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Effects of Floor Vegetation and Fertility Management on Weed Biomass and Diversity in Organic Peach Orchards

Andrew S. Tebeau, Diane G. Alston, Corey V. Ransom, Brent L. Black, Jennifer R. Reeve, and Catherine M. Culumber*

Treerow vegetation abundance and biodiversity were measured in response to six orchard floor management strategies in organic peach in northern Utah for three growing seasons. A total of 32 weed species were observed in the treerow; the most common were field bindweed, dandelion, perennial grasses (e.g., red fescue and ryegrass), clovers, and prickly lettuce. Weed biomass was two to five times greater in unmanaged (living mulch) than in manipulated treatments. Tillage greatly reduced weeds for approximately one month; however, vegetation rebounded midseason. Tillage selected for species adapted to disturbance, such as common purslane and field bindweed. Straw mulch provided equivalent weed suppression to tillage in the early season. Straw required annual reapplication with material costs, labor, and weed-seed contamination (e.g., volunteer grains and quackgrass) as disadvantages. Plastic fabric mulch reduced weeds the most, but had high initial costs and required seasonal maintenance. Weed biomass declined within seasons and across the three years of the study, likely due to tree canopy shading. Neither birdsfoot trefoil nor a perennial grass mixture planted in the alleyways influenced treerow weeds. Our results demonstrate several viable alternatives to tillage for weed management in treerows of organic peach orchards in the Intermountain West.
Nomenclature: Birdsfoot trefoil, *Lotus corniculatus* L.; clover, *Trifolium*; common purslane, *Portulaca oleracea* L.; dandelion, *Taraxacum officinale* G.H. Weber ex Wiggers; field bindweed, *Convolvulus arvensis* L.; red fescue, *Festuca rubra* L.; perennial ryegrass, *Lolium perenne* L.; green foxtail, *Setaria viridis* (L.) Beauv.; prickly lettuce, *Lactuca serriola* L.; quackgrass, *Elymus repens* (L.) Gould; peach, *Prunus persica* L. Batsch.
Key words: Cover crops, management systems, mulching, nonchemical weed control, weed community dynamics.

Orchard floor vegetation and its impact on the agroecosystem can have both positive and negative effects on tree fruit production. A thorough examination is necessary to understand the influence of understory vegetation dynamics on specific orchard crop systems and to aid in the development of sustainable management strategies. This is especially important in organic production, which relies heavily on ecological strategies to manage weeds and insect and disease pests and to meet plants' nutritional needs. In this study, the vegetation dynamics associated with six orchard floor management strategies applied to organic peach was characterized in northern Utah.

The orchard floor is the foundation of tree fruit agroecosystems (Granatstein and Sanchez 2009). It anchors tree roots and supplies nutrients. It hosts noncrop plants such as weeds and cover crops. It impacts tree-available resources, soil properties, microclimate, animal and microbial communities, and ultimately, crop yield and quality. Fruit trees have low root density relative to many herbaceous plants; thus, they are poor competitors for resources (Merwin 2003). Moreover, fruit production requires high inputs of nitrogen (Greenham 1980; Van Slyke et al. 1905), and where nitrogen is limiting, noncrop competition can inhibit tree growth, reduce yield, and diminish fruit quality (MacRae et al. 2007; Majek et al. 1993; Meyer et al. 1992). Excess nitrogen can stimulate unwanted tree vigor and delay dormancy, as well as promote pest populations

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* First and second authors: Graduate Student and Professor, Department of Biology, Utah State University, Logan, UT 84322; Third, fourth, and fifth authors: Professors, Department of Plants, Soils and Climate, Utah State University, Logan, UT 84322; Sixth author: Farm Advisor, University of California Cooperative Extension, Fresno County, 550 East Shaw Avenue, Suite 210-B, Fresno, CA 93710. Corresponding author's E-mail: diane.alston@usu.edu

through eutrophication (Granatstein and Sanchez 2009; Marsh et al. 1996).

To minimize crop competition, most growers follow the standard orchard floor management practices, which are to maintain bare, or nearly bare, soil surfaces beneath the tree canopy, closely manage fertilization corresponding to crop phenology, and prophylactically suppress pests. In conventional systems, these goals can be achieved relatively inexpensively and conveniently with commercial pesticides and fertilizers. Organic production restricts synthetic products and relies heavily on tillage and compost-based fertilizers (Hoagland et al. 2008). Such practices, while technically acceptable, can be more challenging to successfully implement and may not fully align with the philosophy of sustainability. The benefits of tillage are temporary, and recurrent cultivation can disrupt surface tree roots and degrade soil quality (Hoagland et al. 2008; Skroch and Shribbs 1986). To achieve necessary fertility, sufficient quantities of high-quality compost are usually outsourced, leading to high purchase and transportation costs (Granatstein and Sanchez 2009). Furthermore, the release of nitrogen from compost is generally slow and difficult to govern (Marsh et al. 1996), especially in arid and high-elevation regions such as the Intermountain West. A certain amount of weed tolerance is often necessary in organic orchards. As a result, arthropod and pathogen concerns arise because orchard floor vegetation potentially provides resources (such as food, refuge, and alternate hosts) for these pests (Granatstein and Sanchez 2009; Meyer et al. 1992).

