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Functionally diverse cover crops support ecological weed management in orchard cropping systems

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Research Paper

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Abstract

Diverse agricultural management practices are critical for agroecosystem sustainability, and cover crops provide opportunity for varied management and increased biodiversity. Understanding how cover crops fill open ecological niches underneath the trees, interact with weeds, and potentially provide ecosystem services to decrease pest pressure is essential for ecological agricultural management. The goal of this study was to test the weed suppression potential of two cover crop treatments with varied functional diversity compared to standard weed management practices in commercial almond orchards in California. Transect plant surveys were used to evaluate orchard plant communities under a functionally diverse seed mix including grasses, legumes, and brassicas, and a relatively uniform cover crop mix that included only brassica species. Winter annual orchard cover crops reduced bare ground from 39.3% of total land area to 15.9 or 11.4%, depending on treatment. Furthermore, winter cover crops displaced weeds with a negative correlation of 0.74. The presence of cover crops did not consistently affect weed community composition for low-richness weed communities found in California orchards. Diverse cover crop mixes more reliably resulted in increased ground cover across site years compared to uniform cover crop mixes, with coefficients of variation for ground cover at 49.6 and 91.5%, respectively. Cover crops with different levels of functional diversity can contribute to orchard weed management programs at commercial scales. Functional diversity supports cover crop establishment, abundance, and competitiveness across varied agroecological conditions, and cover crop mixes could be designed to address an assortment of orchard management concerns.

Introduction

Cover cropping is a management strategy which adds potentially beneficial biodiversity to agroecosystems. Depending on specific cover crop management practices (Bergtold et al., 2019), farmers may leverage planned biodiversity to enhance regulating ecosystem services (Beillouin et al., 2021; McClelland, Paustian, and Schipanski, 2021; Tamburini et al., 2020), increase cropping system resilience (Reiss and Drinkwater, 2018; Renwick et al., 2021), reduce agricultural externalities, and support sustainable intensification (Wittwer et al., 2017). In particular, cover crops can increase beneficial insect populations (English-Loeb et al., 2003), reduce pest insect populations (Bugg, 1992; Bugg and Waddington, 1994), support several aspects of soil health (Romdhane et al., 2019; Unger and Vigil, 1998), reduce soil erosion (Novara et al., 2011), reduce pollutants in agricultural runoff (Dabney, Delgado, and Reeves, 2001), increase crop yield stability (Gaudin et al., 2015), increase farm profitability (Correia et al., 2015), sequester atmospheric carbon (Novara et al., 2019), and otherwise increase the ecological value of farmland.

Whereas a large body of research has rigorously addressed the ecological impacts of annual cover crops grown in the fallow period between two annual cash crops (e.g., Teasdale, Beste, and Potts 1991), there is less information about cover crop impacts in perennial systems. In contrast to cover crops in annual cropping systems, orchard cover crops are grown under the tree canopy and rely on spatial separation to avoid competition with the main cash crop. Cover crops have demonstrated impacts on abiotic factors in perennial systems, including improving soil structure (Ramos et al., 2010; Walsh et al., 1996), increasing soil nutrition (Sánchez et al., 2007), increasing water use (Monteiro and Lopes, 2007), and reducing orchard temperature (O'Connell and Snyder, 1999). More research is needed to fully understand how the biotic functioning of orchard cover crops affects horticultural management.

Such research would support ecological systems-based approaches to agricultural sustainability, such as integrated pest (or weed) management, which rely on biodiversity and regulating ecosystem services to support multiple aspects of the agroecosystem (Haring, 2021). Integrated pest management highlights the practical importance of basic ecological knowledge. For example, weeds can indicate the absence of unfilled ecological niches within the orchard system (Smith, Mortensen, and Ryan, 2010). Therefore, reducing available ecological niches (such as by planting predictable, domesticated plants that reduce resource availability) could displace weeds (Kruidhof, Bastiaans, and Kropff, 2008; Mirsky et al., 2011), suppress herbicide-resistant weeds (Bunchek et al., 2020; Pittman, Barney, and Flessner, 2019), and provide additional sustainability benefits (Liebman and Davis, 2000). Whereas conventional orchards have significant unused resource pools that lead to the need for intensive vegetation control, cropping systems with diverse ground covers limit weed proliferation by regulating resource availability and safe sites for seed germination (Adeux et al., 2019).

Winter annual cover crops have a life cycle that is coincidental with winter rains in Mediterranean climates as well as the dormant period of deciduous orchard trees (Baumgartner, Steenwerth, and Veilleux, 2008; Bugg et al., 1996; DeVincentis et al., 2022). This phenology allows winter annual weeds to have significant temporal niche differentiation compared to the orchard crop while allowing exploitative competition between cover crops and orchard weeds. Other forms of interference, such as allelopathy or suppression of summer weed germination with cover crop residues (Creamer et al., 1996; Putnam, Defrank, and Barnes, 1983) may also be regulating weed suppression potential of cover crop communities. The relative contribution of these mechanisms varies seasonally and over the life cycle of the orchard as changes in resource availability often alter the phenology of competition (Pearson, Ortega, and Maron, 2017).

