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Living mulch cover crops for weed control in small-scale applications

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Abstract

A primary challenge of managing vegetable production on a small land base is the maintenance and building of soil quality. Previous studies have demonstrated the benefits of cover crops for improved soil quality; however, small growers struggle to fit cover crops into rotations. Small-scale growers with limited available land are under significant pressure to maximize their saleable yield and often work to maximize output by using intensive cropping practices that may include both early and late season crops, thus limiting the typical shoulder season windows in which cover crops can be grown. In-season living mulches may be an effective strategy to provide small-scale growers the benefits of cover crops with less land commitment than cover crops used in typical rotations. However, research on living mulches is generally not suited to small-scale organic production systems due to the typical reliance on chemical herbicide to suppress mulches. An experiment was designed with the goal of evaluating living mulch systems for space-limited organic vegetable production. In a 2-year study, four living mulch crops (buckwheat (*Fagopyrum esculentum*), field pea (*Pisum sativum*), crimson clover (*Trifolium incarnatum*) and medium red clover (*Trifolium pratense*)) and a cultivated control with no mulch cover were planted in early spring each year. Snap beans (*Phaseolus vulgaris* var. Tavera), transplanted bell peppers (*Capsicum annuum* var. Revolution), and transplanted fall broccoli (*Brassica oleracea* var. Imperial) were then planted directly into living mulches. During each summer growing season, living mulches and weeds were mown between-rows and hand-weeded in-row approximately every 10–14 days as needed for management. Labor times for mowing and cultivation were found to be higher in all treatments relative to the cultivated control. An inverse relationship between living mulch biomass and weed biomass was observed, demonstrating that living mulches may contribute to weed suppression. However, lower vegetable yields were seen in the living mulch treatments, most likely due to resource competition among vegetables, living mulches and weeds. High pre-existing weed seedbank and drought conditions likely increased competition and contributed to reduced vegetable yield.

Key words: living mulch, cover crop, weed control, buckwheat, *Fagopyrum esculentum*, field pea, *Pisum sativum*, crimson clover, *Trifolium incarnatum*, medium red clover, *Trifolium pratense*, snap bean, *Phaseolus vulgaris*, bell pepper, *Capsicum annuum*, broccoli, *Brassica oleracea*

Introduction

Small farms contribute significantly to the US agricultural economy. Defined by the United States Department of Agriculture (USDA) as grossing less than US$250,000 annual gross cash farm income, small farms make up 91% of all US farms (Hoppe et al., 2010). Though many of these small farms have very low individual production levels, they account for 23% of total US agricultural production (Hoppe et al., 2010). However, since many of these small farms do not operate as commercial producers, it is useful to distinguish between those small farms that engage in commercial production, defined by proxy of gross cash farm income. Farms grossing between US$10,000 and 249,999 can be considered small commercial operations and account for 36% of US farms and US$65 billion of annual agricultural production (Hoppe et al., 2010). Though small commercial farms tend to focus on commodities with relatively low labor inputs such as livestock and cash-grain production rather than high value crops such as vegetables, peri-urban farms (farms on the outskirts of urban areas, and likely growers for farmers' markets and Community Supported Agriculture programs) and urban vegetable farms are increasingly seen as a means of providing urban populations with fresh, nutritious produce and a connection to their food supply (Hendrickson and Porth, 2012). Due to their close proximity to urban areas, peri-urban and urban farms very commonly face high land prices and limited space availability.

Soil quality is critical to the sustainability and productivity of any farming operation. A multitude of studies have established the role of cover crops in improving soil quality, including reducing erosion, building soil organic matter, improving water infiltration and contributing to weed management (Infante and Morse, 1996; Bond and Grundy, 2001). However, for smaller acreage farms, such as those that characterize many small-scale urban vegetable farms across the USA, the incorporation of cover crops into their farm plan is difficult; with a limited land base, these growers struggle to fit non-income generating crops into their rotations if sacrificing the cash crop acreage is required. Additionally, smaller-scale farmers may be limited in the availability and scalability of the equipment needed to manage the planting and incorporation of cover crops. Systems that allowed the production of income-generating crops while also gaining the benefit of cover crops would be a welcome innovation for these growers.