Sustainable, alternative strategies for organic orchard floor management are needed. Of interest are those that 1) comply with organic standards, 2) reduce input costs of materials and labor, 3) are capable of providing multiple agroecosystem services, and 4) enhance crop yield and quality. A challenge, however, is the interdependent nature of fruit production and orchard floor dynamics; small changes in understory structure may have profound consequences on tree development and fruit production. As a result, outcomes of orchard vegetation management methods often vary for a particular system, tree species, site, scale, and season. Locally relevant research is needed to identify effective orchard floor management methods that optimize organic tree fruit production in relation to nutrients, irrigation, and pests.

Our objectives were to characterize and quantify vegetation dynamics of six orchard floor alleyway and tree-row combinations and to assess intra- and interseasonal dynamics for three years. The treatments included a combination of industry standard and alternative practices. Tree-row manipulations included varied levels of aboveground biomass with cultivation, mulches, or no management. Alleyways were planted with a nitrogen-fixing legume or an industry standard perennial grass mixture. Results presented here focus on ground cover vegetation, biodiversity, and community composition. We anticipate that our findings will not only demonstrate successful organic peach production strategies for the Intermountain region, but also broaden the research knowledge base for organic production, ecosystem services, and agroecological community dynamics.

Materials and Methods

Experimental Design. Weed community dynamics in the tree row were studied in response to orchard floor management in the tree row and adjacent alleyways. The research site was at the Utah State University Horticultural Experiment Station in Kaysville, UT (41.02°N, 111.93°W). An experimental peach orchard was established with 360 trees arranged in twelve rows of 30 trees (4.88- by 2.44-m spacing; 0.43 ha total area). The twelve rows were divided into four blocks, each consisting of three rows. The four blocks were further divided into six plots each, for a total of 24 plots. Six orchard floor treatments were applied at random to one of the six plots in each of the four blocks. Plots were the experimental unit and each consisted of 15 trees arranged in three rows of five trees. There were three interior trees in each plot that were used for sampling; sample trees were surrounded by guard trees of the same treatment.

The experimental orchard was planted in April, 2008, and composed of equal numbers of two peach cultivars from the Stellar™ series (Fruit Acres, Sandy Lake, MI): 'Coralstar®' and 'Starfire®'. All cultivar scions were grafted onto 'Lovell' rootstock. The two cultivars were selected for their staggered fruit maturity dates, to facilitate harvest. The two cultivars were planted in a pattern that alternated between blocks (three rows each). Blocks 1 and 3 had trees with Coralstar scions and blocks 2 and 4 had trees with Starfire scions. We assumed that the closely related peach cultivars would not have

Table 1. Organic peach orchard ground vegetation treatment combinations; those denoted by "-" were incompatible with blowing cut biomass into the tree row and were not applied

Treatment	Tree row	Alleyway	Abbreviation
1	Living mulch	Trefoil	LT
2	Living mulch	Grass	LG
3	Straw mulch	Trefoil	ST
4	Straw mulch	Grass	SG
5	Tillage	Grass	TG
6	Weed fabric	Grass	FG
NA	Tillage	Trefoil	-
NA	Weed fabric	Trefoil	-

different effects on orchard floor vegetation. A large number of trees failed in the first year due to graft incompatibility. To ensure that sample trees were of a uniform age, in spring 2009, all sample trees and poorly performing guard trees were replaced with new trees of the original cultivar. All management practices complied with US Department of Agriculture National Organic Program standards.

Six orchard floor treatments were initially applied in the summer of 2008 (Table 1): four types of tree-row weed management and two types of alleyway cover. The tree-row management treatments included tillage, weed fabric, straw mulch, and a living stand of vegetation. The alleyways were either a perennial grass mix (red fescue seeded at 22 kg ha^{-1} and perennial ryegrass seeded at 56 kg ha^{-1}) or birdsfoot trefoil (seeded at 13 kg ha^{-1}). Alleyways were mowed approximately monthly from May to September. Upon mowing, trefoil clippings were blown into the tree row to provide supplemental nitrogen; however, this was not done with the grass. The tillage and weed fabric tree-row treatments were incompatible with deposited trefoil clippings; thus, these two treatment combinations were excluded from the factorial design, resulting in six rather than eight treatments (Table 1).

Tillage represented the organic industry standard, and was implemented with a rotary tiller mounted on a lawn tractor (Roto-Hog™ Tow-Behind Tiller, DR Power Equipment, Vergennes, VT) and an in-row tiller attachment mounted to a farm tractor (Weed Badger®, Town and Country Research & Development Inc., Marion, ND). Tillage was conducted in May and September, after the first and last sample dates. The tillage treatment was applied to the entire 1.5-m tree row strip. Two passes with the tow-behind tiller (one on either side) were necessary to cover the majority of the tree-row area, while also avoiding contact with the tree trunks. The Weed Badger was used to till at the base of the trees. The target soil depth for tillage was 10 cm. Straw mulch (wheat, *Triticum aestivum* L., or barley, *Hordeum vulgare* L.) was applied each year in April to a depth of 15 cm. The source and species of straw used varied among years. Woven black polypropylene weed fabric (Pro-5 Weed-Barrier®, Dewitt Co., Sikeston, MI) was laid down over the entire tree-row strip (24.4 by 1.5 m) and secured with yard staples. The fabric was pulled back each fall to prevent rodent damage to tree trunks during the winter, and was then returned in the spring. The "living mulch" of vegetation was initially sweet alyssum [*Lobularia maritima* (L.) Desv.] seeded at 22 kg ha^{-1} in the spring of 2008 and 2009. The alyssum failed to adequately reseed itself, and in 2010 the alleyways were allowed to transition to endemic vegetation species (weeds).