Life cycle is just one example of many functional traits that affect how the functional ecology of a cover crop species can support weed suppression, and other functions such as nutrient acquisition or germination ecology could be critical (Smith and Gross, 2007). Many researchers have investigated the performance of cover crop mixes based on the functional traits of component species (Haramoto and Pearce, 2019; Kaye et al., 2019; McKenzie-Gopsill et al., 2022; Ramírez-García et al., 2015; Smith, Atwood, and Warren, 2014; Trichard et al., 2013). By combining multiple species with complementary functional traits that match specific management goals, multispecies cover crops can enhance the resilience of an agroecosystem while providing several ecosystem services. Studies in unmanaged ecosystems likewise highlight the importance of diverse, multifunctional plant communities for reducing invasibility through mechanisms like niche differentiation (e.g., through resource partitioning and phenological differences) and variation in developmental biology and phenotypic plasticity (Levine and D'Antonio, 1999; Naeem et al., 2000; Tilman, Wedin, and Knops, 1996).

Despite a growing body of research on the functional ecology of multispecies cover crops, the relationships between cover crop species in a mix are frequently distinctive and unpredictable (Stefan, Engbersen, and Schöb, 2021). There remains uncertainty in how these patterns emerge at scales relevant to intensive, commercial agricultural given increased disturbance and decreased species richness in such systems (Bybee-Finley, Mirsky, and Ryan, 2017; Smith, Warren, and Cordeau, 2020). More practical and hands-on information about the functional diversity of multispecies cover crop mixes at large scales could improve how orchard managers employ complementarity to design species mixes that balance multiple management goals. This study aims to fill a critical knowledge gap in understanding the ecological effects of multispecies cover crops when they are integrated into existing large-scale, intensified orchard cropping systems.

Our goal for this study was to determine how cover crop mixes with different levels of diversity perform within existing orchard management systems, and our experiment and analyses were selected to focus on plant communities across a range of variable, real-world conditions found in commercial almond orchards. We hypothesize that both functionally uniform and diverse cover crop mixes can provide living ground cover that displaces weeds, but that functionally diverse cover crops will emerge and compete for resources more consistently across growing seasons and locations and are therefore better able to impact weed community composition. To evaluate these hypotheses, we examined four indicators of cover crop function: (1) area of bare ground underneath cover crops and weedy resident vegetation, (2) relative ground cover of cover crops and weeds, (3) stability of ground cover provided by cover crops over space and time, and (4) impacts on weed communities.

Materials and methods

We evaluated plant communities under two multi-species cover crop mixes, one that is functionally diverse and one that is functionally uniform, over two seasons in three commercial almond (*Prunis dulcis* (Mill.) D.A. Webb) orchards in the Central Valley of California. We used two different cover crop mixtures that were designed to fulfill different agroecological goals within almond orchards. Namely, we used a mix with high functional diversity that is used commercially for improving soil structure and limiting soil erosion because its constituent species come from plant families with contrasting root architecture among other characteristics, as well as a mix with lower functional diversity that is used for providing floral resources to foraging pollinators with species from one plant family that have overlapping flowering phenology. We evaluated their impact on weed population density and species communities across a wide geographical area in central California.

Experimental design and management

We created replicated, large-plot experiments in commercial almond orchards in Tehama, Merced, and Kern Counties in California (Table 1). These locations span nearly 600 km in the Central Valley of California. This region produces over 99% of the almonds in the United States (Anonymous, 2020). The experiment used a randomized block design with four replicates of three or four different ground cover treatments at each site. Ground cover treatments were implemented for two years on the same plots, beginning in the fall of 2017 and ending in the late summer of 2019 (Table 2). These treatments represented commercial-standard management practices and two different five-species cover crop mixes with different levels of functional diversity. Plots were 25.5 m wide at each site, encompassing four orchard alleys and three tree rows with another tree row between plots. In the perpendicular direction, plots extended the entire length of the orchard (195 m at the Tehama site, 385 m at the Merced site, and 320 m at the Kern site).

The study was designed to use commercially relevant spatial and temporal scales, and orchard management was determined by grower cooperators for agronomic relevance. All orchards were equipped with microsprinkler irrigation, and irrigation schedules were determined based on almond evapotranspiration models in accordance with local weather conditions and recommendations (Fereres and Goldhamer, 2003). Irrigation,

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Table 1. Description of the three commercial almond orchards used as experimental sites in this study

Site name	Location	Coordinates	Soils	Planted varieties	Establishment
Tehama	Corning, CA, USA	39°56′56.3″N, 122°07′36.5″W	Kimball loam (Mollic Palexeralfs)	50% 'Nonpareil', 50% 'Monterey'	2016
Merced	Atwater, CA, USA	37°23′54″N, 120°32′52″W	Alamo clay (Typic Duraquolls)	50% 'Nonpareil', 12.5% each 'Monterey', 'Fritz', 'Carmel', 'Wood Colony'	2008
Kern	Arvin, CA, USA	35°14′22″N, 118°47′15″W	Hesperia sandy loam (Xeric Torriorthents)	50% 'Nonpareil', 25% each 'Monterey', 'Fritz'	2006

Table 2. Description and dates of cover crop management actions at each of the three commercial almond orchards over two years in this study