One approach to the management of cover crops is living mulches. In these systems, the cover crop is interplanted and grown in tandem with an annual vegetable crop. Previous living mulch studies have shown mixed success with results often dependent upon specific environmental conditions or crop interactions (Brainard et al., 2012). A review by Leary and DeFrank (2000) describes the potential season-long weed suppression benefits of living mulches but notes that the selection of an appropriate mulch crop that minimizes competition with the cash crop is critical to minimize yield losses. Living mulches provide effective weed control primarily by outcompeting weeds; however, this can also result in the mulch competing with the cash crop, necessitating management strategies to reduce competition between living mulches and cash crops (Teasdale, 1996). An inverse relationship has been found between living mulch dry biomass and both weed biomass and density and crop yield; vigorous living mulch growth more effectively suppresses weeds but also limits crop yield (Hiltbrunner et al., 2007). Strategies such as root pruning of the cover crops, staggered planting of the cover crop and cash crop, or use of living mulches in established perennial crops may assist in the reduction of competition during key growth periods and increase the success of a living mulch system (Paine et al., 1995; Kolota and Adamczewska-Sowinska, 2004; Båth et al., 2008). Additionally, past cover crop research has rarely tested specific management practices that are appropriate to small-scale organic growers.

This study builds upon previous cover crop research with the goal of identifying living mulch species that can improve small-scale organic vegetable production. We specifically test the hypothesis that living mulches can be used to reduce weed pressure or labor inputs in small-scale organic vegetable production while maintaining vegetable yields. Data collected include vegetable yield, labor requirements and crop quality.

Materials and Methods

A living mulch study was conducted in 2012 and 2013 at the University of Wisconsin West Madison Agricultural Research Station (WMARS) (Kegonsa silt loam, 2–6% slopes; 43°03′37″N, 89°31′54″W). Experimental plots had an average pH of 7.08, with a range from 6.9 to 7.16, and an average of 3.45% organic matter, with a range from 3.1 to 3.8. All management was in accordance to the United States Department of Agriculture National Organic Program (USDA-NOP) regulations (National Organic Program) and was conducted on certified organic land. Experimental plots at WMARS in 2012 and 2013 were on separate adjacent fields. The experiment was established as a strip-plot design, with living mulch species as one whole-plot factor and vegetable crop as another factor. Living mulch treatments included four species (buckwheat, field pea, crimson clover and medium red clover), and a cultivated control with no living mulch planted. Sub-plot factors included three vegetable crops (snap beans, transplanted broccoli and transplanted peppers). Four replicates were included. All field management practices utilized equipment and protocols intended to be easily replicable by a small-scale grower with access to limited equipment.

Living mulch treatments

Living mulch treatments were spring planted into 4.6 m wide × 6.1 m long plots. Plots were tilled using a Kubota tractor (model BX2350; 23 horsepower; hydrostatic transmission, Osaka, Japan) with a power take-off (PTO) driven tiller (Land Pride, model RTR1042, 1.07 m width, Salina, KS, USA). Tillage was completed in the spring as soon as soil conditions were dry enough to allow mechanical tillage. Immediately after tillage, living mulch seed was broadcast by hand and incorporated with a hard rake. Seeding rates used for living mulches were: Medium red clover: 22.4 kg ha^{-1}; crimson clover: 33.6 kg ha^{-1}; buckwheat: 107.6 kg ha^{-1}; and field peas: 224.2 kg ha^{-1}. All living mulch seed was sourced from Albert Lea Seed (Albert Lea, MN, USA) in 2012. In 2013, medium red clover was sourced from Albert Lea Seed; crimson clover, buckwheat and field pea seed was sourced from Johnny's Selected Seeds (Fairfield, ME, USA). Dates for all the field activities are listed in Table 1.