Each plot was irrigated weekly with micro sprinklers at an independent rate determined by the soil volumetric water content measured using a capacitance probe (Diviner 2000, Sentek Technologies, Stepney, Australia). Each plot was individually fertilized at a rate that was determined based on tree growth. Cow paunch manure was applied at a set rate of 2.26 kg per tree. Additional nitrogen was added via organic feather meal (NatureSafe 13-0-0) to reach the target amount; in 2011, 2012, and 2013, these targets were 95, 188, and 267 g of nitrogen per tree, respectively. For additional details regarding site properties, orchard establishment, and treatment maintenance, see Reeve et al. (2017).

Vegetation Sampling. Tree-row weeds were measured preceding a mowing or tillage event, and represented the previous month of productivity. Vegetation coverage was visually estimated for the entire tree row. Cover data were the average of estimates made by two observers. The frequency that a species was present among all samples (constancy) was calculated. Rare species (those observed with less than 5% constancy) were not reported. Dry biomass was determined by collecting two samples of vegetation cut at ground level from a 0.5- by 0.5-m quadrat randomly placed into the tree-row sampling area. Vegetation was placed into paper bags, transported to a lab, sorted to species (Burrill et al. 1991), and weighed after drying (≥36 hours at 70 C). Aboveground biomass was measured in grams per 0.25 square meters and averaged for the two subsamples. Biodiversity indices were calculated from biomass data with the Species Diversity and Richness software package (version 4.1.2, Pisces Conservation Ltd., Lymington, England). The species richness index was the count of vegetation species in a sample, and the Simpson's diversity index (Simpson 1949) was the effective number of species given the evenness and richness of species in the sample.

Statistical Analyses. Data were analyzed to determine differences among treatments and sampling periods (within a season and across seasons). Generalized linear mixed models were utilized for all vegetation responses, via the GLIMMIX procedure (SAS version 9.3, SAS Institute Inc., Cary, NC). Following the method of Stroup (2012), the fixed effects of treatment, time, and their interactions were estimated by maximum likelihood, given their random effects (by block and plot). Biomass data were square-root transformed to stabilize the variance. Coverage was a continuous proportion and modeled with a beta distribution. Species richness was a count and modeled with a Poisson distribution. Species diversity was normally distributed.

The two time factors, year and month, were analyzed separately. Annual analyses from 2011 through 2013 used data from August, the month with the most complete representation across years. Seasonal analyses were performed using May through August data for 2012; that year has the most complete data set and is most representative of established orchard floor vegetation (four years after initial planting). Time, a repeated measure, used a correlated error structure determined by minimizing information criteria among competing models. The first-order autoregressive covariance structure was parsimonious in most analyses. Denominator degrees of freedom were approximated with the between-within method. Simple effects were evaluated by least square means. Treatment differences across time were compared from one sequential sample period to the next. Temporal differences were reported within a single treatment and only for changes from one sequential time period to the next. The influence of alleyway treatment was assessed by comparing the average response value from the trefoil and grass alleyway plots for corresponding tree-row treatments using estimable contrast statements (lsmestimate statement). For multiple comparisons, family-wise error rate was controlled by applying the simulation-based multiplicity adjustment (adjust = sim option).

Results and Discussion

All four vegetation responses (cover, biomass, richness, and diversity) differed by treatment and time (month and year) with numerous treatment by time interactions (Table 2). Percentage cover in the annual analysis was an exception, with no significant interactions between treatment and year. For all responses, statistical contrasts of birdsfoot trefoil versus grass alleyways were nonsignificant, indicating a lack of alleyway effects on tree-row vegetation. Therefore, data for trefoil alleyway treatments were omitted from analyses. However, weed species composition in tree rows did vary between the two alleyway treatments; thus, trefoil alleyway results are presented in Table 3.

The treatment by month interactions were largely attributed to the tillage treatment and timing of its application as compared to timing of the other treatments. Tillage was applied after the first sample collection in May, causing the June samples to have fewer weeds. In contrast, orchard floor management in the living mulch, straw mulch, and weed fabric treatments was conducted earlier in the spring, leading to less disruption just before sample collection was initiated in May. We anticipated that seasonal vegetation responses in tilled plots would reflect infrequent disturbances, and differ from seasonal vegetation growth and succession in the living and inert mulch treatments.

All four vegetation responses in the tillage treatment did, in fact, decline from May to June, before increasing again in July and August (Figure 1). However, tillage was not the only treatment to have distinct seasonal patterns that contributed to the treatment by month interactions. Biomass estimates in the living mulch declined markedly from June to July (Figure 1a), presumably due to hot and dry conditions in late summer that limited biomass production. Estimates of weed cover in the straw mulch treatment increased dramatically between May and June (Figure 1b), likely because of seeds that were introduced with the straw in April.

Table 2. Mixed model results for effects of tree-row treatment, month or year, and their interaction on responses of weed biomass, percent cover, species richness (number calculated from biomass samples), and species diversity (Simpson's D calculated from biomass samples). The f-statistic (F), p-value (P), and a significance indicator[b] are given for each response. In the bottom row, "contrast" is the least square means comparison of grass versus trefoil alleyway.