Site-year	Cover crop establishment	Establishment method	Groundcover surveys	Termination mowing	Rainfall (mm)	Management notes
Tehama 2018	November 6, 2017	Drill seeded in 3.6 m swath down each alleyway	March 29, 2018	March 30, 2018	244	Young trees pruned in February 2018, and alternate alleys were subsequently mowed to mulch prunings; data were collected from unmowed alleys
Tehama 2019	November 9, 2018	Drill seeded in 3.6 m swath	March 22, 2019	May 25, 2019	577	Whole orchard mowed on January 29, 2019 for naval orangeworm (*Amyelois transitella* Walker, 1863) sanitation; data observed from cover crop regrowth
Merced 2018	November 2, 2017	Drill seeded in 3.6 m swath	March 30, 2018	April 9, 2018	140	First replicate of uniform mix not planted due to planting error
Merced 2019	December 21, 2018	Broadcast seeded with rotary spreader	March 15, 2019	March 19, 2019; April 12, 2019	288	Cover crop broadcast spread due to logistical issues and equipment availability
Kern 2018	October 30, 2017	Drill seeded in 4.8 m swath	March 27, 2018	April 2, 2018	122	Disk tillage to 150 mm depth prior to cover crop planting due to soil compaction concerns
Kern 2019	November 1, 2018	Drill seeded in 4.8 m swath	March 16, 2019	April 5, 2019	152	Disk tillage to 150 mm depth prior to cover crop planting due to soil compaction concerns

insecticide, fungicide, and fertilizer treatments and rates were determined by each grower and applied to the tree rows only. Tree rows were maintained with conventional herbicide programs to create vegetation-free zones at the base of trees. These herbicide applications were performed with shielded sprayers at each site, and we did not observe any herbicide injury that would indicate herbicide drift to the cover crops throughout the experiment. Each of the sites was subjected to regular traffic from machinery and farmworkers to complete normal orchard management operations throughout the cover crop growing season.

Ground cover treatments

Two different winter cover crop mixes were planted in orchard alleyways and compared against two different control treatments that reflect mainstream orchard vegetation management programs (Table 3). These cover crop mixes were selected because of their current commercial availability in California and their contrasting functional diversity. Both mixes have the same number of species but represent different levels of functional diversity, with the uniform mix having five quite similar species and the diverse mix having species from several plant families and contrasting biological characteristics. Each mix was established at rates and with methods based on recommendations from the seed supplier.

The 'uniform' mix consisted of five functionally similar species, and this mix is used commercially in California and distributed as 'PAm Mustard Mix' by the Project *Apis m.* (Salt Lake City, UT, USA) Seeds For Bees program because its component species provide abundant floral resources for pollinators but slightly different flowering phenologies. The 'diverse' mix consisted of five species from the grass, brassica, and legume groups that are commonly used together in functionally diverse cover crop mixes (Altieri et al., 2011) to support soil health by providing abundant biomass, multiple kinds of root architectures, and complementary resource needs.

The 'resident' vegetation treatment involved winter vegetation management primarily with mowing. The 'bare' treatment involved more intensive vegetation management, including one to two broadcast herbicide applications in the winter. For the bare treatment, herbicide applications timing and product choice were determined by grower cooperators but included broad spectrum herbicides without residual activity, which are common in California almond production, including glyphosate and glufosinate. The Tehama site included only the resident treatment due to the preference of our cooperator and to better reflect standard practices in this region of California which has more abundant winter rainfall. The Merced and Kern sites featured both the resident and bare treatments to better reflect high-intensity production systems in these regions.

Table 3. Description of the two cover crop and two commercial standard ground cover treatments evaluated in this experiment

Treatment name	Description	Planting rate (kg per planted ha)
Uniform	35% canola (*Brassica napus* L.) 15% 'Bracco' white mustard (*Sinapis alba* L.) 15% 'Nemfix' yellow mustard (*Brassica juncea* (L.) Czern.) 20% daikon radish (*Raphanus sativus* L.) 15% common yellow mustard (*Sinapis alba* L.)	9
Diverse	10% 'Bracco' white mustard 10% daikon radish 30% 'Merced' rye (*Secale cereale* L.) 20% 'PK' berseem clover (*Trifolium alexandrinum* L.) 30% common vetch (*Vicia sativa*)	56
Resident	Standard commercial practices for winter vegetation management, including repeated alley mowing and herbicides in tree strips	–
Bare	Intensive winter vegetation management, including broadcast herbicide applications in winter, as determined by grower cooperators	–

Data collection

Orchard alley plant communities were evaluated with point-intercept transects. Transect surveys coincided with cover crop flowering for most species as well as winter weed flowering for many endemic species in the study area (dates are in Table 2). Each plot was surveyed with a single 50 m long transect with points observed evenly at each meter along the transect, and observations from all 50 points were combined to estimate plant cover across each plot. Transects were placed in the same location in each plot, with the starting point located 75 m from the end of the plot and inside the second tree row from the side of the plot. Transects extended diagonally across a single orchard alley, starting and ending on opposite edges of the planted swath.

