ha^{-1}			
Control	0	156	120	22.04
Tiafenacil	74	184	130	10.3
Tiafenacil	148	180	130	25.4
Tiafenacil	222	184	140	11.6
Tiafenacil + tolpyralate	74 + 38	191	140	11.4
Tiafenacil + tolpyralate	148 + 38	183	150	26.4
Saflufenacil	49	171	140	26.4
Saflufenacil	98	172	140	25.1
Saflufenacil	147	176	140	24.2

[a]Almond trees received one herbicide application in May 2020, 3 applications in February-April 2021, and 3 applications in February-April 2022 on a 21-day retreatment interval

[b]Regression parameters: y = a + bx, where y is the expected values of the tree trunk diameter (mm), a is the y intercept, b is the slope, and x is the rate of treatments in g ai ha^{-1}

Table 3. Regression parameters for trunk diameter increase in California orchard crops after 7 tiafenacil and other tank-mixed herbicide applications made during 2020-2023.

		Pistachio			Walnut			Prune		
Treatment[a]	Rate	A[b] (mm)	B	SE	A(mm)	B	SE	A(mm)	B	SE
	g ai ha^{-1}									
Control	0	17	8.9	1.8	46	22	2.6	43	22	1.9
Tiafenacil	74	19	8	1.7	51	24	2.3	43	25	2.3
Tiafenacil	148	19	9.6	1.8	50	26	2.3	46	24	2.8
Tiafenacil + tolpyralate	74 + 38	19	10	1.9	52	26	2.6	48	24	3.3
Saflufenacil	49	15	9	1.8	49	28	2.6	46	24	3.3
Saflufenacil	98	17	10	1.0	50	24	2.5	45	24	2.9

[a]Pistachio, prune, and walnut trees received one herbicide application in May 2020, 3 applications in February-April 2021, and 3 applications in February-April 2022 on a 21- day interval

[b]Regression parameters: $y = a + bx$, where y is the expected values of the tree trunk diameter (mm), a is the y intercept, b is the slope, and x is the treatments in g ai ha^{-1}

Table 4. Glyphosate-resistant hairy fleabane control at 7, 14, and 28 days after treatments (DAT) and total weed biomass from a trial conducted in a fallow field near Davis, CA in April 2022.

Treatment[a]	Rate	7 DAT	14 DAT		28 DAT Dry biomass
	g ai ha^{-1}		%		g m^{-2}
Untreated	N/A	N/A	N/A	N/A	146 a
Tiafenacil	25	53 bc[d]	65 bc	48 ab	72 bc
Tiafenacil	50	58 ab	70 ab	50 ab	31 c
Tiafenacil + glyphosate[c]	25 + 1037	45 c	58 c	45 b	50 bc
Tiafenacil + glufosinate	25 + 984	60 ab	78 a	55 ab	55 bc
Tiafenacil + glyphosate	50 + 1037	53 bc	70 ab	53 ab	56 bc
Tiafenacil + glufosinate	50 + 984	63 ab	75 ab	55 ab	43 bc
Tiafenacil + glyphosate + glufosinate	25 + 1037 + 984	68 ab	78 a	58 ab	53 bc
Tiafenacil + glyphosate + glufosinate	50 + 1037 + 984	60 ab	78 a	58 ab	38 c
Glufosinate	984	60 ab	75 ab	55 ab	73 bc
Glyphosate	1037	10 d	10 d	10 c	83 b
Glyphosate + glufosinate	1037 + 984	58 ab	80 a	60 a	57 bc
P-value	NA	<0.0001	<0.0001	<0.0001	0.0010

[a]All herbicide treatments include methylated seed oil (MSO) at 1% v/v and ammonium sulfate (AMS) at 2.5% v/v
[b]ai = active ingredients
[c]Glyphosate rate expressed as g acid equivalent ha^{-1}
[d]Means followed by the same letter are not significantly different (α= 0.05, LSD)

Table 5. Visual control of annual bluegrass and filaree at 7 DAT from field trials conducted in two established almond orchards in Davis, CA in January and November 2021.

		January 2021		November 2021	
Treatments[a]	Rate[b]	Filaree	Annual bluegrass	Filaree	Annual bluegrass
	g ai ha^{-1}	%			
Untreated	N/A	N/A	N/A	N/A	N/A
Tiafenacil	9	43	48	50 cde[c]	30 bc
Tiafenacil	12	53	50	40 e	38 c
Tiafenacil + glufosinate	9 + 180	58	50	58 a-d	45 ab
Tiafenacil + glufosinate	9 + 270	45	48	60 a-d	45 ab
Tiafenacil + glufosinate	9 + 361	48	40	65 ab	50 a
Tiafenacil + glufosinate	9 + 451	53	50	63 abc	48 a
Tiafenacil + glufosinate	9 + 541	45	50	63 abc	48 a
Tiafenacil + glufosinate	12 + 229	53	47	65 ab	45 ab
Tiafenacil + glufosinate	12 + 361	53	50	68 a	48 ab
Tiafenacil + glufosinate	12 + 482	60	55	48 de	45 ab
Tiafenacil + glufosinate	12 + 602	50	48	55 a-d	43 ab
Tiafenacil + glufosinate	12 + 722	43	43	53 b-e	45 ab
P-value	NA	0.275	0.637	0.0038	0.0009

[a]All herbicide treatments include ammonium sulfate (AMS) and methylated seed oil (MSO) at 1% v/v
[b]ai = active ingredients
[c]Means followed by the same letter are not significantly different (α = 0.05, LSD)

Table 6. Visual control of annual bluegrass and filaree at 14 and 28 DAT from field trials conducted in two established almond orchards in Davis, CA in January and November 2021.