		Biomass			Cover			Richness			Diversity		
	df [a]	F	P		F	P		F	P		F	P	
Seasonal													
Treatment	5, 15	104.47	<0.0001	***	83.69	<0.0001	***	34.46	<0.0001	***	10.30	0.0002	***
Month	3, 9	16.49	0.0005	***	47.40	<0.0001	***	56.24	<0.0001	***	7.27	0.0089	**
Interaction	15, 45	10.90	<0.0001	***	9.05	<0.0001	***	10.49	<0.0001	***	4.83	<0.0001	***
Contrast			0.9967	NS		0.4639	NS		0.1684	NS		0.8236	NS
Annual													
Treatment	5, 15	53.09	<0.0001	***	49.27	<0.0001	***	46.84	<0.0001	***	43.32	<0.0001	***
Year	2, 6	14.24	0.0053	**	12.23	0.0076	**	30.98	0.0007	***	3.03	0.1232	NS
Interaction	10, 30	5.59	0.0001	***	1.52	0.1811	NS	5.76	<0.0001	***	2.83	0.0153	*
Contrast			0.9841	NS		0.1399	NS		0.7985	NS		0.1759	NS

[a] The numerator and denominator degrees of freedom (df) are separated by a comma. Modeled degrees of freedom were identical for each response.

[b] NS, *, **, *** indicates nonsignificant and significant differences at $P \leq 0.05$, $P \leq 0.01$, and $P \leq 0.001$, respectively.

Only the results of the species richness analysis were consistent, with the expectation that tillage was the solitary treatment with a unique seasonal pattern (Figure 1c). The number of species in the living mulch, straw mulch, and weed fabric treatments was low in May, increased in June, peaked in July, and declined in August. The number of species in tillage plots dropped from May to June. Lastly, in the analysis of biodiversity, weed fabric was unique in that the Simpson's index spiked in July and then declined in August (Figure 1d). Fabric tree rows had consistently low levels of weed biomass, weed coverage, and species richness throughout the season, and so the Simpson's index may have been particularly sensitive to the changes in species richness that occurred in July.

Interactions for treatments by year were less prominent than those within a season (Table 2). Tree-row weed biomass declined annually in living mulch, straw mulch, and tillage treatments, and increased in weed fabric treatments (Figure 2a). The annual decline of biomass in the living mulch, straw mulch, and tillage treatments was likely a result of tree canopy growth blocking sunlight. The rise of biomass in the fabric treatments was due to degradation of fabric integrity. Living mulch ground cover in the tree rows was close to 100% throughout the three years (alyssum transitioned to weeds in 2010; Figure 2b). In contrast, cover in the straw and fabric treatments started at lower levels in 2011 and increased during the three-year study period. Tree-row weed cover in tillage treatments did not change annually. Species richness in living mulch, straw mulch, and tillage treatments peaked in 2012 and declined in 2013 (Figure 2c). Species richness in weed fabric plots rose from 2012 to 2013, at which point it was at its greatest. Weed biodiversity responded in a pattern similar to that of species richness, but there were fewer significant differences amongst years (straw mulch declined from 2012 to 2013; Figure 2d).

Living Mulch. Tree-row vegetation in the living mulch treatment had the greatest aboveground biomass, ground cover, species richness, and biodiversity in both the seasonal (Figure 1) and annual (Figure 2) analyses, among the treatments tested. Weed biomass was at least twice that of other treatments, and completely covered the tree-row area from June through August. It was not surprising then that the living mulch plots also contained the greatest species richness. Of the 32 tree-row species observed throughout the study, 28 were present in living mulch treatments (Table 3). The only unique species to the treatment were sweet alyssum, which was intentionally planted in 2008 and 2009, and common ragweed (*Ambrosia artemisiifolia* L). The most dominant species were legumes, either birdsfoot trefoil (27% cover) that encroached from the trefoil-planted alleyways or a mix of clovers (37% cover) in plots with grass alleyways. The predominate species of clover was white clover, *Trifolium repens* L. Other prevalent species in living-mulch tree rows included

Table 3. Tree-row weeds observed throughout the study, listed by taxonomical family, common name, species, percent cover for each tree-row and alleyway treatment, and the total constancy (frequency of occurrence in all samples combined). Data are averaged over all sample dates. Abbreviations: LT, living-mulch tree row with trefoil alleyway; LG, living mulch with grass alleyway; ST, straw mulch with trefoil; SG, straw mulch with grass; TG, tillage-grass; FG, fabric with grass; Total, constancy. A hyphen (-) indicates that the species was not present in the any samples of the treatment.