At each point along the transect, plant cover was observed for the top layer of vegetation as observed from above, which varied depending on the height of target species. The observed vegetation type (plant species or bare ground) was recorded. Plants were identified to species visually in the field, except in the case of the white and yellow mustards in the uniform mix which were identified as one operational taxonomic unit due to morphological similarities at the observed growth stage, and the observed plant species or bare ground was recorded. The total number of occurrences of each vegetation type along each transect were summed and converted to a percentage to estimate ground cover in each plot. Transects described plant community composition for each plot, as well as bare ground (the portion of each transect that was not covered by any kind of vegetation) and ground cover from cover crops or weeds (found by counting the number of occurrences of all of the species associated with each vegetation type).

Statistical analysis

Analyses were performed in R 4.2.3 (R Core Team, 2023). To evaluate the first objective (evaluating ground cover and reduction of bare ground), comparisons of bare ground among treatments were made with ANOVA. ANOVA assumptions were inspected visually with *qqPlot* from the *car* package (Fox and Weisberg, 2019). We detected a heavy tailed distribution and subsequently repeated the analyses using an arcsine square root transformed response variable as well as with a generalized linear model with a Poisson distribution. However, results were similar among the different analyses, and we display results from the untransformed ANOVA below. One outlier was identified with the Bonferroni outlier test using *outlierTest*. This outlier value was excluded from further analyses because it was collected in the same plot at the Merced site that had been previously excluded because it had not been planted in 2017 (i.e., no data from this plot from either study year were included). The model we used included these fixed effects as predictors: treatment, year, site, the interaction between year and site, and replicate nested within site. ANOVA was performed with *Anova* from the *car* package using type II sums of squares. Multiple comparisons were made with least-squares means using the *emmeans* package (Lenth, 2021).

For the second objective (evaluating tradeoffs in relative ground cover between cover crops and weeds), we evaluated the general relationship between cover crop and weed cover within cover crop treatments (i.e., not including the bare or resident treatments) across sites and years in this study. The relative ground cover from cover crops and weeds were modeled with the *lm* function in base R, and we used *Anova* for hypothesis testing. We used weed cover as the response variable and cover crop cover and cover crop treatment as predictors.

To evaluate the third objective (evaluating stability of cover crop cover over space and time), we assessed cover crop stability by comparing coefficients of variation for cover of each cover crop mix as pooled across sites and years in this study. Pooled coefficients of variation and their 95% confidence intervals were calculated with the *ci.cv* function in the *MBESS* package (Kelley, 2022) before they were compared with the modified signed-likelihood ratio test as implemented in the *cvequality* package (Marwick and Krishnamoorthy, 2019). These comparisons are based on recommendations by Reiss and Drinkwater (2018). For the final objective (evaluating impacts on weed communities), weed communities in the different cover crop treatments were analyzed with nonmetric multidimensional scaling (NMDS). We evaluated weed community groupings based on treatment, year, and site, as well as treatment and year within each site. NMDS was based on Bray–Curtis dissimilarity and was calculated using the *metaMDS* function in the *vegan* package (Oksanen et al., 2020). We evaluated grouping variables using *anosim*, also from *vegan*, with 9999 permutations.

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Results

Bare ground

Cover crop treatment ($F_{3,65} = 93.23$, $P < 0.001$), site ($F_{2,65} = 30.21$, $P < 0.001$), and their interaction ($F_{5,65} = 10.56$, $P < 0.001$) had significant effects on the amount of bare ground observed in orchard alleys, while year ($F_{1,65} = 1.34$, $P = 0.251$) and block ($F_{9,65} = 0.84$, $P = 0.582$) did not (Fig. 1). Overall, the uniform and diverse mixes resulted in similar levels of bare ground ($P = 0.289$), at 15.9 ± 3.09 and 11.4 ± 2.89%, respectively, when averaged across sites and years. These values are less than the 39.3 ± 2.89% bare ground in the resident vegetation treatment ($P < 0.001$ for both comparisons).

Within the Kern site, each of the cover crop treatments resulted in significantly different ($P = 0.003$) levels of bare ground from one another, with the diverse mix (6.0 ± 4.64%) resulting in less bare ground than the uniform mix (28.0 ± 4.64%). Within the Merced site, the diverse mix (25.0 ± 6.55%) resulted in a similar level of bare ground to both the uniform mix (14.8 ± 7.88%, $P = 0.332$) and the resident vegetation treatment (36.5 ± 6.55%, $P = 0.228$). The Tehama site had low levels of bare ground across all three treatments, which were similar to one another ($P > 0.25$ for all comparisons). Both cover crop mixes had somewhat differing performance within sites, but both cover crop mixes on average reduced bare ground compared to standard commercial management practices.

Weed and cover crop cover

Across this study, cover crop cover was negatively associated with weed cover (Fig. 2; slope = −0.74, $R^2 = 0.83$, $P < 0.001$). When including cover crop treatment as a predictor, we found that cover crop cover was significant ($F_{1,43} = 176.72$, $P < 0.001$) while cover crop treatment was not ($F_{1,43} = 0.35$, $P = 0.56$). Regardless of the cover crop mix, we observed that increased ground cover from cover crops resulted in reduced ground cover from weeds. This relationship was described by a line with a slope less steep than negative one, indicating that every increase in the cover crop canopy covered some amount of bare ground in addition to the displaced weed vegetation.