Table 1. Summary of field activities by date.

Date (2012)	Date (2013)	Activity
April 23	April 28	Spring planting of living mulches
June 8	June 3	Living mulches clipped; bell peppers transplanted and snap beans seeded
Every 10–14 days throughout growing season, prior to living mulch suppression		Living mulch height, weed species counts and biomass of weed and living mulch samples collected
Every 10–14 days throughout growing season		Living mulches suppressed by mowing, hoeing of control plots and in-row weeding for all plots
July 31	July 30	Broccoli transplanted
July 31, August 15, October 6	August 8, August 29, September 13	Bell peppers harvested
August 30	September 5	Snap beans harvested
October 17	October 10	Broccoli harvested

Post emergence living mulch stand density was quantified approximately 4 weeks after seeding by counting individual plants in a quadrat (three samples per plot, 0.25 m^2 quadrat). Living mulches were clipped prior to vegetable planting in early June with a walk-behind sickle bar mower (Jari USA 'Monarch', 1.22 m cutting width; Mankato, MN, USA).

Living mulches were suppressed by mechanical mowing with a standard walk behind lawn mower (0.56 m wide; Briggs & Stratton 'Classic MTD' 0.56 m; Milwaukee, WI, USA) every 10–14 days throughout the production season to manage weed and living mulch growth. Prior to each mowing, living mulch height (three random samples per plot), biomass of both weed and living mulch and weed species counts were collected by clipping weeds and mulches at the soil surface (two randomly selected 0.125 m^2 quadrats per plot). At the time of each mowing, weeds in control plots were cultivated with a hoe. Following mowing or cultivation, both control and living mulch plots were hand-weeded within vegetable rows. Labor time for mechanical and hand cultivation was recorded for each plot. Biomass samples were dried in a heated air drier (54 °C) at WMARS for 14 days and then weighed on an electronic balance at the UW-Madison campus.

Snap beans and bell peppers were planted immediately after living mulch clipping in early June. Snap beans were direct seeded at a rate of 20 seeds per 1 m section of row into a 0.2 m tilled strip using a walk-behind seeder (EarthWay 1001-B Precision Garden Seeder, Bristol, IN, USA). Bell pepper and broccoli transplants were punch-planted directly into living mulch by digging a small hole with a trowel; as such, transplants were completely surrounded by living mulch. Bell peppers and fall broccoli were transplanted with a 0.46 m in row spacing. All vegetable rows were 0.76 m apart. Snap bean seed was purchased from Johnny's Selected Seeds (Fairfield, ME, USA); Broccoli transplants (established 6 weeks prior to transplanting in 50-cell trays) and pepper transplants (established 8 weeks prior to transplanting in 50-cell trays) were sourced from West Star Organics (Cottage Grove, WI, USA).

Approximately 10 days after transplanting, or after plants had developed their first true leaves, vegetables were side dressed by hand with granulated composted chicken manure (Chickity Doo Doo, Onalaska, WI, USA; 5-3-2.5 N-P-K) at rates recommended by the University of Wisconsin for commercial vegetable production (snap beans 44.8 kg N ha^{-1}, bell peppers and broccoli 89.7 kg N ha^{-1}) (Bussan et al., 2012).

In 2012 early season irrigation was applied by garden hose and watering wand as needed to achieve approximately 0.025 m of water per week. Drip irrigation was installed in mid-July 2012, with water applied through this system for the remainder of the 2012 season. Due to the extremely hot, dry conditions (designated D2/D3 severe-extreme drought by United States Drought Monitor) all crops demonstrated signs of water stress despite regular water application. In 2013, drip irrigation was in place throughout the season and water was applied as needed.

Determination of vegetable marketability was based on standards generally accepted by growers serving community supported agriculture, farmers' markets and similar direct-to-consumer outlets. Vegetables were considered marketable if they met a minimum size, had a uniform appearance and minimal pest or disease damage. Non-marketable vegetables were those harvested either at an immature or overly mature stage, having irregular shape or appearance, or with more than minimal pest or disease damage.