		LT	LG	ST	SG	TG	FG	Total
Species	Common name	%						%
Amaranthus retroflexus L.	Redroot pigweed	0.7	<0.1	<0.1	-	0.6	-	41.7
Ambrosia artemisiifolia L.	Annual ragweed	0.2	0.2	-	-	-	-	8.3
Avena fatua L.	Wild oat	-	-	0.7	2.3	-	-	29.2
Bromus tectorum L.	Downy brome	0.1	<0.1	0.2	-	-	-	12.5
Capsella bursa-pastoris (L.) Medik.	Shephard's-purse	0.4	<0.1	0.1	-	0.9	-	41.7
Cerastium arvense L.	Field chickweed	0.3	0.1	-	-	0.3	-	33.3
Chenopodium album L.	Common lambsquarters	1.7	<0.1	0.3	<0.1	1.7	0.3	58.3
Convolvulus arvensis L.	Field bindweed	5.2	7.4	33.2	32.4	12.2	4.5	100.0
Conyza bonariensis (L.) Cronq.	Hairy fleabane	0.2	0.3	-	-	<0.1	-	16.7
Conyza canadensis (L.) Cronq.	Horseweed	<0.1	0.4	<0.1	-	0.1	<0.1	37.5
Elymus repens (L.) Gould	Quackgrass	-	-	19.7	5.3	-	-	33.3
Festuca rubra L. /*Lolium perenne* L.	Red fescue/perennial ryegrass	10.3	15.6	11.7	7.6	0.3	0.1	79.2
Grindelia squarrosa (Pursh) Dunal	Curlycup gumweed	0.2	-	-	-	0.7	-	20.8
Hordeum jubatum L.	Foxtail barley	0.6	0.3	-	0.2	-	-	41.7
Lactuca serriola L.	Prickly lettuce	13.2	7.5	1.9	5.2	1.3	0.3	95.8
Lamium amplexicaule L.	Henbit	0.3	-	<0.1	-	<0.1	-	25.0
Lobularia maritima (L.) Desv.	Sweet alyssum	0.7	0.8	-	-	-	-	29.2
Lotus corniculatus L.	Birdsfoot trefoil	26.9	1.5	0.6	<0.1	-	0.1	45.8
Malva neglecta Wallr.	Common mallow	1.5	-	<0.1	-	<0.1	0.3	37.5
Medicago lupulina L.	Black medic	0.5	1.0	<0.1	0.1	0.1	0.2	62.5
Medicago sativa L.	Alfalfa	0.2	0.3	-	3.8	-	-	25.0
Poa bulbosa L.	Bulbous bluegrass	0.2	-	-	0.7	-	-	8.3
Polygonum aviculare L.	Prostrate knotweed	-	<0.1	-	0.1	-	<0.1	12.5
Portulaca oleracea L.	Common purslane	<0.1	<0.1	-	-	6.9	-	25.0
Setaria viridis (L.) Beauv.	Green foxtail	12.1	4.7	2.6	0.2	1.5	1.1	83.3
Sonchus oleraceus L.	Annual sowthistle	-	<0.1	-	-	<0.1	-	12.5
Taraxacum officinale G.H. Weber ex Wiggers	Dandelion	12.3	13.8	2.8	2.9	2.6	0.2	87.5
Tragopogon dubius Scop.	Western salsify	-	0.1	<0.1	0.1	-	-	29.2
Tribulus terrestris L.	Puncturevine	-	-	-	-	0.6	-	8.3
Trifolium spp.	Clover mix	2.0	36.6	0.5	0.4	5.0	2.6	75.0
Triticum aestivum L.	Volunteer wheat	-	-	0.2	1.2	-	-	25.0
Veronica persica Poir.	Persian speedwell	0.5	1.1	0.2	<0.1	0.3	-	45.8

those with growth habits that competed well for vertical growing space (e.g., grasses, dandelion, prickly lettuce, and green foxtail). Field bindweed was present in every treatment, but was less dominant in tree rows with living mulch as compared to straw mulch, tillage, or weed fabric.

Living mulch represents the "worst-case" scenario for weed control, or the "best-case" for biodiversification. The success of weed tolerance as a strategy for orchard floor management is contingent upon mitigating the competitive effects of weeds on tree growth and productivity (Granatstein and Sanchez 2009; Merwin et al. 1994). Vegetation biomass in living-mulch tree rows was high, especially in May and June (Figure 1a). Most crop and pest management recommendations advise growers to suppress weeds early in the season. For example, Merwin and Ray (1997) studied the effects of weed-free timing and duration in an establishing apple orchard in New York for five years; productivity was greatest when weed density was reduced in May to July. In their study, treatments with weeds present early in the season resulted in trees that had reduced trunk cross-sectional area, delayed tree maturation, and reduced total fruit weight per tree. Exposure to weed competition had similar adverse effects in the present

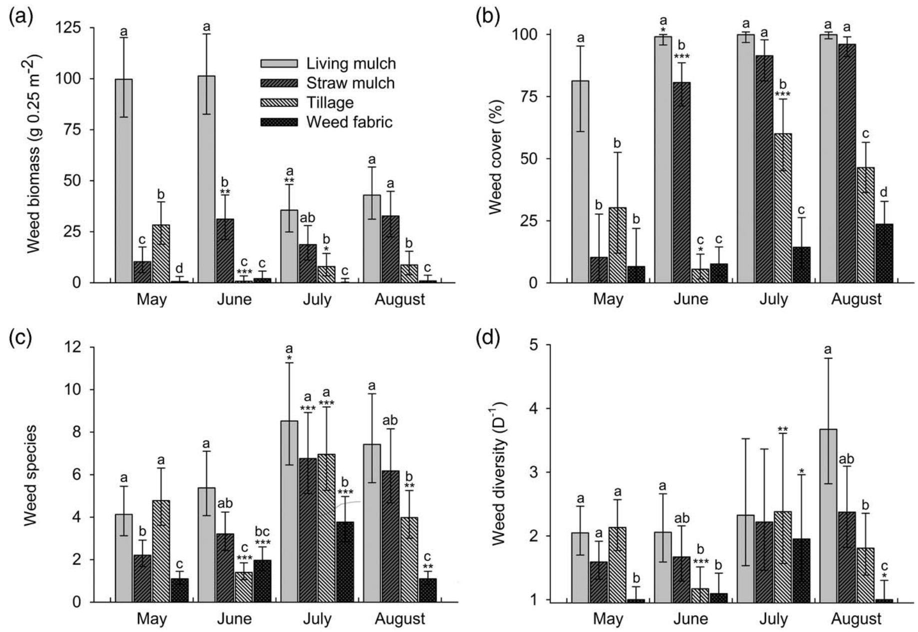

Figure 1. (a–d). Tree-row weed biomass, weed cover, species richness (number calculated from biomass samples), and species diversity (Simpson's D calculated from biomass samples) for treatments across months in 2012. Letters denote significant differences among treatments within a month at $P \leq 0.05$. Asterisks denote a significant difference between that month and the previous month, within a treatment, at the P-value indicated by the number of asterisks (*, $P \leq 0.05$; **, $P \leq 0.01$; and ***, $P \leq 0.001$).