Cover crop stability

The coefficient of variation for cover crop cover from the diverse mix was 48.6%, significantly less variation than the 91.5% variation observed in the uniform mix (Fig. 3; $P = 0.035$). Across the experiment, the diverse mix resulted in more consistent levels of ground cover than the uniform mix, reliably creating ground cover across a range of geographical, environmental, and management-related variation.

Weed communities

The Tehama site had three to five times greater species richness than either of the other sites (Table 4). All the sites were

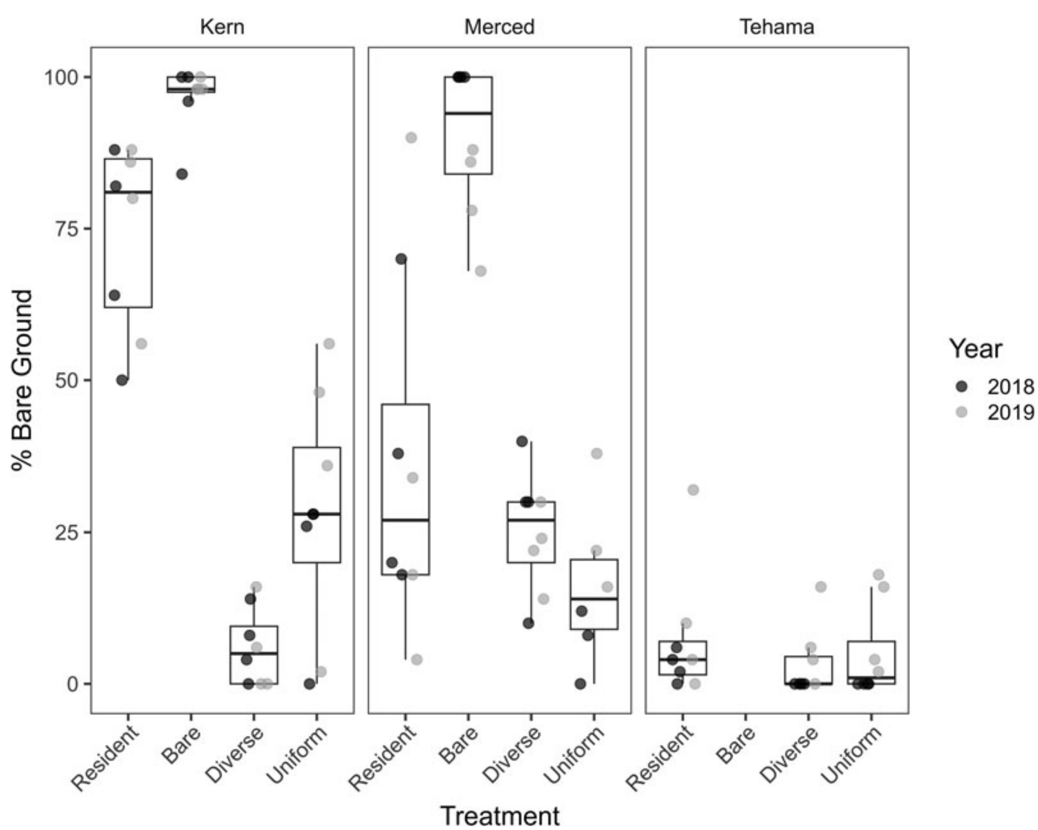

Figure 1. Impacts of various four cover crop treatments on amount of uncovered ground soils in orchard alleyways (2018 and 2019). Two cover crop mixes (one consisting of functionally diverse species and the other consisting of uniform species) were compared against two commercially standard orchard management treatments (a treatment accommodated some resident vegetation and a higher intensity treatment to maintain bare ground) in three commercial orchards in Kern, Merced, and Tehama Counties, California, USA (the bare treatment was not included at the Tehama County site). The center line represents median, hinges represent first and third quartiles, and whiskers represent minimum and maximum values within 150% of the interquartile range.