Snap beans were harvested once per season. Two 3.05 m sections were chosen from the center of each plot (one per row) and all snap beans within the designated area were harvested by hand. Following harvest, snap beans were categorized as marketable or non-marketable. Marketable snap beans were counted, weighed and 20 randomly selected snap beans were measured for length. Non-marketable snap beans were counted, weighed and reasons for non-marketability were noted. Snap beans were classified as non-marketable if they showed signs of disease or insect damage, mower damage, or were immature or overly mature. All others were considered marketable.

Table 2. Weather data collected at UW-Madison Charmany Farms Experiment Station (3.3 miles from study site).

Time period	Total precipitation (cm)	Temperature (avg, °C)	GDDU 50
April–May 2012	15.4	12.8	447
June–September 2012	19.4	21.6	2516
April–May 2013	34.2	10.3	336
June–September 2013	40.5	20.6	1958
2012–13 Average April–May	20.0	11.1	321
2013–13 Average June–September	41.9	19.6	2053
Snowfall and winter precipitation 2011–12	68.1		
Snowfall and winter precipitation 2012–2013	134.6		
2011–13 Average snowfall and winter precipitation	98.0		

Times periods are presented to reflect spring cover crop growth periods (April–May) and vegetable growing periods (June–September). (Wisconsin State Climatology Office, personal communication). GDDU, Growing Degree Day Units.

Bell peppers were harvested at the green-ripe stage on three dates each year. In each plot the number of plants was counted and all ripe and damaged bell peppers were harvested. Harvested bell peppers were sorted as marketable or non-marketable. All marketable bell peppers were weighed and counted. A randomly selected subset of 10 marketable bell peppers were graded on shape and measured for length, width and wall thickness. Non-marketable bell peppers were counted, weighed and reasons for non-marketability were noted. Marketable bell peppers were firm with no mechanical damage and absent or extremely minor surface blemishes. Unmarketable bell peppers were those with surface blemishes, evidence of rot, insect damage, mechanical damage, or sun scald. Marketable bell peppers were graded as follows: (1): Uniform lobes, blocky shape; (2): Blocky shape but lacks uniform lobes; (3): Lacks both blocky shape and uniform lobes.

Broccoli was harvested once per season. In each plot, stand counts were obtained and all heads were harvested. Harvested broccoli was sorted as marketable or non-marketable. All marketable heads were weighed and counted. Diameter was recorded for a randomly selected subset of 10 marketable heads. Non-marketable broccoli was counted, weighed and reasons for non-marketability were noted. Broccoli was considered non-marketable if the head diameter was less than 10 cm.

Data analysis

The SAS (Cary, NC, USA) Mixed Model (PROC mixed) procedure was used to model treatment effects of living mulches on management variables (living mulch biomass, weed biomass, weed density (as a whole as well as partitioned as broadleaf and grass or sedge species) and management time per hectare), and yield variables (bell pepper, snap bean and broccoli marketable yield). Weed biomass, weed density, bell pepper yield and snap bean yield data were log transformed before analysis to improve assumptions of normality and equal variance of population distributions. Treatment means were compared using Tukey's Honestly Significant Difference test at $P < 0.05$. All figures are shown with non-transformed data though significance groupings are based on transformed data when applicable. The focus of this research was the efficacy of the living mulch for each crop, rather than a comparison of the system among vegetable crops. For this reason, data for each vegetable crop were analyzed separately.