study; living-mulch tree rows in combination with grass alleyways reduced trunk cross-sectional area by 40% to 50% in the first three years (2009 to 2011) (Reeve et al. 2017). However, over time, nitrogen from birdsfoot-trefoil alleyway inputs mitigated the effects of early weed competition; by 2011, trees in living-mulch tree rows with trefoil alleyways were no different in size than trees grown in straw, fabric, and

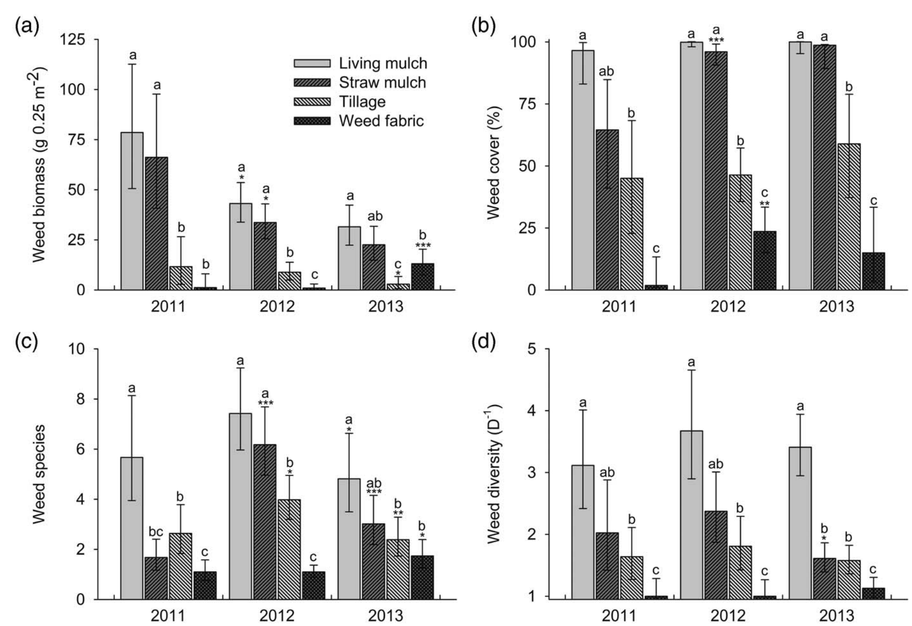

Figure 2. (a–d). Tree-row weed biomass, weed cover, species richness (number calculated from biomass samples), and species diversity (Simpson's D calculated from biomass samples) for treatments in August across years. Letters denote significant differences among treatments within a year at $P \leq 0.05$. Asterisks denote a significant difference between that year and the previous year, within a treatment, at the P-value indicated by the number of asterisks (*, $P \leq 0.05$; **, $P \leq 0.01$; and ***, $P \leq 0.001$).

tillage tree rows (Reeve et al. 2017). These results show that living mulch can be a viable solution for organic orchard–floor management, at least in the Intermountain West. In terms of sustainability, the living-mulch treatment had the lowest maintenance requirements of any treatment. Tree rows needed to be mowed monthly, or weeds would overgrow the irrigation system, but otherwise it was a practice with minimal management requirements.

Straw Mulch. Weed suppression with straw mulch was intermediary between living mulch and tillage treatments. Species richness in straw-mulched tree rows was similar to that in rows that received tillage in July and August of 2012 (Figure 1c) and in two of three years (Figure 2c); biodiversity estimates were similar for the two treatments (Figures 1d and 2d). Twenty-four species were found in straw-mulch tree rows (Table 3); dominant weeds included field bindweed and those that were imported with the straw: grasses and volunteer cereals. The most potentially harmful species was quackgrass; it is a persistent, fast-spreading rhizomatous weed. The appearance of quackgrass was a source of concern because the plant had not been previously seen at the research farm. The risk of weed introduction was a known possibility, as sanitation issues with imported straw have been documented before, including introduction of quackgrass specifically (Merwin et al. 1994).

In spring, recently applied straw mulch provided substantial weed control, presumably via obstruction of physical space and sunlight. Other authors have reported similar success. Miñarro (2012) found straw mulch to be superior to tillage in reducing vegetation cover in an apple orchard. In peach, Thakur et al. (2012) reported that straw mulch provided ≥90% weed suppression. In their trials, straw mulch was not superior to weed fabric in suppressing weeds, but straw-mulched treatments produced the greatest fruit size and yield. Proebsting (1958) also reported improved fruit yield with straw-mulch treatment in Washington peach orchards. Merwin and Stiles (1994) demonstrated benefits of straw mulch in a New York apple orchard, including enhanced yield and tree trunk cross-sectional area. They found that straw-mulch plots produced more fruit than did herbicide or tillage treatments; these results suggest that straw mulch provides additional benefits beyond reducing competition between weeds and trees. In that study, and a concurrent one (Merwin et al. 1994), researchers attributed improved productivity to enhanced edaphic properties—specifically, higher levels of potassium, phosphorous, boron, and soil organic matter, as well as increased water-holding capacity and tree root area. In the study orchard discussed here, Culumber (2016) could not identify differences in edaphic properties between living and straw mulches, but did find greater peach tree root diameters in tree rows mulched with straw.