Treatment[a]	Rate[b]	January 2021 Filaree 14 DAT	January 2021 Annual bluegrass 14 DAT	January 2021 Filaree 28 DAT	January 2021 Annual bluegrass 28 DAT	November 2021 Filaree 14 DAT	November 2021 Annual bluegrass 14 DAT	November 2021 Filaree 28 DAT	November 2021 Annual bluegrass 28 DAT
	g ai ha^{-1}	%							
Untreated	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Tiafenacil	9	48	60	55	50	70 cd[c]	70	48 cd	53
Tiafenacil	12	48	58	55	55	65 c	63	45 d	53
Tiafenacil + glufosinate	9 + 180	48	58	63	50	70 bc	73	58 ab	50
Tiafenacil + glufosinate	9 + 270	50	58	53	55	75 ab	75	63 ab	55
Tiafenacil + glufosinate	9 + 361	48	55	58	50	80 a	78	58 ab	55
Tiafenacil + glufosinate	9 + 451	50	58	58	55	75 ab	75	63 ab	58
Tiafenacil + glufosinate	9 + 541	50	45	58	40	80 a	78	58 ab	60
Tiafenacil + glufosinate	12 + 229	53	59	50	50	78 ab	73	65 a	55
Tiafenacil + glufosinate	12 + 361	43	50	60	50	78 ab	83	60 ab	60
Tiafenacil + glufosinate	12 + 482	53	60	63	57	75 ab	80	58 ab	58
Tiafenacil + glufosinate	12 + 602	60	53	50	50	75 ab	78	58 ab	55
Tiafenacil + glufosinate	12 + 722	58	58	60	55	75 bc	75	58 ab	55
P-value[c]	NA	0.913	0.134	0.627	0.0618	0.0154	0.125	0.0115	0.604

[a]All herbicide treatments include ammonium sulfate (AMS) and methylated seed oil (MSO) at 1% v/v

[b]ai = active ingredients

[c]Means followed by the same letter are not significantly different (α = 0.05, LSD)

Table 7. Visual control of glyphosate-resistant hairy fleabane, Italian ryegrass, and filaree at 7, 14, and 28 DAT in a mixed-species orchard in Winters, CA in April 2022.

Treatment[a]	Rate[b]	Hairy fleabane 7 DAT	Filaree 7 DAT	Italian ryegrass 7 DAT	Hairy fleabane 14 DAT	Filaree 14 DAT	Italian ryegrass 14 DAT	Hairy fleabane 28 DAT	Filaree 28 DAT	Italian ryegrass 28 DAT	Total biomass 28 DAT
	g ai ha^{-1}	———	———	———	———	%	———	———	———	———	g m^{-2}
Untreated	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	NA	96
Tiafenacil	9	67 b[c]	50 c	53	100	50 b	50	90	43	40	47
Tiafenacil	12	87 a	63 b	60	100	63 a	53	90	53	47	61
Tiafenacil + glufosinate	9 + 180	90 a	67 ab	70	100	70 a	57	90	57	53	57
Tiafenacil + glufosinate	9 + 270	90 a	70 ab	73	100	67 a	57	90	60	57	76
Tiafenacil + glufosinate	9 + 361	90 a	68 ab	70	100	63 a	50	90	53	53	64
Tiafenacil + glufosinate	9 + 451	90 a	63 b	70	100	67 a	57	90	50	53	75
Tiafenacil + glufosinate	9 + 541	90 a	63 b	73	100	63 a	57	90	53	53	49
Tiafenacil + glufosinate	12 + 229	83 a	67 ab	73	100	67 a	53	90	57	57	61
Tiafenacil + glufosinate	12 + 361	90 a	67 ab	77	100	67 a	60	90	60	57	74
Tiafenacil + glufosinate	12 + 482	90 a	77 a	80	100	73 a	60	90	60	57	57
Tiafenacil + glufosinate	12 + 602	90 a	73 ab	80	100	73 a	61	90	60	60	42
Tiafenacil + glufosinate	12 + 722	90 a	63 b	70	100	65 a	60	90	60	67	62
P-value	N/A	0.0479	0.0120	0.243	0.471	0.0301	0.352	1.000	0.514	0.0618	0.309

[a]All herbicide treatments include ammonium sulfate (AMS) and methylated seed oil (MSO) at 1% v/v
[b]ai = active ingredients
[c]Means followed by the same letter are not significantly different (α = 0.05, LSD)

Table 8. Visual weed control at 14 DAT with tiafenacil alone or tank-mixed with glufosinate in a fallow field trial conducted in November 2021.

Treatment[a]	Rate[b]	Annual bluegrass 14 DAT	Filaree 14 DAT	Shepherd's purse 14 DAT	Annual bluegrass 28 DAT	Filaree 28 DAT	Shepherd's purse 28 DAT
	g ai ha^{-1}	%					
Untreated	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Tiafenacil	9	75 b[c]	60 b	60 b	68 b	55 b	55 b
Tiafenacil	12	100 a	99 a	100 a	100 a	100 a	100 a
Tiafenacil + glufosinate	9 + 180	100 a	99 a	100 a	100 a	100 a	100 a
Tiafenacil + glufosinate	9 + 270	100 a	100 a	100 a	100 a	100 a	100 a
Tiafenacil + glufosinate	9 + 361	100 a	100 a	100 a	100 a	100 a	100 a
Tiafenacil + glufosinate	9 + 451	100 a	100 a	100 a	100 a	100 a	100 a
Tiafenacil + glufosinate	9 + 541	100 a	100 a	100 a	100 a	100 a	100 a
Tiafenacil + glufosinate	12 + 229	100 a	100 a	100 a	100 a	100 a	100 a
Tiafenacil + glufosinate	12 + 361	100 a	100 a	100 a	100 a	100 a	100 a
Tiafenacil + glufosinate	12 + 482	100 a	100 a	100 a	100 a	100 a	100 a
Tiafenacil + glufosinate	12 + 602	100 a	100 a	100 a	100 a	100 a	100 a
Tiafenacil + glufosinate	12 + 722	100 a	100 a	100 a	100 a	100 a	100 a
P-value	N/A	0.0002	0.0021	0.0031	0.0030	0.0001	0.0001

[a]All herbicide treatments include ammonium sulfate (AMS) and methylated seed oil (MSO) at 1% v/v
[b]ai = active ingredients
[c]Means followed by the same letter are not significantly different (α = 0.05, LSD)

Table 9. Visual control and total biomass of junglerice and barnyardgrass at 14 DAT from two greenhouse experiments conducted in June and October 2022 to evaluate the efficacy of tiafenacil alone or tank-mixed with glufosinate.