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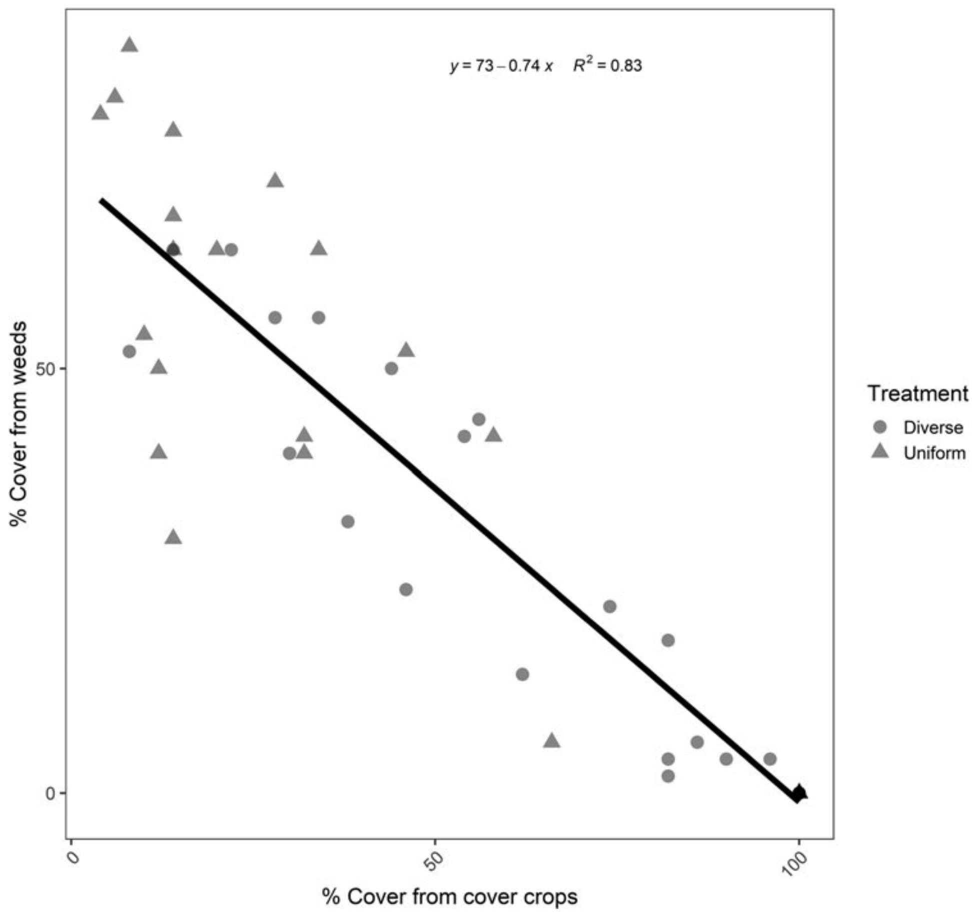

Figure 2. Relationship between cover crop and weed cover in orchard alleyways (2018 and 2019). The line displays marginal replacement of each vegetation type relative to the other as determined by a linear model. Point shapes represent two different cover crop species mixes (one consisting of functionally diverse species and the other consisting of uniform species), though cover crop treatment was not a predictor of weed cover ($P = 0.56$) and was not included in linear model displayed here.

dominated by small-statured, winter annual weed species such as annual bluegrass (*Poa annua* L.) and common chickweed (*Stellaria media* (L.) Vill.). The remainder of the species at all sites included both grass and broadleaf (dicotyledonous) species, with some additional summer annual and perennial species present at the Tehama site. Cover crops influenced weed communities but to different extents depending on the site and year. When using ANOSIM to test whether weed communities had similar constituent species (stress = 0.166), we found that weed communities were strongly associated with their site ($R = 0.569$, $P < 0.001$) and cover crop treatments ($R = 0.091$, $P = 0.005$). However, effect sizes were generally small and clusters can be difficult to identify visually when weed communities from each plot were plotted in nonmetric scaled space (Fig. 4). As described above, the differences between weed community diversity at each site were relatively clear, while there were few noticeable differences between weed communities in different cover crop treatments.

Because of the inherent differences between weed communities at each site, we also analyzed similarity of weed communities within each site individually. Weed communities were similar across years and treatments at Merced, and weed communities remained relatively sparse and homogenous throughout the experiment at that site (stress = 0.119). At the Tehama site, weed communities differed across years ($R = 0.981$, $P < 0.001$; stress = 0.150), which is logical given that cover crop establishment was very strong in 2018 to the point that we observed no weeds in the cover crop treatments that year. Weed communities differed with cover crop treatment at the Kern site ($R = 0.316$, $P < 0.001$; stress = 0.036), though we observed few qualitative differences in weed communities at the Kern site.

Discussion

Orchard cover crop mixes, as implemented in this study, were effective at establishing, reducing bare ground, and suppressing weeds. However, these effects were variable, and there is little evidence that the cover crop mixes we used had fixed impacts on the composition of orchard weed communities. Differences among sites, which could include climate and management factors, contributed to some of this variability. Our goal was to observe cover crops as they would be implemented by commercial almond growers in California, which entailed a variety of unique management decisions at each site. Growers will always implement some level of site-specific management that could affect cover crop performance, but it remains encouraging that cover crops that are sold and used commercially for different purposes could result in weed suppression across the three locations of the experiment. The diverse mix resulted in more consistent ground cover in this

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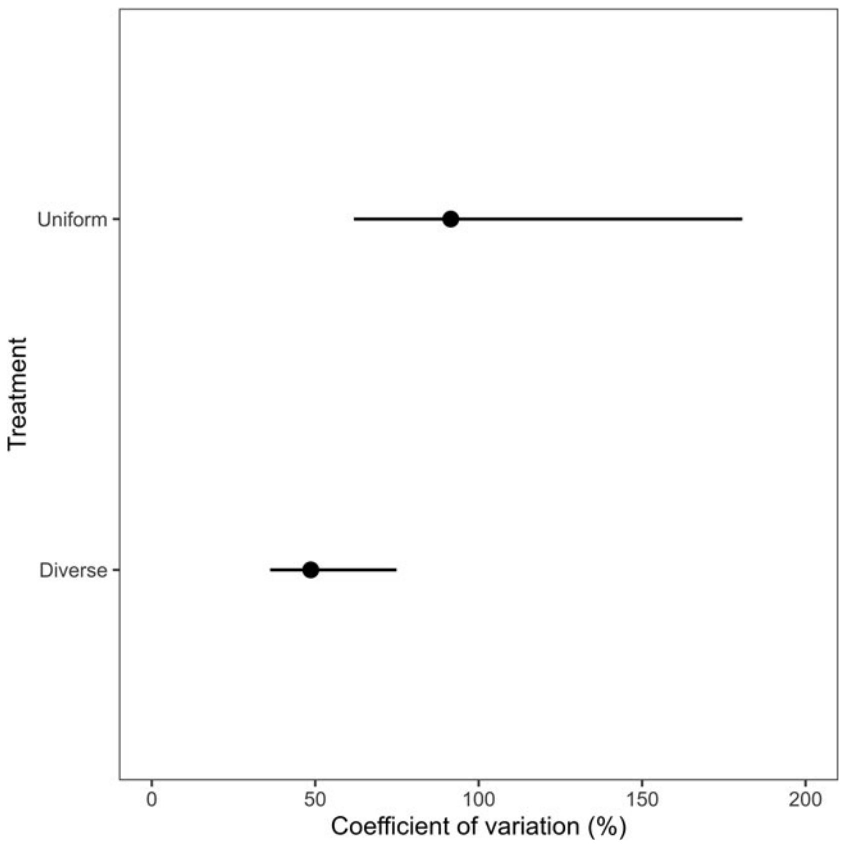