A disadvantage of straw mulch is its relatively rapid decomposition, thus requiring annual reapplication. Each application brings with it risk for introduction of unwanted plant species. Production of straw on-site could lessen this risk; however, the time and production costs may be burdensome for fruit growers. Another consideration is the seasonal maintenance requirements of straw mulch, including the necessity to source, purchase, transport, and apply straw. Lastly, according to the literature, the greatest negative aspect of straw mulch is its association with pest problems. Increased soil moisture has been shown to promote root-rot pathogens, and straw mulch can harbor meadow voles [*Microtus pennsylvanicus* (Ord)], resulting in unacceptable tree mortality (Merwin et al. 1992). We did not experience rodent problems in our study. The arid climate of Utah may thwart hydrophilic pathogens in all but the wettest years.

Tillage. Tillage provided adequate control of the majority of weeds, as would be expected from the industry-standard practice. Here, we implemented cultivation twice to minimize peach tree root damage; some studies have employed up to six tillage treatments per year (Merwin 2003). The recommendation for more frequent tillage is supported by the short periods in which cultivation was effective in our study. Within approximately one month after tilling, vegetation returned (Figure 1a,b). However, a contrasting argument supporting tillage efficacy is that neither plant biomass nor cover in tillage plots ever reached the levels seen in the living mulch treatment after tree rows were tilled in May. A total of 20 species were present in tillage treatments, with field bindweed being the most abundant (Table 3). There appeared to be a strong selection for therophytes (annual species that overwinter as seeds) as well. For example, common purslane, henbit (*Lamium amplexicaule* L.), Persian speedwell

(*Veronica persica* Poir.), and shepherd's-purse [*Capsella bursa-pastoris* (L.) Medik.] were associated with tree rows managed with tillage. These results are consistent with those of other studies (Miñarro 2012). Because space was rarely limiting in the tillage plots, prostrate and creeping species were particularly favored, as well as those that can propagate through fragmentation. It was these functional life-history traits that were characteristic of the weed-species assemblage in tillage plots.

Endorsements for tillage are that it is widely accepted, relatively effective (compared to living mulch), simple to perform, and technically organic. The elimination of weeds has been shown to promote tree growth and yield (Hoagland et al. 2008). However, studies have also associated tillage with negative effects on soil chemistry and structure, as well as damage to tree roots and tree health (Granatstein and Sanchez 2009). Additionally, cultivation has been shown to disturb beneficial arthropods (Sharley et al. 2008). To fully assess the merits of tillage, it is important to weigh the value of reducing competitive interference with potential damage to the soil, trees, and/or invertebrate communities. The organic industry standard of tillage in the tree rows produces reasonable yields despite concerns for damage to tree roots from physical soil disruption. The infrequent application of tillage in this study, only twice per season, is a likely explanation for the absence of the harm to yields that has been observed in other studies.

Weed Fabric. Weed fabric plots had the least vegetation biomass, least weed cover, and lowest plant diversity of the four tree-row treatments tested in this study (Figures 1 and 2). Thakur et al. (2012) also reported virtual elimination of weeds using black polythene mulch in peach orchards located in India. In our study, rooting space for weeds in the tree row was restricted to the fabric edge (where the tree row and alleyway met), between gaps in the fabric at the base of trees, damaged areas of the fabric, and holes cut for access to the soil. Just 12 species were found in fabric tree rows, and only three were observed at greater than 1% cover (Table 3). Field bindweed and clover had the ability to creep horizontally across the plastic, whereas green foxtail grew erect, similar to grasses in the Thakur et al. (2012) study. The ability of the fabric mulch to suppress weeds is its strongest merit. Enhanced fruit yield and tree growth in fabric-covered plots were observed in the current study (Reeve et al. 2017) and others (Granatstein and Sanchez 2009; Irmaileh 2011; Nunez-Elisea et al. 2005; Yin et al. 2007). Weed fabric can be expensive to install and maintain, particularly in young orchards prior to fruit production; however, enhanced production resulting from the benefits of the treatment has been reported to offset this cost (Yin et al. 2007). We anticipated that fabric would require minimal maintenance over time. However, because vole pressure at this site was not known when the orchard was established, based on commercial grower advice we took preventative action to pull the weed fabric back each fall and reinstall it each spring. In hindsight, fabric removal in winter was likely unnecessary for this research site. Over the five years since installation of the weed fabric (mid-2008 to mid-2013), wear was evident, but repair was fairly simple. The manufacturer rates the fabric's minimum life-span as five years, but good care should extend it further. Interestingly, the weed fabric provided little yield productivity benefit despite keeping the tree rows relatively free of weeds. Tree-row cover with an organic mulch, straw, or living mulch, i.e., weeds, provided yield benefits over the weed fabric.