		Summer 2022				Fall 2022			
Treatment[a]	Rate[b]	Junglerice	Barnyardgrass	Junglerice	Barnyardgrass	Junglerice	Barnyardgrass	Junglerice	Barnyardgrass
	g ai ha^{-1}	——— % ———		mg plant^{-1}	mg plant^{-1}	——— % ———		mg plant^{-1}	mg plant^{-1}
Untreated	N/A	N/A	N/A	7040 b	9008 a	N/A	N/A	2210 a	2680 a
Tiafenacil	12	95 ab[c]	100 a	73 a	448 b	98 a	98 a	73 c	98 b
Glufosinate	180	95 ab	93 bc	413 a	458 b	93 a	85 a	63 c	118 b
Saflufenacil	49	10 c	10 d	1410 a	485 b	0 b	0 b	1540 b	2060 a
Tiafenacil + glufosinate	12 + 180	97 a	100 a	60 a	325 b	98 a	95 a	108 c	85 b
Saflufenacil + glufosinate	49 + 180	93 b	98 ab	180 a	515 b	85 a	75 c	88 c	70 b
P-value	NA	0.0004	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

[a]All herbicide treatments include ammonium sulfate (AMS) and methylated seed oil (MSO) at 1% v/v

[b]ai = active ingredients

[c]Means followed by the same letter are not significantly different (α = 0.05, LSD)

Appendix

Table A1. Year, location, application information, soil characteristics, and weather information for seven field trials conducted in orchards and fallow fields in California during 2021 and 2022.

Year	Location	Coordinates	Application date	*Soil texture	*pH	*SOM (%)	Air temperature (∘F)	Soil temperature (∘F)	Wind speed (MPH)	Relative humidity (%)
2021	Pomology	38.5403776, -121.7849871	Feb 5, 2021	Rincon silty clay loam	6.45	2.35	59	59.8	4.8	56
	Pomology	38.5403776, -121.7849871	Nov 29, 2021	Rincon silty clay loam	6.46	2.37	63	54	5.6	72
	UCD Plant Sciences	38.5387579, -121.7819151	Aug 9, 2021	Yolo silt loam	6.79	1.52	76	69.1	2.8	56
	UCD Plant Sciences	38.5387579, -121.7819151	Nov 29, 2021	Yolo silt loam	6.79	1.52	53	52.6	3.7	94
2022	Pomology	38.5403776, -121.7849871	Jan 28, 2022	Rincon silty clay loam	6.46	2.37	63	54.4	6	72
	UC Plant Sciences		Apr 26, 2022	Yolo silt loam	6.79	1.52	68	59.4	4.1	42
	Wolfskill Experimental Orchard	38.5053790, -121.9807380	Apr 12, 2022	Yolo loam	7.56	2.76	52	57.4	6.4	38

*Based on soil test of the upper 15 cm of the soil profile

Table A2. Applications in crop safety experiments conducted in walnut, pistachio, almond, and prune orchards during 2020-2022 in California.

Year	Coordinates	Application date	Soil* texture	pH*	Soil* organic matter (%)	Air temperature (F)	Soil temperature (F)	Wind speed (MPH)	Relative humidity (%)	Trunk diameter date
2020	38°32'19.7"N 121°47'40.3"	May 1, 2020	Yolo silt loam	6.69	2.97	53.6	61.1	3.3	71	May 8, 2020
2021	38°32'19.7"N 121°47'40.3"	Feb 5, 2021	Yolo silt loam	6.69	2.97	47.4	46.3	4.3	79	Feb 1, 2021
	38°32'19.7"N 121°47'40.3"	Feb 25, 2021	Yolo silt loam	6.69	2.97	57.9	47.7	8.6	20	
	38°32'19.7"N 121°47'40.3"	Mar 17, 2021	Yolo silt loam	6.69	2.97	50.7	50.2	3.4	68	
2022	38°32'19.7"N 121°47'40.3"	Feb 25, 2022	Yolo silt loam	6.69	2.97	51.6	47.0	9.1	34	Feb 24, 2022
	38°32'19.7"N 121°47'40.3"	Mar 17, 2022	Yolo silt loam	6.69	2.97	55.8	52.9	5.0	74	
	38°32'19.7"N 121°47'40.3"	Apr 8, 2022	Yolo silt loam	6.69	2.97	66.1	57.2	6.0	60	Nov 15, 2022

*Based on soil test of the upper 15 cm of the soil profile from a composite sample for the multi-species orchard block.

Table A3. Visual weed control of summer weeds at 7 days after treatment with tiafenacil alone or tank-mixed with glufosinate in a fallow field study conducted in August 2021 near Davis, CA

Treatments[a]	Rate[b]	Common purslane	Yellow nutsedge	Lovegrass	Common lambsquarters	Overall control
	g ai ha^{-1}	%				
Tiafenacil	9	90	15	43 bcd[c]	80	45
Tiafenacil	12	90	20	35 d	55	53
Tiafenacil + glufosinate	9 + 180	90	23	35 d	50	68
Tiafenacil + glufosinate	9 + 270	90	18	38 d	63	40
Tiafenacil + glufosinate	9 + 361	90	23	35 d	48	58
Tiafenacil + glufosinate	9 + 451	90	23	75 a	65	48
Tiafenacil + glufosinate	9 + 541	90	23	50 a-d	60	63
Tiafenacil + glufosinate	12 + 229	90	23	55 a-d	70	53
Tiafenacil + glufosinate	12 + 361	90	28	53 a-d	68	53
Tiafenacil + glufosinate	12 + 482	90	20	58 a-d	70	63
Tiafenacil + glufosinate	12 + 602	90	18	63 abc	75	50
Tiafenacil + glufosinate	12 + 722	90	30	68 ab	65	70
P-value	NA	1.0000	0.357	0.0229	0.562	0.485

[a]All treatments include ammonium sulfate (AMS) and methylated seed oil (MSO) at 1% v/v
[b]ai = active ingredients
[c]Means followed by the same letter are not significantly different (α = 0.05, LSD)

Table A4. Visual weed control of summer weeds at 14 days after treatment with tiafenacil alone or tank-mixed with glufosinate in a fallow field study conducted in August 2021 near Davis, CA

