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Agronomic cover crop management supports weed suppression and competition in California orchards

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Abstract

Cover crops enhance the biodiversity of cropping systems and can support a variety of useful ecosystem services, including weed suppression. In California orchards, cover crops are typically implemented as annual plants that can replace resident vegetation in orchard alleyways during the rainy winter season. Our research objective was to evaluate cover crop management factors that support a competitive, weed-suppressing cover crop in the unique orchard systems of central California. We conducted two experiments: an experiment evaluating cover crop management intensification in walnuts (*Juglans regia* L.) and an experiment evaluating multispecies cover crop mixes and planting date in almonds [*Prunus dulcis* (Mill.) D.A. Webb]. These experiments demonstrate that timely cover crop planting is important for producing an abundant cover crop, and a variety of cover crop management programs can produce weed-suppressing cover crops. However, cover crops do not result in weed-free orchards and should be considered within the context of integrated management programs. The apparent flexibility of orchard cover crop management provides an opportunity to promote other agroecosystem services, with vegetation management and weed suppression as complementary management goals.

Introduction

Orchard cropping systems require vegetation management programs that produce accessible orchard floors while minimizing management intensity. Orchard systems in California require significant upfront investment that exposes orchard growers to heightened risks related to climate change, water scarcity, and land use change compared with more flexible annual cropping systems (Pope et al. 2016). Diversified management systems could reduce risk for orchard growers who manage over 1 million ha of almonds [*Prunus dulcis* (Mill.) D.A. Webb], walnuts (*Juglans regia* L.), stone fruit (*Prunus* spp.), and similar orchard crops (Anonymous 2020). Weed management is an important area for orchard sustainability improvements, given that vegetation and vegetation management practices affect many environmental quality parameters across the orchard agroecosystem, including factors such as herbicide use intensity, soil health, water quality, and air contaminants (De Leijster et al. 2019). Rather than seeking vegetation-free orchard floors, growers could potentially cultivate orchard floor vegetation that contributes to ancillary management goals and provides additional ecosystem services (Schipanski et al. 2014).

Cover crops offer flexible management options for diversifying agroecosystems and increasing the ecological function of orchard floors (Brodt et al. 2019). As one cultural management practice within a suite of integrated pest management practices, cover crops can provide a framework for understanding the seasonality and phenology of weed life cycles while also promoting grower acceptance for some level of orchard vegetation (Linares et al. 2008; Ramos et al. 2010). Typically, commercial orchards in California will have a zone of high-intensity weed management in a strip centered on the tree row, often 25 to 50% of the orchard floor, with less intensive weed management in the remainder of the alley between rows (Roncoroni et al. 2017). The high-intensity tree strip is maintained to keep weeds from interfering with irrigation infrastructure and minimize non-crop water use in the irrigated area. In crops that are harvested from the orchard floor, which includes many tree nut crops, the alley is generally managed to be weed free ahead of crop harvest in the late summer, when heavy plant residues could impede sweepers and other harvest equipment.

Alley management in the winter can vary with grower preferences, but cover crops could be implemented in this zone so long as cover crop residues do not affect crop harvest operations (DeVincentis et al. 2022). California has mild, rainy winters that are conducive to cover crop growth. Furthermore, tree nut and stone fruit crops are deciduous, and dormant tree canopies allow ample light to reach the orchard floor throughout the winter, until trees leaf out in

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mid-February for almonds and later in the spring for other species. Winter annual plants have a life cycle that is aligned with almond production, because these plants likely do not require supplemental irrigation in the winter and will senesce during hot, dry summers.

With this context, winter annual cover crop species could be used to displace winter weeds in orchard alleys. Literature focusing on cover crops and weed management often centers on annual cropping systems, with cover crops growing in the off season between annual cash crops, resulting in temporal separation (Mirsky et al. 2011, 2013; Teasdale et al. 1991). Heavy cover crop residues drive weed control by limiting the emergence of weed seedlings before and during cash crop emergence (Creamer et al. 1996). In contrast, cover crops in orchard systems have spatial separation between cover crops and cash crops, which increases the importance of interference with concurrently growing weeds (Baumgartner et al. 2008). Spatial separation also creates flexibility by reducing restrictions on the cover crop growing season imposed by annual cash crop planting and harvest, and information about the phenology of plant competition could help optimize the management of an abundant, competitive cover crop (Bugg et al. 1996). Finally, California orchards undergo dormant-season management like pruning and orchard sanitation, which could create trade-offs between these management practices and a winter cover crop. For these reasons, weed-suppressing cover crops require additional research that informs practical management guidelines relevant to orchard systems in California.