Figure 3. Stability of cover crop cover in orchard alleyways for two cover crop mixes (one consisting of functionally diverse species and the other consisting of uniform species) (2018 and 2019). Points show the average coefficient of variation across six site-years in this study, and bars show 95% confidence intervals. The diverse cover crop mix exhibited less variation in ground cover compared to the uniform mix ($P = 0.035$).

study, and ground cover led to greater weed suppression. However, cover crop cover, not the specific cover crop treatment, was the primary driver for weed suppression and other effects on weeds in this study.

Cover crop abundance

This study demonstrates the critical importance of cover crop abundance for weed competition. As hypothesized, the diverse cover crop mix more reliably created an abundant cover crop compared to the uniform cover crop mix. However, the diverse cover crop mix was not inherently more competitive, and both cover crop mixes suppressed weeds when abundant. The present study is currently the largest-scale study focusing on weed suppression and cover crop mixes in orchard systems and demonstrates that weed-suppressing cover crops can be integrated into existing commercial production systems.

The importance of cover crop abundance is consistent with numerous existing studies of weed suppressing cover crops in annual cropping systems (Bybee-Finley, Mirsky, and Ryan, 2017; Creamer et al., 1996; Florence et al., 2019; MacLaren et al., 2019; Smith, Warren, and Cordeau, 2020). It is important to note that these studies primarily observed plant abundance by measuring cover crop and weed biomass, while the present study came to a similar conclusion by measuring abundance through ground cover. While cover and biomass are distinct from one another, both are useful measures of plant abundance (Wright, 1991). The present study confirms through field experiments that ground cover is an important measure of cover crop abundance, which can support higher-throughput, non-destructive cover crop research compared to previous studies that rely on biomass collection.

Previous research has established that an abundant and competitive cover crop is likely to have features that contribute to

Table 4. Weed species found at each site over the course of the experiment

Site name	Observed species	Number of species
Tehama	*Poa annua* L., *Cichorium intybus* L., *Erodium cicutarium* (L.) L'Hér., *Erodium moschatum* (L.) L'Hér., *Anagallis arvensis* L., *Phalaris minor* Retz., *Plantago lanceolata* L., *Cynodon dactylon* (L.) Pers., *Convolvulus arvensis* L., *Medicago polymorpha* L., *Capsella bursa-pastoris* (L.) Medik., *Senecio vulgaris* L., *Stellaria media* (L.) Vill., *Ranunculus parviflorus* L., *Rumex crispus* L., *Lactuca serriola* L., *Taraxacum officinale* F. H. Wigg., *Erigeron canadensis* L., *Dichondra micrantha* Urb., *Geranium dissectum* L., *Sonchus oleraceus* L.	21
Merced	*Erodium moschatum*, *Poa annua*, *Avena fatua* L., *Medicago polymorpha*, *Stellaria media*, *Malva parviflora* L.	6
Kern	*Stellaria media*, *Poa annua*, *Capsella bursa-pastoris*, *Malva parviflora*	4

Species are listed in order of prevalence, based on the cumulative total number of observations at each site.