Treatments[a]	Rate[b]	Common purslane	Yellow nutsedge	Lovegrass	Common lambsquarters	Overall control
	g ai ha^{-1}			%		
Tiafenacil	9	90	24	48 bcd[c]	88	80
Tiafenacil	12	90	26	40 d	55	88
Tiafenacil + glufosinate	9 + 180	90	28	40 d	53	85
Tiafenacil + glufosinate	9 + 270	90	23	48 bcd	65	88
Tiafenacil + glufosinate	9 + 361	90	25	43 cd	43	88
Tiafenacil + glufosinate	9 + 451	90	30	75 a	63	88
Tiafenacil + glufosinate	9 + 541	90	23	55 a-d	65	90
Tiafenacil + glufosinate	12 + 229	90	30	58 a-d	78	85
Tiafenacil + glufosinate	12 + 361	90	30	58 a-d	68	70
Tiafenacil + glufosinate	12 + 482	90	28	60 a-d	68	90
Tiafenacil + glufosinate	12 + 602	90	30	65 ab	78	88
Tiafenacil + glufosinate	12 + 722	90	35	70 ab	78	90
P-value	NA	1.0000	0.357	0.0280	0.378	0.213

[a]All treatments include ammonium sulfate (AMS) and methylated seed oil (MSO) at 1% v/v
[b]ai = active ingredients
[c]Means followed by the same letter are not significantly different (α = 0.05, LSD

Table A5. Visual weed control and above-ground plant biomass of summer weeds with tiafenacil alone or tank-mixed with glufosinate in a fallow field study conducted in August 2021 near Davis, CA

		28 DAT				35 DAT
Treatments[a]	Rate[b]	Common purslane	Yellow nutsedge	Lovegrass	Common lambsquarters	Aboveground biomass
	g ai ha^{-1}	%				g m^{-2}
Untreated	NA	N/A	N/A	N/A	N/A	260
Tiafenacil	9	98	15	10	88	158
Tiafenacil	12	100	20	15	58	188
Tiafenacil + glufosinate	9 + 180	100	15	18	53	131
Tiafenacil + glufosinate	9 + 270	98	13	15	65	150
Tiafenacil + glufosinate	9 + 361	100	20	30	48	128
Tiafenacil + glufosinate	9 + 451	98	20	40	68	215
Tiafenacil + glufosinate	9 + 229	98	23	20	73	178
Tiafenacil + glufosinate	12 + 361	98	20	23	78	148
Tiafenacil + glufosinate	12 + 482	95	20	18	70	155
Tiafenacil + glufosinate	12 + 602	100	23	18	75	145
Tiafenacil + glufosinate	12 + 722	98	15	15	78	73
P-value[c]	NA	0.4453	0.6795	0.2944	0.5554	0.7269

[a]All treatments include ammonium sulfate (AMS) and methylated seed oil (MSO) at 1% v/v
[b]ai = active ingredients
[c]Means were not statistically different (α = 0.05, LSD)

Table A6. Visual weed control at 10 days after treatment from a field trial evaluating the efficacy of tiafenacil alone and tank-mixed with glufosinate on weeds relevant to California orchards in a fallow field near Davis, CA in fall 2021

Treatment[a]	Rate[b]	Filaree	Malva	Shepherd's purse	Annual bluegrass	Overall control
	g ai ha^{-1}	%				
Tiafenacil	9	50 b[c]	65 b	50 b	55	48 b
Tiafenacil	12	90 a	98 a	90 a	73	90 a
Tiafenacil + glufosinate	9 + 180	88 a	100 a	90 a	73	90 a
Tiafenacil + glufosinate	9 + 270	88 a	95 a	90 a	73	90 a
Tiafenacil + glufosinate	9 + 361	90 a	100 a	90 a	83	88 a
Tiafenacil + glufosinate	9 + 451	90 a	98 a	88 a	75	90 a
Tiafenacil + glufosinate	9 + 541	90 a	98 a	90 a	83	90 a
Tiafenacil + glufosinate	12 + 229	90 a	100 a	90 a	83	90 a
Tiafenacil + glufosinate	12 + 361	90 a	100 a	90 a	83	90 a
Tiafenacil + glufosinate	12 + 482	90 a	100 a	88 a	80	90 a
Tiafenacil + glufosinate	12 + 602	73 c	78 c	90 a	65	73 c
Tiafenacil + glufosinate	12 + 722	90 a	100 a	78 c	88	90 a
P-value	NA	0.0002	0.0100	0.0003	0.1900	0.00034

[a]All treatments include ammonium sulfate (AMS) and methylated seed oil (MSO) at 1% v/v
[b]ai = active ingredients
[c]Means followed by the same letter are not significantly different (α = 0.05, LSD)

Table A7. Visual weed control at 17 days after treatment from a field trial evaluating the efficacy of tiafenacil alone and tank-mixed with glufosinate on weeds relevant to California orchards in a fallow field near Davis, CA in fall 2021.

Treatment[a]	Rate[b]	Filaree	Malva	Shepherd's purse	Annual bluegrass	Overall control
	g ai ha^{-1}	———	———	%	———	———
Tiafenacil	9	60 b[c]	75 b	60 b	75 b	60 b
Tiafenacil	12	100 a	99 a	100 a	100 a	90 a
Tiafenacil + glufosinate	9 + 180	100 a	99 a	100 a	100 a	90 a
Tiafenacil + glufosinate	9 + 270	100 a	100 a	100 a	100 a	90 a
Tiafenacil + glufosinate	9 + 361	100 a	100 a	100 a	100 a	90 a
Tiafenacil + glufosinate	9 + 451	100 a	100 a	100 a	100 a	90 a
Tiafenacil + glufosinate	9 + 541	100 a	100 a	100 a	100 a	90 a
Tiafenacil + glufosinate	12 + 229	100 a	100 a	100 a	100 a	90 a
Tiafenacil + glufosinate	12 + 361	100 a	100 a	100 a	100 a	90 a
Tiafenacil + glufosinate	12 + 482	100 a	100 a	100 a	100 a	90 a
Tiafenacil + glufosinate	12 + 602	100 a	100 a	100 a	100 a	90 a
Tiafenacil + glufosinate	12 + 722	100 a	100 a	100 a	100 a	90 a
P-value	NA	0.0021	0.0011	0.0031	0.0002	0.0001

[a]All treatments include ammonium sulfate (AMS) and methylated seed oil (MSO) at 1% v/v
[b]ai = active ingredients
[c]Means followed by the same letter are not significantly different (α = 0.05, LSD)

Table A8. Visual weed control at 35 days after treatment from a field trial evaluating the efficacy of tiafenacil alone and tank-mixed with glufosinate on weeds relevant to California orchards in a fallow field near Davis, CA in fall 2021.