Specific cover crop management recommendations could support adoption by helping growers understand and balance the many functions, ecosystem services, and management goals associated with cover crops. To address this need, we developed specific questions about cover crop planting date, the phenology of crop–weed competition, and intensified cover crop practices. Research on intensified cover crop management could help us understand how agronomic practices such as planting rate, fertilizer or herbicide inputs, cover crop species mixtures, and cover crop termination practices interact with the many aspects of agroecosystem function (Finney and Kaye 2017; Romdhane et al. 2019). Likewise, varied cover crop planting date information helps us understand how cover crop establishment affects cover crop development and when weed competition occurs relative to cover crop establishment and the onset of winter rains.

Our objectives were to assess how different aspects of orchard cover crop management affect winter weed management. In two separate experiments, we evaluated how cover crop management systems, including factors like planting date and agronomic inputs, impact cover crop and weed emergence, biomass, and summer regrowth. Together, these research questions can provide information about the extent to which cover crops contribute to overall orchard floor vegetation management and which cover crop management practices have the largest effect on weed suppression.

Materials and Methods

We initiated two different experiments to separately examine the effects of intensified cover crop management systems and cover crop planting date in nut orchards. These small-plot experiments in research orchards used commercially relevant cultural practices, including tree spacing, tree strip management, and irrigation. The "intensification experiment" involved a range of cereal rye (*Secale cereale* L.) cover crop management intensities, from minimal management to an intensively managed forage intercrop, planted in a walnut orchard. The "planting date experiment" involved two different multispecies cover crop mixes each planted at early and late planting dates in an almond orchard. These experiments focused on plant population and community characteristics of orchard floor vegetation in the orchard alleys only.

Intensification Experiment

The intensification experiment was implemented in an established walnut orchard at the Plant Sciences Field Facility in Davis, CA, USA (38.540343°N, 121.793977°W). The orchard was planted in the spring of 2015 with 'Chandler' walnuts. The entire orchard was 0.7 ha in area consisting primarily of Yolo silt loam soils (fine-silty, mixed, superactive, nonacid, thermic Mollic Xerofluvents). Consistent with commercial practice in California, orchards were maintained with a vegetation-free strip at the base of the tree rows using directed applications of burndown and preemergence herbicides throughout the year as needed. These strips are important for protecting irrigation equipment, and this orchard was irrigated using one microsprinkler per tree. Cover crops were planted in the orchard alleys between tree strips and were not affected by the strip sprays.

The experiment was laid out as a randomized complete block design with four replications. Experimental plots included the orchard alley between seven pairs of trees, approximately 6 m by 40 m. Cover crop programs were based on cereal rye, because it is known to be a competitive, weed-suppressing species that has desirable termination characteristics (Barnes and Putnam 1983; Teasdale and Mohler 1993). Furthermore, this species thrives under various cultural management conditions and has cultivars that are well adapted to grow as a winter cover crop in central California. We used 'Merced' rye, which is sold commercially as a cover crop in California (Kamprath Seed Company, Manteca, CA 95337). This variety is taller than varieties for used for grain, which increases its competitive potential as a cover crop.

The experiment was conducted in one orchard over two growing seasons. Cover crops were established in the fall of each year, on November 11, 2019, and November 9, 2020, and terminated in the spring of each study year, on April 24, 2020, and April 9, 2021. Each plot received the same cover crop management program in both years of the experiment. Except for the forage treatment (described later), cereal rye was direct planted with a seed drill at 22.5 kg planted ha^{-1}, and cover crop termination was performed with a flail mower. Planting and termination operations were planned to minimize equipment traffic in the orchard, and only one tractor pass was made across each orchard alley at each planting and termination date. Flail mowers are practical for cover crop termination in California, as these implements are extremely common on large California farms and finely chop cover crop residues, which is important for achieving a smooth orchard floor ahead of nut harvest.