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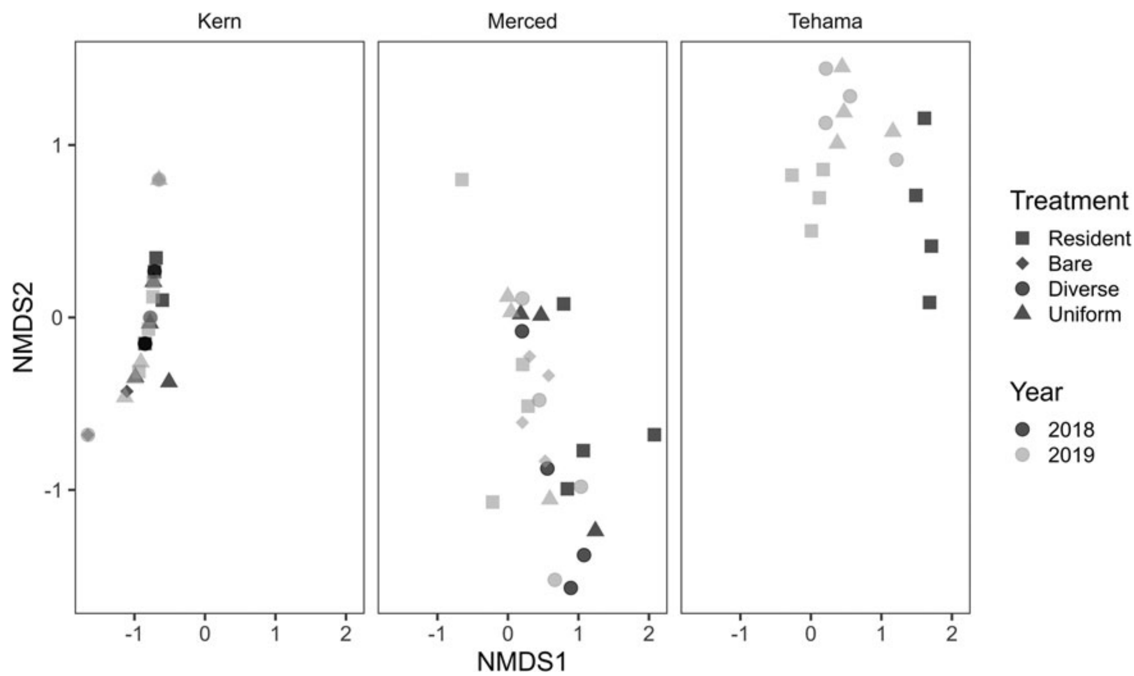

Figure 4. Ordination plots representing weed communities in orchard alleyways (2018 and 2019). Two cover crop mixes (one consisting of functionally diverse species and the other consisting of uniform species) were compared against two commercially standard orchard management treatments (a treatment accommodated some resident vegetation and a higher intensity treatment to maintain bare ground) in three commercial orchards in Kern, Merced, and Tehama Counties, California, USA (the bare treatment was not included at the Tehama County site). Plots were created with nonmetric multidimensional scaling. Each panel was created with from the same ordination analysis but displays points from only one site.

weed suppression as well as other ecosystem services. For example, large and abundant cover crops are effective in exploitative competition due to asymmetric resource acquisition, such as root competition for soil nutrients (Weiner, 1990). Large and abundant root systems can also improve soil structure and increase soil organic matter (Pierret et al., 2016) or create traps for pest insects while creating safe sites for beneficial insects (Hassanali et al., 2008). This abundance could also cause other challenges for orchard managers. For example, cereal rye was included in the multifunctional mix in this study and is known to be an important component species for weed suppression (Akemo, Regnier, and Bennett, 2000; Barnes and Putnam, 1983). However, large amounts of cereal rye residue are frequently reported by nut growers as a concern because of potential interference with on-ground nut harvest. While this experiment focused on winter management, and thus we did not evaluate almond yield, future development of orchard cover crops should aim to identify cover crop termination strategies that create acceptable conditions for nut harvest in the summer.

Cover crops and plant diversity

This study highlights that cover crop mixes with different levels of functional diversity can successfully support weed management across different orchard contexts. The addition of cover crop mixes in this study contributed significantly to orchard plant diversity, essentially doubling species richness in the mature orchards (Merced and Kern sites). Weed species richness was highest in the young orchard (Tehama site), where the orchard floor was relatively unshaded and still populated with many weed species carried over from the previous pasture system. This study implemented cover crops on a time scale relevant for adoption in contemporary orchards, but more research is needed to understand the cumulative effects of cover crop competition on weed community assembly over the decades-long lifespans of commercial orchards. Maintaining biodiversity is a major challenge for agroecosystems. While there is ongoing conflict between promoting functional diversity and achieving some vegetation management goals, this study reinforces the idea that cover crops are flexible tools that can support multiple management goals if planned appropriately (Crézé and Horwath, 2021; De Leijster et al., 2019; Mia et al., 2020).

Cover crop mixes in this study were primarily selected for their existing commercial uses, which are intended to address almond management goals other than weed suppression. In this study, the diverse mix provided functional diversity that led to more stability. We intentionally focused on the end performance of existing multifunctional cover crops, but optimization of cover crop mixes through agronomic management programs and additional species selection could improve weed suppression as well as other ecosystem services (Haring and Hanson, 2022). Multifunctional cover crop mixes could be improved by additional recognition of the specific ecological relationships between constituent species and their resulting agroecosystem services (Baraibar et al., 2018; Finney and Kaye, 2017; Ingels et al., 1994; Schipanski et al., 2014). Pest management is generally used to reduce biodiversity in cropping systems, but cover crops provide an opportunity to support pest management goals while simultaneously promoting biodiversity through functional vegetation management. Agricultural systems are designed to support ample plant growth, and this resource-rich environment could be more practical and efficient if it supported competitive, complementary, and useful biodiversity instead of unwanted weedy plants.

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Author contributions. All authors developed hypotheses, contributed to experimental design, and critically revised the manuscript. S. H. led field data collection, data analysis, and manuscript drafting. Stakeholders, including orchard growers and cooperative extension professionals, were included in project design and management, and specific parties are listed in the acknowledgements.

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