Treatment[a]	Rate[b]	Filaree	Malva	Shepherd's purse	Annual bluegrass	Overall control
	g ai ha^{-1}	———	———	%	———	———
Tiafenacil	9	55 b[c]	68 b	55 b	68 b	68 a
Tiafenacil	12	100 a	100 a	90 a	100 a	100 b
Tiafenacil + glufosinate	9 + 180	100 a	100 a	90 a	100 a	100 b
Tiafenacil + glufosinate	9 + 270	100 a	100 a	90 a	100 a	100 b
Tiafenacil + glufosinate	9 + 361	100 a	100 a	90 a	100 a	100 b
Tiafenacil + glufosinate	9 + 451	100 a	100 a	90 a	99 a	99 b
Tiafenacil + glufosinate	9 + 541	100 a	100 a	90 a	100 a	100 b
Tiafenacil + glufosinate	12 + 229	100 a	100 a	90 a	99 a	99 b
Tiafenacil + glufosinate	12 + 361	100 a	100 a	90 a	93 a	100 b
Tiafenacil + glufosinate	12 + 482	100 a	100 a	90 a	100 a	100 b
Tiafenacil + glufosinate	12 + 602	100 a	100 a	90 a	100 a	100 b
Tiafenacil + glufosinate	12 + 722	100 a	100 a	90 a	99 a	100 b
P-value	NA	0.0001	0.0001	0.0050	0.0030	0.0001

[a]All treatments include ammonium sulfate (AMS) and methylated seed oil (MSO) at 1% v/v
[b]ai = active ingredients
[c]Means followed by the same letter are not significantly different (α = 0.05, LSD)

Table A9. Visual weed control at 10 days after treatment with tiafenacil alone or tank-mixed with glufosinate in a young almond orchard in California in November 2021.

Treatment[a]	Rate[b]	Annual bluegrass	California burclover	Filaree	Overall control
	g ai ha^{-1}	——— % ———			
Tiafenacil	9	30 bc[c]	61	50 cde	53 cd
Tiafenacil	12	38 c	63	40 e	48 d
Tiafenacil + glufosinate	9 + 180	45 ab	60	58 a-d	65 ab
Tiafenacil + glufosinate	9 + 270	45 ab	73	60 a-d	60 bc
Tiafenacil + glufosinate	9 + 361	50 a	60	65 ab	70 a
Tiafenacil +glufosinate	9 + 451	48 a	70	63 abc	68 ab
Tiafenacil + glufosinate	9 + 541	48 a	53	63 abc	67 ab
Tiafenacil + glufosinate	12 + 229	45 ab	50	65 ab	65 ab
Tiafenacil + glufosinate	12 + 361	48 ab	58	68 a	70 a
Tiafenacil + glufosinate	12 + 482	45 ab	53	48 de	65 ab
Tiafenacil + glufosinate	12 + 602	43 ab	57	55 a-d	60 bc
Tiafenacil + glufosinate	12 + 722	45 ab	58	53 b-e	63 ab
P-value	NA	0.0009	0.1462	0.0038	0.0005

[a]All treatments include ammonium sulfate (AMS) and methylated seed oil (MSO) at 1% v/v
[b]ai = active ingredients
[c]Means followed by the same letter are not significantly different (α = 0.05, LSD)

Table A10. Visual weed control at 17 days after treatment with tiafenacil alone or tank-mixed with glufosinate in a young almond orchard in California in November 2021.

Treatment[a]	Rate[b]	Annual bluegrass	California burclover	Filaree	Overall control
	g ai ha^{-1}	———	——— %	———	———
Tiafenacil	9	70	70 cd[c]	73 abc	63 bc
Tiafenacil	12	63	68 d	65 c	55 c
Tiafenacil + glufosinate	9 + 180	73	78 abc	70 bc	68 ab
Tiafenacil + glufosinate	9 + 270	75	75 bcd	75 ab	63 bc
Tiafenacil + glufosinate	9 + 361	78	85 a	80 a	70 ab
Tiafenacil + glufosinate	9 + 451	75	83 ab	75 ab	72 a
Tiafenacil + glufosinate	9 + 541	78	85 a	80 a	68 ab
Tiafenacil + glufosinate	12 + 229	73	83 ab	78 ab	68 ab
Tiafenacil + glufosinate	12 + 361	83	83 ab	78 ab	70 ab
Tiafenacil + glufosinate	12 + 482	80	78 abc	75 ab	68 ab
Tiafenacil + glufosinate	12 + 602	78	80 ab	75 ab	65 ab
Tiafenacil + glufosinate	12 + 722	75	75 bcd	70 bc	63 bc
P-value	NA	0.1251	0.0233	0.0154	0.0438

[a]All treatments include ammonium sulfate (AMS) and methylated seed oil (MSO) at 1% v/v
[b]ai = active ingredients
[c]Means followed by the same letter are not significantly different (α = 0.05, LSD)

Table A11. Visual weed control at 35 days after treatment with tiafenacil alone or tank-mixed with glufosinate in a young almond orchard in California in November 2021.