We had five treatments that represented a range of different cover crop management intensities. The "sprayed" treatment was used as our nontreated control, and the cereal rye planted in these plots was terminated with a glyphosate application when cereal rye plants reached 5 to 10 cm in height. These burndown applications occurred on January 13, 2020, and January 12, 2021, and included a broadcast application of Roundup WeatherMax® (Bayer Crop Science, St Louis, MO, USA) at 868 g ae ha^{-1} (1.607 L product ha^{-1}) with a CO_2-propelled backpack sprayer. The backpack sprayer included a four-nozzle boom equipped with AIXR11002 nozzles (TeeJet Technologies, Glendale Heights, IL, USA) on 50.8-cm spacing and applied at a ground speed of 3.2 km h^{-1}. This treatment mimics a relatively intense commercial management system in which orchard alleys are kept weed free. The "standard" treatment included cereal rye with no other cover crop management until termination. The "multispecies" treatment included the base planting of cereal rye and several additional cover crop species. The other cover crop species in the mix were common vetch (*Vicia sativa* L.) at 4.5 kg planted ha^{-1}, 'PK' berseem clover (*Trifolium alexandrinum* L.) at 4.5 kg planted ha^{-1}, daikon radish (*Raphanus sativus* L.) at 2.25 kg planted ha^{-1}, and 'Braco' white mustard (*Sinapis alba* L.) at 2.25 kg planted ha^{-1}. These seeds were broadcast using a belly spreader immediately before cereal rye was planted. We used these methods to establish the sprayed and multispecies treatments to minimize logistical challenges and orchard traffic, while also relying on the tractor and seed drill to enhance seed-to-soil contact of our additional cover crop species in the multispecies treatment. The multispecies treatment in this experiment has the same species and approximate planting rates as the multispecies mix in the planting date experiment described later.

The "boosted" treatment included a 45 kg ha^{-1} N top-dress with granular urea after cereal rye tillering, which was made on February 25, 2020, and February 26, 2021. The "forage" treatment was managed as a cereal rye hay intercrop. This treatment was planted at a rate of 45 kg planted ha^{-1}. At planting, we fertilized with 40 kg ha^{-1} N and 28 kg ha^{-1} P as granular urea and monoammonium phosphate at planting. We also top-dressed with 45 kg ha^{-1} N after cereal rye tillering. On the same day as top-dressing, we broadcast-applied carfentrazone (Shark EW, FMC Corporation, Philadelphia, PA, USA) at 16 g ai ha^{-1} (73 ml product ha^{-1}) with a backpack sprayer as a postemergence herbicide application for broadleaf weed control. The backpack sprayer included a four-nozzle boom equipped with XR11002-VS nozzles on 50.8-cm spacing and applied at a ground speed of 3.2 km h^{-1}. The top-dressing and herbicide applications were applied on February 25, 2020, and February 26, 2021. The forage treatment was terminated with a swather, and the crop material was subsequently baled and removed.

Immediately before cover crop termination, we destructively sampled cover crop and weed biomass. We collected biomass samples from two random 0.25-m^2 quadrat subsamples in each plot. Cover crops and weeds were separated before being dried in forced-air drying ovens at 60 C. Finally, we weighed dry plant biomass. Summer weed emergence was assessed after cover crop termination using point intercept transects. One transect was placed diagonally across the alley in each plot. Transects were 25-m long with 25 points spaced evenly along the transect. Plants were identified visually at each point. These summer weed transects were performed on June 17, 2020, and May 21, 2021, when summer weed emergence and potential cover crop regrowth might be scouted by a grower planning summer weed management.

Planting Date Experiment

The planting date experiment was implemented in a nonbearing almond orchard at the Wolfskill Experimental Orchard near Winters, CA, USA (38.504788°N, 121.978657°W). The orchard was established in the fall of 2017 with alternating rows of 'Nonpareil' and 'Aldrich' almonds. The entire site was about 1.1 ha in area with primarily Yolo loam soils (fine-silty, mixed, superactive, nonacid, thermic Mollic Xerofluvents). Orchard management included commercial-standard microsprinkler irrigation and weed-free tree strips treated with preemergence herbicides, as in the walnut orchard described earlier.

The experiment was laid out as a randomized complete block design with five replications. Experimental plots were roughly 25-m long and 12-m wide, comprising five trees in length and two orchard alleys in width. We had five treatments, including a nontreated control and two multispecies cover crop mixes each planted at two different planting dates. The nontreated control underwent commercial standard vegetation management practices, which included several glyphosate applications throughout the winter months. We used cover crop mixes in this experiment because of their existing use by California orchard growers (Ingels et al. 1994). Orchard growers frequently choose among cover crop mixes that support a variety of ecosystem services aside from vegetation management, such as pollinator health or improved soil structure, and multispecies cover crops can support some of these multifunctionality goals. Additionally, using different cover crop mixes allowed us to evaluate cover crops with different germination timings and a range of emergence phenologies.

The two cover crop mixes used in this study were a "multispecies" mix and a "brassica" mix. The multispecies mix used the same species as the multispecies treatment in the intensification study, and it included a common combination of cover crop functional groups, including a small grain, legumes, and mustards (Altieri et al. 2011). The mix consisted of 10% Braco white mustard, 10% daikon radish, 30% Merced rye, 20% PK berseem clover, and 30% common vetch planted at 56 kg planted ha^{-1}. The brassica mix is used commercially in California through the Project *Apis m.* (Salt Lake City, UT, USA) Seeds for Bees program. It consisted of 35% canola (*Brassica napus* L.), 15% Braco white mustard, 15% 'Nemfix' yellow mustard [*Brassica juncea* (L.) Czern.], 20% daikon radish, and 15% common yellow mustard (*Sinapis alba* L.) at 9 kg plant ha^{-1}.