Results

Weather

Precipitation during spring living mulch establishment (April 1–May 31) in 2012 (154 mm) was less than half of precipitation during the same period in 2013 (342 mm). Average total precipitation during the period from 1981 to 2010 was 200 mm. Temperatures, reported as the difference between the daily average temperature [TAV = (TMAX + TMIN)/2] and the base temperature of 50° F (Growing Degree Day Units (GDDU) 50 = TAV – 50) (GDDU 50) during the same period were higher in 2012 (447 GDDU 50) than in 2013 (336 GDDU 50). Both years were above the 1981–2012 average of 321 GDDU 50. Precipitation during the growing season (June 1–September 31) was lower in 2012 (194 mm) than 2013 (405 mm), though total June through September precipitation for both years was below the average of 419 mm. Growing season temperatures in 2012 were above average (2516 GDDU 50) and below average in 2013 (1958 GDDU 50). The multi-year average for June to September is 2053 GDDU 50 (Wisconsin State Climatology Office, personal communication). Further weather data are presented in Table 2.

Vegetable yield

For all vegetable species, yield was lower in all living mulch treatments than the cultivated control. Broccoli head development was delayed in all plots and resulted in non-marketable yield in the living mulch plots.

Table 3. Marketable vegetable yield data (kg ha^{-1}) (± standard error across living mulch treatments, within the same year) in 2012 and 2013 relative to four living mulch treatments and a cultivated control.

Living Mulch	2012 Yield	2013 Yield
Broccoli		
Buckwheat	0 b	0 b
Crimson clover	0 b	0 b
Field peas	0 b	0 b
Medium red clover	0 b	0 b
No cover	2059 a	4168 a
Bell pepper		
Buckwheat	1224 b	1887 b
Crimson clover	816 b	2102 b
Field peas	741 b	3074 b
Medium red clover	290 b	1895 b
No cover	6479 a	11512 a
Snap bean		
Buckwheat	775 b	272 b
Crimson clover	576 b	420 b
Field peas	602 b	327 b
Medium red clover	447 b	336 b
No cover	1387 a	1879 a

Column means with the same letter were not significantly different across living mulch treatments, within the same year at $P \leq 0.05$. All data are shown without transformation. Standard error for all treatments: Broccoli: 267.43 in 2012, 435.5 in 2013; bell pepper: 291.61 in 2012, 725.82 in 2013; snap bean: 121.97 in 2012, 175.66 in 2013.

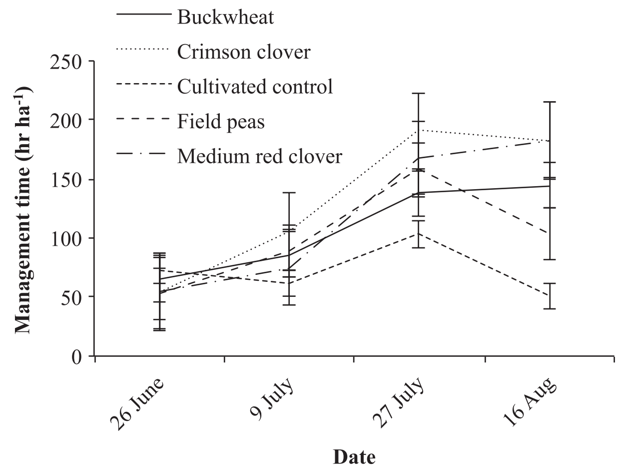

Figure 1. Management time (hr ha^{-1}) (± standard error across living mulch treatments) in four living mulch treatments and a cultivated control, 2012.

Broccoli yield in cultivated control treatments had a mean of 2,059 kg ha^{-1} in 2012 and 4,168 kg ha^{-1} in 2013 while all living mulch treatments had a mean yield of 0 kg for both years. Though all broccoli heads that formed in the living mulch treatments were designated as non-marketable due to small size, these heads were otherwise of high quality. Yield data for all vegetables are shown in Table 3.

In 2012, bell pepper yield was greatest in the cultivated control, while yield in medium red clover was significantly lower than all other treatments. There was no difference in bell pepper yield among field pea, buckwheat and crimson clover treatments. In 2013, bell pepper yield was greater in the cultivated control treatment than in any of the living mulch treatments (Table 2). The primary reason for bell pepper non-marketability was rot, including blossom end rot and sun scald. Managing mulches and weeds by mowing when plants were fruiting was a challenge and injured about 10% of the non-marketable bell peppers. Reasons for non-marketability, calculated as a percentage of harvest, did not vary by treatment. In 2012, bell pepper diameter, length, wall width and grade were greater for bell peppers in the cultivated control and buckwheat plots relative to the medium red clover treatment. In 2013, bell pepper diameter in the cultivated control treatment was greater than those from the crimson clover and medium red clover treatments, but not different from the field peas or buckwheat treatments. No treatment effect was observed for bell pepper wall width, length or grade in 2013 (data not shown).