Seasonal and Annual Effects. Seasonal variation in the biomass of orchard floor vegetation differed among the tree-row treatments (Figure 1a). Living-mulch plots contained the greatest amount of biomass in May and June, but then the amount of biomass declined in July. Biomass in tillage plots was at its maximum in May, its minimum in June (after the plots were tilled), and increased from June to July. Biomass in straw-mulch plots was lowest in May (after straw was applied), increased in June, and did not change thereafter. Biomass in weed-fabric plots remained low throughout the season and did not differ between months. The estimates of biomass from the living mulch treatment show that the general response of orchard floor vegetation is that it is greatest at the beginning of the season (May) and then declines over time. In contrast, estimates of percent cover, richness, and diversity were generally lowest in May and increased in the mid- to late-season (Figure 1b-d). Typically, all the responses are expected to be positively correlated (Henderson and Magurran 2010). This discrepancy suggests that, across a season, biomass production was governed by factors different from those that govern percent cover and richness. The Utah climate in July is hot and dry, potentially limiting plant growth. However, the richness of weeds was not as negatively affected by hot, dry weather in July and August as was biomass. Coverage and species indices increased over time, suggesting that the plant densities increased seasonally, filling in available space.

Our study targeted the postestablishment, rapid growth phase of orchard development (years four through six). Orchard-floor vegetation biomass notably declined in tree-row treatments with dense vegetation during the three years studied, including living mulch, straw mulch, and tillage. In contrast, percent cover and species richness and diversity increased over time or was stable. We hypothesize that reduction in sunlight reaching the orchard floor due to tree canopy expansion was the major limiting factor. Interestingly, species richness did not decline in relation to biomass. Although we anticipated that an increase in shading with orchard age would select for more shade-tolerant cover species, our results may support that shading rarely caused local species extinctions. We conclude that our study successfully captured the orchard postestablishment phase as vegetation measures appeared to reach plateau minima (biomass) or maxima (cover) by the final year. We anticipate that a similar trajectory will continue in future years.

Alleyway Cover. The last factor of interest in this study, alleyway cover crop, was the least influential. Comparison of an industry-standard perennial grass mix to a legume, birdsfoot trefoil, found no to minimal effects. This was an unanticipated, but beneficial, finding. At the very least, we are able to conclude that nitrogen produced by birdsfoot trefoil blown into the tree row did not promote weed biomass. A possible conclusion may be that, in general, nitrogen was not a limiting factor in this orchard system. Plant rooting space and solar access appeared to be greater factors governing orchard floor vegetation (after treatment effects). We anticipated a greater impact of legume vs. grass alleyway cover on tree-row vegetation because other components of our study found marked influences of birdsfoot trefoil planted in alleyways on the orchard system, including enhanced tree growth, fruit yield, arthropod dynamics, and soil quality (Culumber 2016; Reeve et al. 2017). However, other studies have also demonstrated minimal impact of fertility on tree-row weeds (Miñarro 2012).

The largest alleyway effect was observed in the living mulch treatment: a negative correlation between the trefoil in alleyways and other legumes in tree rows (Table 3, percent cover for clover mix in living mulch-trefoil vs. living mulch-grass). This phenomenon is likely due to competitive exclusion between similar species or their endosymbionts. In contrast, in straw-mulch tree rows, quackgrass appeared to be stimulated by the nitrogen from birdsfoot trefoil alleys. While there were no differences between the two alleyway types in total abundance of weeds in straw mulch, quackgrass is a particularly harmful species, and the leguminous alleyways may have exacerbated this weed concern. There was four times more quackgrass in tree rows adjacent to trefoil alleyways than there was in rows adjacent to grass alleyway treatments (20% and 5% cover, respectively).

The value of birdsfoot trefoil as an alleyway cover centers on its ability to generate nitrogen within the agroecosystem. While legumes have benefits in terms of improving soil health, tree growth, and yield (Hoagland et al. 2008, Mullinix and Granatstein 2011), legumes are well documented as a favored host of a suite of true bug species collectively dubbed “cat-facing insects” for their characteristic damage to peach fruits (Killian and Meyer 1984; Young 1986). As a result, concerns about cat-facing insects have dissuaded Utah growers from adopting legume cover crops in stone-fruit orchards (personal communication). Further, sustainable water use is an important concern to fruit growers, and the irrigation requirement for either alleyway type will likely play an important role in the net economics of production. In a related report on this study, Culumber (2016) found that trefoil alleyways required slightly more water, which was attributed to the greater tree size. Site maintenance in trefoil alleys was minimal after establishment, yet did require mowing with appropriate side-discharging equipment. Cover-crop stands in both alleyways held up to traffic and were persistent (data not shown).

We demonstrated that straw mulch and weed fabric were generally equally as effective as tillage in managing weeds in an organic peach system in the Intermountain West. These conclusions were supported by results for aboveground vegetation, percent cover, species composition, and relative abundance of noncrop plants. In contrast, while living mulch had more weeds than did tillage and nonliving mulches, it required the least maintenance, and when combined with a legume alleyway showed good promise for supporting peach tree growth, fruit yield, soil quality, and arthropod community balance, and did not unduly increase water use or pest pressures (Culumber 2016; Reeve et al. 2017). Season and orchard age were major influencers of ground cover phenology and succession. Alleyway cover type (grass vs. trefoil) had a negligible effect on the total abundance of tree-row vegetation, but did influence plant community structure. The findings presented here will aid in the development of viable organic orchard–floor management for the Intermountain West and other arid regions with hot summers and cold winters.

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