Each of the cover crop mixes was planted at a relatively early planting date and a late planting date. These dates were chosen to represent a timely cover crop planting soon after nut harvest and coincident with the onset of winter rains as well as a later cover crop planting coincident with pruning, sanitation, and other winter management activities. This experiment was conducted in one orchard over three growing seasons. The early planting date occurred on October 15, 2018, October 24, 2019, and November 9, 2020. The late planting date occurred on January 31, 2019, February 10, 2020, and January 21, 2021. Cover crops were direct seeded with a conventional grain drill. Ground preparation occurred before each planting date. Before the early planting date, the whole orchard (i.e., all treatments) received light tillage immediately before a glyphosate burndown. Before the late planting date, late-planted plots and the nontreated control received an additional glyphosate burndown but no additional soil disturbance. This burndown application was made with a boom sprayer mounted on an four-wheeler using commercial standard practices as determined by farm managers at our field site. Cover crops were terminated with a flail mower on April 19, 2019, April 27, 2020, and April 22, 2021.

Weed emergence was monitored throughout the cover crop growing season using permanent point intercept transects. Each plot had one transect placed diagonally across one orchard alley. Each transect was 10-m long with 10 points along the transect. Plants were identified at each point along the transect, and monitoring took place weekly while cover crops were growing. This experiment did not have different residue management treatments, so summer weeds were not evaluated. Immediately before cover

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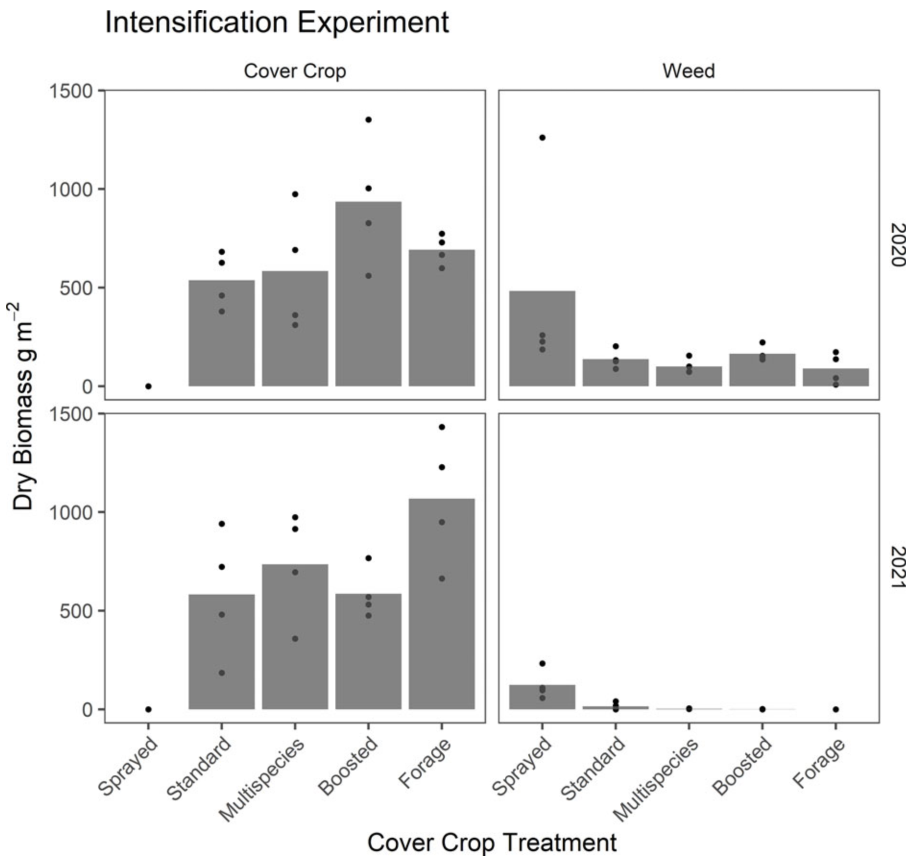

Figure 1. Cover crop and weed biomass across a range cover crop management intensities. Bars represent the mean value of points. The sprayed treatment was planted with a cover crop but treated with a postemergence herbicide following cover crop emergence and served as a nontreated control. The LSD for crop biomass was 324.6 g m^{-2} in 2020 and 376.2 g m^{-2} in 2021. The LSD for weed biomass was 357.5 g m^{-2} in 2020 and 52.6 g m^{-2} in 2021.

crop termination, we sampled cover crop and weed biomass using the methodology described earlier, including two 0.25-m^2 quadrat subsamples in each plot, with one subsample placed randomly in each of the two alleys in each plot.