Treatment[a]	Rate[b]	Annual bluegrass	California burclover	Filaree	Overall control
	g ai ha^{-1}	%			
Tiafenacil	9	53	63	48 cd[c]	60 cd
Tiafenacil	12	53	60	45 d	53 d
Tiafenacil + glufosinate	9 + 180	50	60	58 ab	73 a
Tiafenacil + glufosinate	9 + 270	55	63	63 ab	63 bc
Tiafenacil + glufosinate	9 + 361	55	70	58 ab	68 abc
Tiafenacil + glufosinate	9 + 451	58	60	63 ab	70 ab
Tiafenacil + glufosinate	9 + 541	60	63	58 ab	68 abc
Tiafenacil + glufosinate	12 + 229	55	70	65 a	65 abc
Tiafenacil + glufosinate	12 + 361	60	65	60 ab	70 ab
Tiafenacil + glufosinate	12 + 482	58	68	58 ab	68 abc
Tiafenacil + glufosinate	12 + 602	55	58	58 ab	63 bc
Tiafenacil + glufosinate	12 + 722	55	65	58 ab	70 ab
P-value	NA	0.6038	0.3861	0.0115	0.0239

[a]All treatments include ammonium sulfate (AMS) and methylated seed oil (MSO) at 1% v/v
[b]ai = active ingredients
[c]Means followed by the same letter are not significantly different (α = 0.05, LSD)

Table A12. Visual weed control at 7 days after treatment with tiafenacil alone or tank-mixed with glufosinate in an established walnut orchard in California in January 2022.

Treatment[a]	Rate[b]	Hare barley	Little mallow	Common chickweed	Shepherd's purse	Overall control
	g ai ha^{-1}			%		
Tiafenacil	9	43	65	53	53	53 a[c]
Tiafenacil	12	53	78	65	68	58 a
Tiafenacil + glufosinate	9 + 180	58	75	65	68	70 b
Tiafenacil + glufosinate	9 + 270	45	80	58	63	90 b
Tiafenacil + glufosinate	9 + 361	48	73	60	68	90 b
Tiafenacil + glufosinate	9 + 451	53	78	63	63	73 b
Tiafenacil + glufosinate	9 + 541	45	68	58	65	88 b
Tiafenacil + glufosinate	12 + 229	53	73	60	65	88 b
Tiafenacil + glufosinate	12 + 361	53	75	65	63	90 b
Tiafenacil + glufosinate	12 + 482	60	75	63	70	90 b
Tiafenacil + glufosinate	12 + 602	50	70	60	63	74 b
Tiafenacil + glufosinate	12 + 722	43	70	55	60	90 b
P-value	NA	0.206	0.964	0.949	0.964	<0.0001

[a]All treatments include ammonium sulfate and methylated seed oil at 1% v/v
[b]ai = active ingredients
[c]Means followed by the same letter are not significantly different (α = 0.05, LSD)

Table A13. Visual weed control at 14 days after treatment with tiafenacil alone or tank-mixed with glufosinate in an established walnut orchard in California in January 2022.

Treatment[a]	Rate[b]	Hare barley	Little mallow	Common chickweed	Shepherd's purse	Overall control
	g ai ha^{-1}	%				
Tiafenacil	9	73	73	70	87	72
Tiafenacil	12	83	83	80	90	77
Tiafenacil + glufosinate	9 +180	90	93	90	95	87
Tiafenacil + glufosinate	9 + 270	93	95	90	85	80
Tiafenacil + glufosinate	9 + 361	93	93	95	90	90
Tiafenacil + glufosinate	9 + 451	75	83	80	80	75
Tiafenacil + glufosinate	9 + 541	95	98	95	87	80
Tiafenacil + glufosinate	12 + 229	93	95	97	95	90
Tiafenacil + glufosinate	12 + 361	93	93	95	97	90
Tiafenacil + glufosinate	12 + 482	100	100	100	100	82
Tiafenacil + glufosinate	12 + 602	93	78	80	96	91
Tiafenacil + glufosinate	12 + 722	95	93	93	84	75
P-value[c]	NA	0.692	0.219	0.871	0.940	0.862

[a]All treatments include ammonium sulfate and methylated seed oil at 1% v/v
[b]ai = active ingredients
[c]Means were not statistically different (α = 0.05, LSD)

Table A14. Visual weed control at 28 days after treatment with tiafenacil alone or tank-mixed with glufosinate in an established walnut orchard in California in January 2022.

Treatment[a]	Rate[b]	Hare barley	Little mallow	Common chickweed	Shepherd's purse	Overall control
	g ai ha^{-1}	%				
Tiafenacil	9	60 c[c]	68 bc	67 bc	68 c	40 b
Tiafenacil	12	40 c	50 c	50 c	50 c	30 b
Tiafenacil + glufosinate	9 + 180	80 ab	83 ab	83 ab	85 ab	70 a
Tiafenacil + glufosinate	9 + 270	90 ab	93 a	95 a	93 a	90 a
Tiafenacil + glufosinate	9 + 361	100 a	100 a	100 a	100 a	90 a
Tiafenacil + glufosinate	9 + 451	78 ab	80 ab	85 ab	80 ab	73 a
Tiafenacil + glufosinate	9 + 541	98 a	98 a	95 a	95 a	88 a
Tiafenacil + glufosinate	12 + 229	93 a	95 a	98 a	98 a	88 a
Tiafenacil + glufosinate	12 + 361	95 a	95 a	95 a	95 a	90 a
Tiafenacil + glufosinate	12 + 482	98 a	98 a	98 a	98 c	90 a
Tiafenacil + glufosinate	12 + 602	80 ab	85 ab	90 a	90 a	73 a
Tiafenacil + glufosinate	12.0 + 722	98 a	100 a	100 c	100 a	90 a
P-value	NA	0.0098	0.0003	0.00025	0.0003	< 0.0001

[a]All treatments include ammonium sulfate (AMS) and methylated seed oil (MSO) at 1% v/v
[b]ai = active ingredients
[c]Means followed by the same letter are not significantly different (α = 0.05, LSD)

Table A15. Visual weed control at 7 days after treatment of an herbicide trial evaluating tiafenacil alone or tank-mixed with glufosinate in a mixed-species orchard in Winters, CA in April 2022.