Data Analysis

Analyses were performed in R v. 3.0.3 (R Core Team 2020). For biomass data from both experiments, we used ANOVA and performed multiple comparisons with Fisher's LSD. ANOVA was performed by specifying a model with *lm* and entering it into *Anova* from the CAR package (Fox and Weisberg, 2019). The models we used had treatment, replicate, and their interaction as predictors and either weed biomass or cover crop biomass as a response variable. We inspected ANOVA assumptions visually using *plot*. Subsequently, weed biomass from the intensification experiment was analyzed with one outlier removed, which we identified visually in the quantile-quantile plot, and a square-root-transformed response variable due to leptokurtosis. However, unabridged and nontransformed data are displayed in the figures. Finally, we performed Fischer's LSD with *LSD.test* from AGRICOLAE using a significance level of $P < 0.05$ (Mendiburu 2020). Summer weed emergence data were analyzed in the same manner but using cover crop regrowth and summer weed emergence as response variables.

Weekly transect surveys were analyzed with multiple linear regression. We compared the slope of each regression line to evaluate the relative rates of weed and cover crop emergence after each plant date. Cover crop emergence was represented as the change in ground cover as observed in weekly observations throughout the first 10 wk following the respective planting date of each treatment. There was only one nontreated plot in each replication, and we evaluated groundcover following both the early and late planting dates in the same nontreated plots. Weed emergence and cover crop emergence were modeled as functions of treatment, weeks after respective planting, and their interaction. These linear models were created using *lm*. We created additional linear models using other possible combinations of predictor variables and compared these various models using *anova*. Using these comparisons, we determined the model described above to be the most parsimonious based on having the fewest number of predictor variables while explaining similar amounts of variation as more complex models. Parameter estimates for the slope of each line were compared with Tukey's HSD using *lstrends* from the EMMEANS package (Lenth 2021). All figures were made with GGPLOT2 (Wickham 2016).

Results and Discussion

In the intensification experiment, cover crop biomass varied with management treatment ($P < 0.001$; Figure 1). While year was not a significant predictor of cover crop biomass ($P = 0.551$), we detected an interaction between year and treatment ($P = 0.058$). Furthermore, multiple comparison testing led to different conclusions from each year of the intensification experiment. With data pooled across years, the forage and boosted treatments resulted in higher cover crop biomass than multispecies or standard

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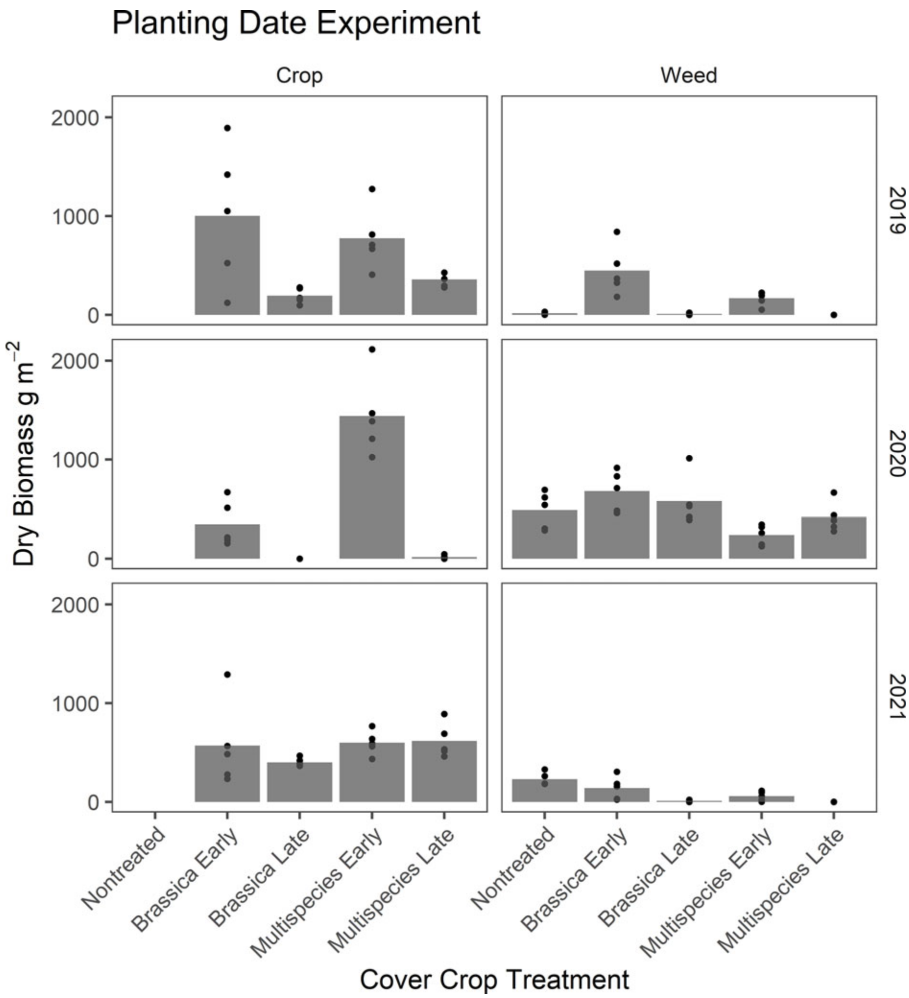