Treatment[a]	Rate[b]	Hairy Fleabane	Italian ryegrass	Filaree	Overall control
	g ai ha^{-1}	%			
Tiafenacil	9	67 b	53	50 c	67
Tiafenacil	12	87 a	60	63 b	67
Tiafenacil + glufosinate	9 + 180	90 a	70	67 ab	77
Tiafenacil + glufosinate	9 + 270	90 a	73	70 ab	77
Tiafenacil + glufosinate	9 + 361	90 a	70	68 ab	80
Tiafenacil + glufosinate	9 + 451	90 a	70	63 b	80
Tiafenacil + glufosinate	9 + 541	90 a	73	63 b	80
Tiafenacil + glufosinate	12 + 229	83 a	73	67 ab	80
Tiafenacil + glufosinate	12 + 361	90 a	77	67 ab	77
Tiafenacil + glufosinate	12 + 482	90 a	80	77 a	77
Tiafenacil + glufosinate	12 + 602	90 a	80	73 ab	73
Tiafenacil + glufosinate	12 + 722	90 a	70	63 b	80
P-value	NA	0.0479	0.243	0.0120	0.241

[a]All treatments include ammonium sulfate (AMS) and methylated seed oil (MSO) at 1% v/v
[b]ai = active ingredients
[c]Means followed by the same letter are not significantly different (α = 0.05, LSD)

Table A16. Visual weed control at 14 days after treatment of an herbicide trial evaluating tiafenacil alone or tank-mixed with glufosinate in a mixed-species orchard in Winters, CA in April 2022.

Treatment[a]	Rate[b]	Hairy fleabane	Italian ryegrass	Filaree	Overall control
	g ai ha^{-1}	———	%	———	
Tiafenacil	9	100	50	50 b	56 ab[c]
Tiafenacil	12	100	53	63 a	63 a
Tiafenacil + glufosinate	9 + 180	100	57	70 a	63 a
Tiafenacil + glufosinate	9 + 270	100	57	67 a	63 a
Tiafenacil + glufosinate	9 + 361	100	50	63 a	58 a
Tiafenacil + glufosinate	9 + 451	100	57	67 a	61 a
Tiafenacil + glufosinate	9 + 541	100	57	63 a	63 a
Tiafenacil + glufosinate	12 + 229	100	53	67 a	61 a
Tiafenacil + glufosinate	12 + 361	100	60	67 a	63 a
Tiafenacil + glufosinate	12 + 482	100	60	73 a	65 a
Tiafenacil + glufosinate	12 + 602	100	61	73 a	88 c
Tiafenacil + glufosinate	12 + 722	100	60	65 a	60 a
P-value	NA	0.471	0.352	0.030	<0.0001

[a]All treatments include ammonium sulfate (AMS) and methylated seed oil (MSO) at 1% v/v
[b]ai = active ingredients
[c]Means followed by the same letter are not significantly different (α = 0.05, LSD)

Table A17. Visual weed control and biomass at 28 days after treatment of an herbicide trial evaluating tiafenacil alone or tank-mixed with glufosinate in a mixed-species orchard in Winters, CA in April 2022.

Treatment[a]	Rate[b]	Hairy fleabane	Italian ryegrass	Filaree	Total biomass
	g ai ha^{-1}		%		g m^{-2}
Untreated	NA	NA	NA	NA	96
Tiafenacil	9	90	40	43	47
Tiafenacil	12	90	47	53	61
Tiafenacil + glufosinate	9 + 180	90	53	57	57
Tiafenacil + glufosinate	9 + 270	90	57	60	76
Tiafenacil + glufosinate	9 + 361	90	53	53	64
Tiafenacil + glufosinate	9 + 451	90	53	50	75
Tiafenacil + glufosinate	9 + 541	90	53	53	49
Tiafenacil + glufosinate	12 + 229	90	57	57	61
Tiafenacil + glufosinate	12 + 361	90	57	60	74
Tiafenacil + glufosinate	12 + 482	90	57	60	57
Tiafenacil + glufosinate	12 + 602	90	60	60	42
Tiafenacil + glufosinate	12 + 722	90	67	60	62
P-value[c]	NA	1.000	0.0618	0.514	0.3093

[a]All treatments include ammonium sulfate (AMS) and methylated seed oil (MSO) at 1% v/v
[b]ai = active ingredients
[c]Means were not statistically different (α = 0.05, LSD)

Figures

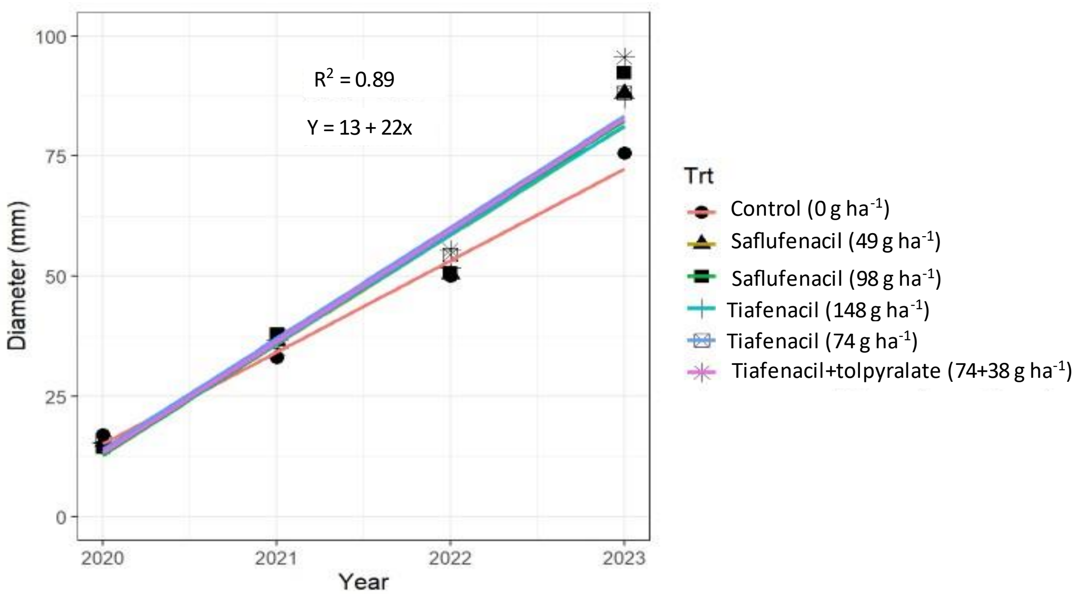

Figure 1. Increase in young walnut trunk diameter over time with or without tiafenacil applied around the base of the tree 7 times over 3 yr.