Figure 2. Cover crop and weed biomass associated with two multispecies cover mixes each planted at timely and delayed planting dates. Bars represent the mean value of points. The LSD for crop biomass was 521.0 g m^{-2} in 2019, 317.4 g m^{-2} in 2020, and 320.4 g m^{-2} in 2021. The LSD for weed biomass was 154.1 g m^{-2} in 2019, 244.3 g m^{-2} in 2020, and 83.9 g m^{-2} in 2021.

treatments. Within each year, the boosted treatment alone resulted in the highest cover crop biomass in 2020, while the forage treatment did so in 2021. Cover crop treatment ($P < 0.001$) and year ($P < 0.001$) both predicted weed biomass, as did the interaction term ($P = 0.035$). We observed major populations of Italian ryegrass [*Lolium perenne* L. ssp. *multiflorum* (Lam.) Husnot], annual bluegrass (*Poa annua* L.), and California burclover (*Medicago polymorpha* L.) for winter weeds, and field bindweed (*Convolvulus arvensis* L.), prostrate knotweed (*Polygonum aviculare* L.), and prostrate spurge [*Chamaesyce prostrata* (Aiton) Small; syn.: *Euphorbia prostrata* Aiton] for summer weeds.

In general, the four cover crop programs resulted in less weed biomass compared with the sprayed treatment and similar weed biomass compared with each other. This conclusion was supported in both years of the study, but we observed less weed biomass overall in 2021. Intensified cover crop programs can increase cover crop biomass, but all of the cover crop programs we tested were similarly effective at reducing weed biomass. Some cumulative effect of 2 yr of cover cropping could have contributed to these differences between study years.

In the planting date experiment, cover crop biomass varied with cover crop treatment ($P < 0.001$; Figure 2). Year was not significant ($P = 0.356$), but the interaction between treatment and year was ($P < 0.001$). In 2019 and 2020, the early-planting treatments resulted in higher cover crop biomass than the late-planting treatments. Differences between cover crop treatments were greatest in 2020, and the multispecies mix also resulted in greater cover crop biomass compared with the brassica mix in this year. There were no differences in cover crop biomass between treatments in 2021. Year ($P < 0.001$), treatment ($P < 0.001$), and their interaction ($P < 0.001$) all contributed to weed biomass. While we observed year-to-year variation, the late-planted multispecies treatment was consistently in the lowest statistical group for weed biomass, and the early-planted brassica treatment was consistently in the highest group. We observed populations of the winter weeds hare barley [*Hordeum murinum* L. ssp. *leporinum* (Link) Arcang.], whitestem filaree [*Erodium moschatum* (L.) L'Hér. ex Aiton], and *P. annua*.

Based on the planting date experiment, early cover planting results in a consistently more abundant cover crop. Winter rainfall is increasingly variable in California, and the late planting date subjects the cover crop to additional uncertainty in rain timing and quantity. This issue was evident in 2020, when the late cover crop planting had to be delayed due to wet conditions in January but subsequently received little rainfall after planting and ultimately produced relatively low biomass. The late planting date sometimes

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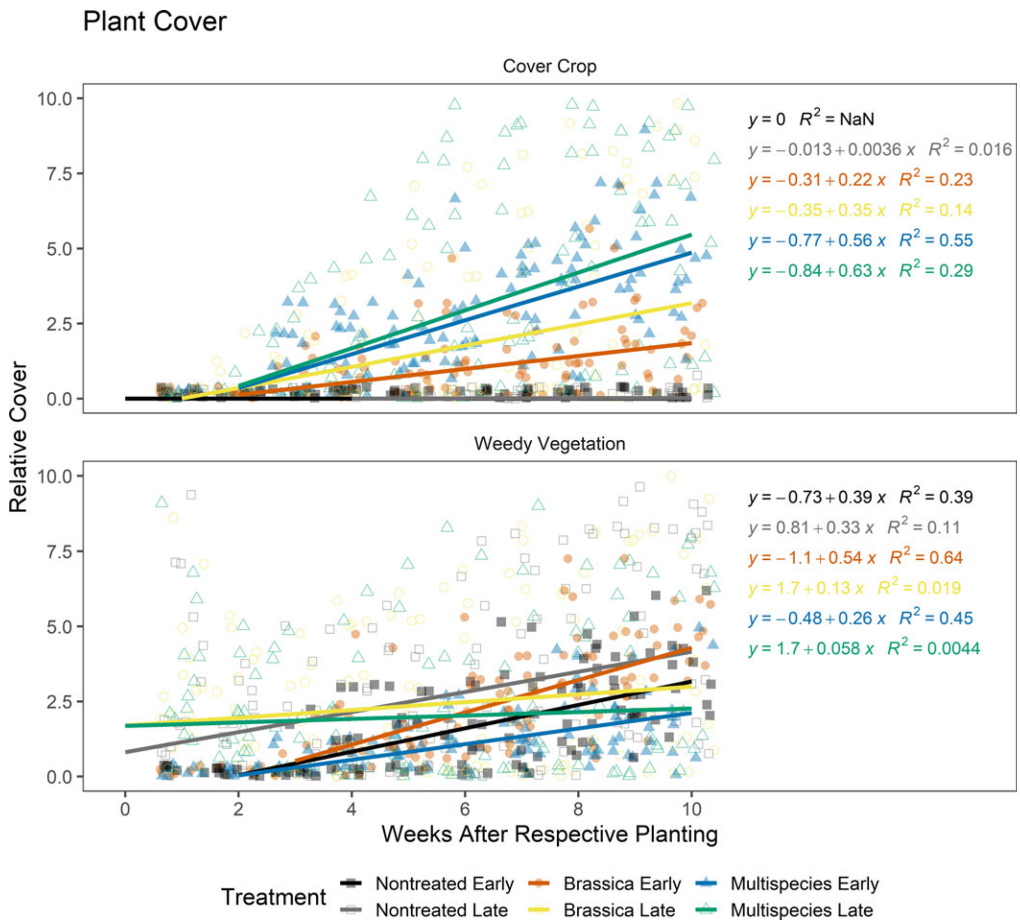

Figure 3. Rates of cover crop and weed emergence, expressed as changes over time in relative groundcover after respective cover crop planting date. Relative cover is based a range from 0 (no ground coverage) to 10 (complete ground coverage). Regression lines were created with linear regression.

was associated with reduced weed biomass, which we attribute to the extra burndown herbicide treatment ahead of late planting. While an extended cover crop growing season may contribute to cover crop abundance and consistency, it also precludes other weed management practices and therefore effectively extends the weed growing season. Likewise, the multispecies cover crop had more consistent biomass compared with the brassica cover crop across year and planting date, but this was not always reflected in consistent reductions in weed biomass.

The multispecies cover crop mix emerged more quickly than the brassica mix, and this effect was similar following both the early and late planting dates (Figure 3). This effect could be related to certain component species in the multispecies mix that were particularly quick to emerge. In nontreated plots, where cover crops were not planted, weed emergence rates were similar after both early and late planting dates. However, when cover crops were present, weed emergence was generally slower after the late planting date, especially in plots seeded with the brassica mix. Weed emergence rates after the late planting could have been affected by existing weed cover at time of late planting, due to continuous weed germination and a slow-acting burndown herbicide before the late planting date. Variations in weed emergence could additionally contribute to reductions in weed biomass from late-planted treatments. Overall, the multispecies cover crop had faster emergence than weedy plants, and the brassica cover crop had similar emergence rates compared with weedy vegetation. However, quicker emergence did not always lead to enhanced weed suppression, which is consistent with previous studies that suggest that biomass, rather than multifunctionality, is the most important factor in weed suppression (Smith et al. 2020). While cover crop mixes did not reliably slow weed emergence in this study, their germination uniformity and predictable emergence could make them a useful management tool compared with less predictable weedy vegetation.

Summer weed cover was affected by cover crop treatment in the intensification experiment ($P < 0.001$; Figure 4). The sprayed and forage treatments had similarly increased levels of summer weed coverage compared with the three cover crop treatments that left residues in place, which were similar to one another. These results indicate that cover crop residues suppress summer weed emergence compared with treatments without any cover crop or where cover crop residues have been removed through baling. Existing literature on cover crops in annual cropping systems supports the value of cover crop residue for reducing summer weed emergence (Bybee-Finley et al. 2017; MacLaren et al. 2019). In perennial systems, the spatial separation of the cover crop from the primary crop provides additional options for cover crop termination, including flexibility related to timing, repeated termination actions, and termination equipment.