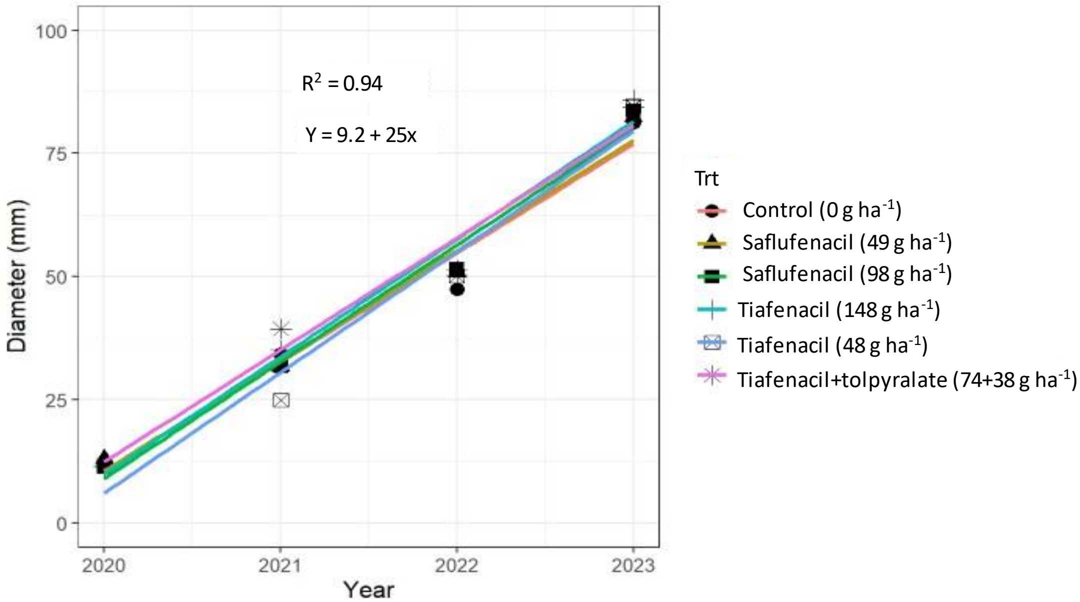

Figure 2. Increase in young prune trunk diameter over time with or without tiafenacil applied around the base of the tree 7 times over 3 yr.

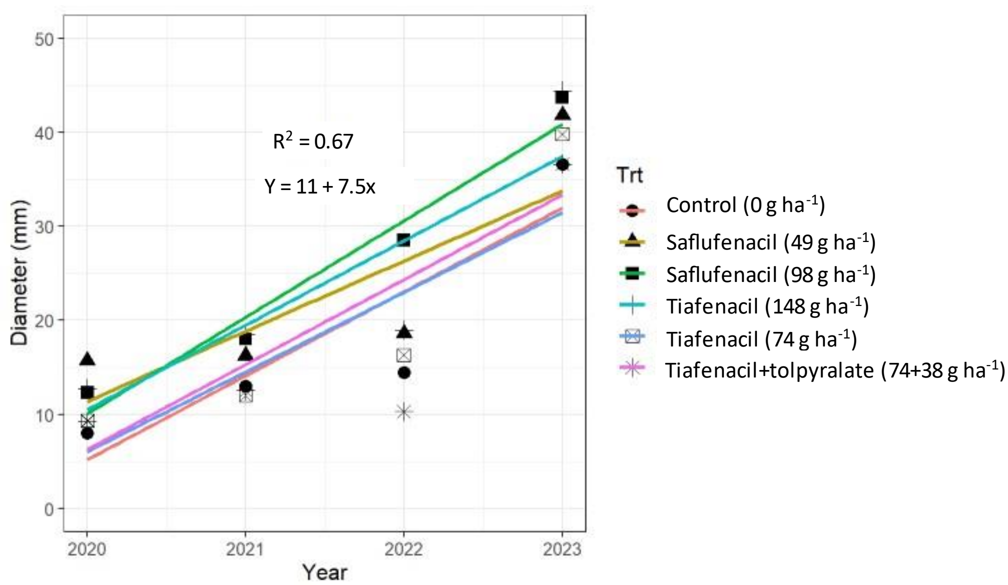

Figure 3. Increase in young pistachio trunk diameter over time with or without tiafenacil applied around the base of the tree 7 times over 3 yr.

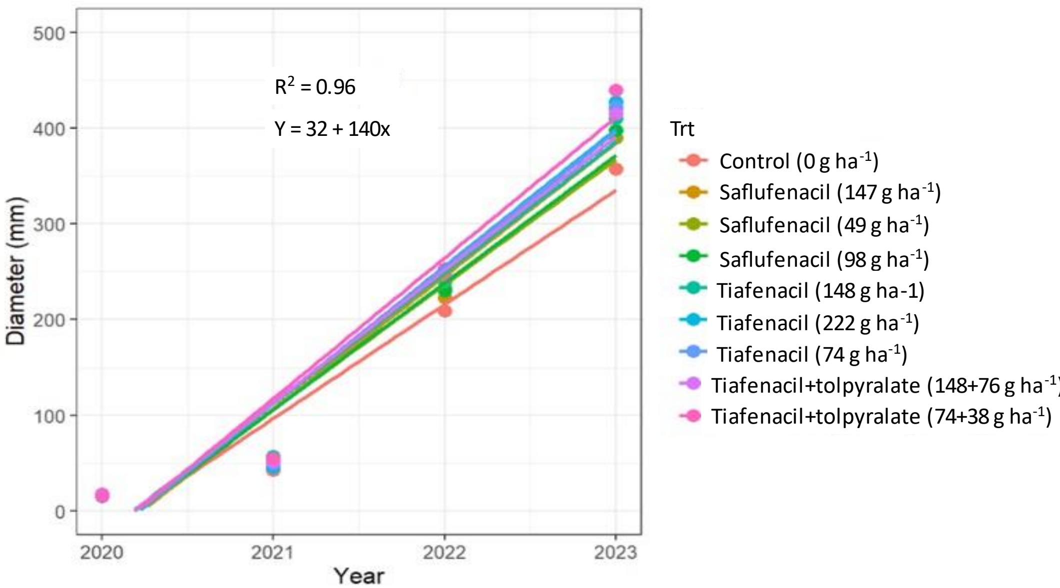

Figure 4. Increase in young almond trunk diameter over time with or without tiafenacil applied around the base of the tree 7 times over 3 yr.