We used the different orchards as a study system but did not intensively monitor orchard crop performance or yield. We acknowledge that some differences exist in orchard floor light

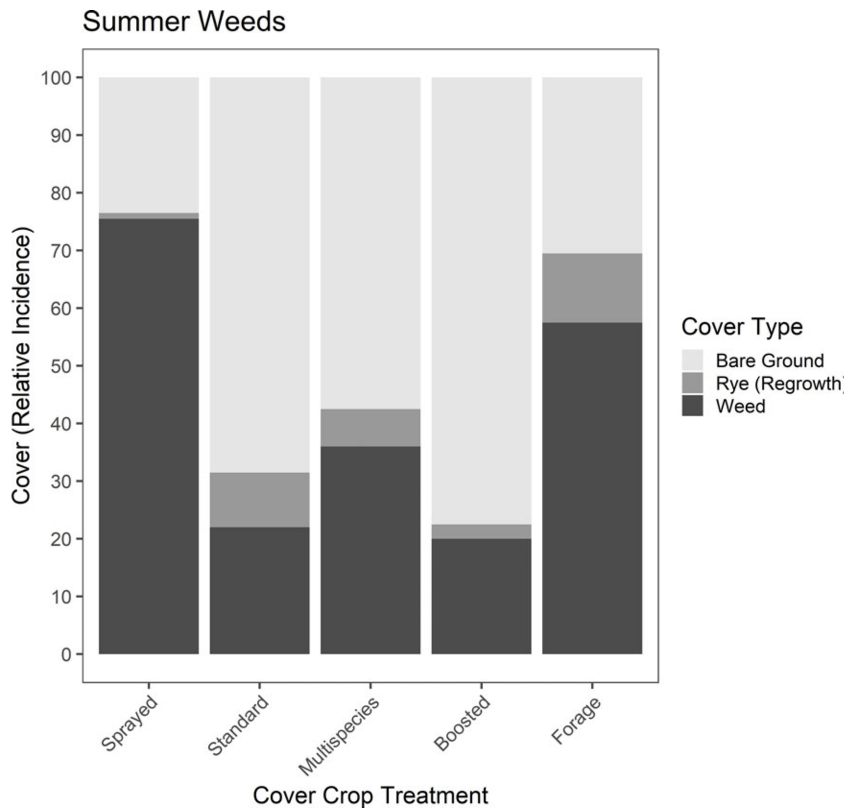

Figure 4. Summer weed emergence following cover crop termination across several levels of cover crop management programs. The sprayed treatment was planted with a cover crop but sprayed with a burndown herbicide following cover crop emergence and served as a nontreated control with no cover crop residue. The standard, multispecies, and boosted treatments were all terminated with flail mowing, while the forage treatment had residues removed. Cereal rye was associated with cover crop regrowth. Cover crop incidence is a range from 0 (no ground coverage) to 100 (complete ground coverage). The least significant difference was 4.5 points of relative cover.

availability between the systems. Namely, almonds maintain a leafy canopy for a greater portion of each year, but the almond orchard in this study was younger, with a smaller tree canopy compared with our older walnut orchard. However, the orchard floor environment is generally similar in almond- and walnut-cropping systems, and each has similar cultural factors, including irrigation, alley and strip management, and winter pruning and pest management operations. For cover crops to be a feasible management strategy, they should work in a variety of orchard systems, conditions, and life cycle stages. Therefore, understanding how cover crops influence vegetation management across different orchards is a key aspect of this study. The intensification and planting date experiments were managed independently of one another, but there is a shared treatment to facilitate comparisons between the experiments.

In this study, we observed that cover crops are not consistently effective as a weed control tool compared with weed management programs with repeated herbicide applications, but they continue to demonstrate value as component of an orchard vegetation management program. Such vegetation management programs allow some plant growth on the orchard floor but result in predictable plant cover and favorable orchard floor conditions for nut harvest. Orchard cover crops flourished under a variety of management programs but were most abundant with timely planting and adequate moisture during establishment. We worked in orchards that had not previously been managed with cover cropping, and any effects of cover crops on weeds could compound over the life cycle of orchard, possibly mediated through processes like depletion of weed seedbanks or weed community filtering. Increased understanding of the broader contributions to ecosystem services, such as soil health and agroecosystem resilience, can enhance the benefit of cover crops and make them an attractive component of integrated orchard management systems. Future research could focus on these underexplored aspects of cover crop management in perennial cropping systems, such as by focusing on high-residue termination methods such as roller-crimpers or delayed cover crop termination in the early summer.

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