Snap bean yield was lower in the living mulch treatments than the cultivated control in both 2012 and 2013. Snap bean length did not vary by treatment in either year. During both study years, about one-third of snap beans classified as unmarketable were immature at the time of harvest. In 2012, bean rust (*Uromyces appendiculatus*) accounted for an additional 21% of non-marketable snap beans. Other reasons for non-marketability included general surface marring and mower damage. No treatment effects were observed among reasons for snap bean non-marketability (data not shown).

Management time per hectare

Management time (mowing and in-row hand weeding) varied by living mulch treatment as well as time of year. Drought conditions in 2012 slowed growth of all plants, including living mulch; thus, less frequent mowing was required. As a result, in 2012, plots were mown a total of four times, while in 2013, plots were mown six times. Data were analyzed separately by year due to a significant year by treatment interaction. In 2012, management time was less for medium red clover and the crimson clover relative to the cultivated control on August 16, 2012 (Fig. 1). In 2013, management time was less for the cultivated control relative to buckwheat, field peas and crimson clover on August 7, 2013 (Fig. 2). A summary of management time by living mulch treatment is shown in Table 4.

Living mulches and weed growth

The interaction of living mulch treatment and sample date was significant for both weed density and weed biomass

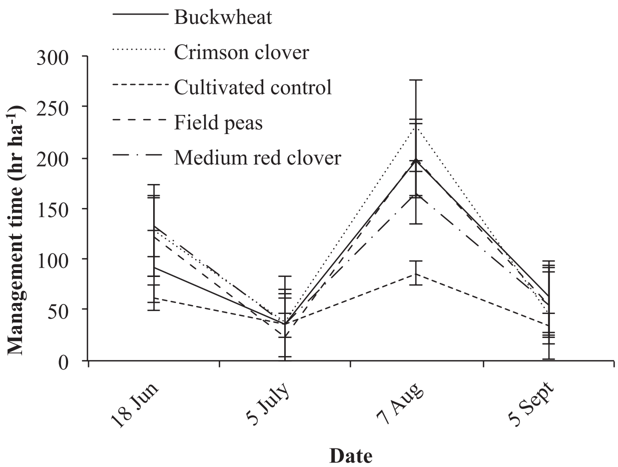

Figure 2. Management time (hr ha^{-1}) (± standard error across living mulch treatments) in four living mulch treatments and a cultivated control, 2013.

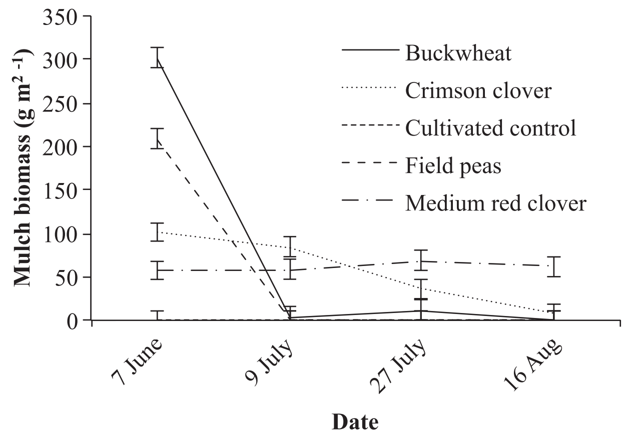

Figure 3. Mulch biomass (g m^{-2}) (± standard error across living mulch treatments) of four living mulch treatments and a cultivated control at four mowing dates, 2012.

Table 4. Management time per cultivation by living mulch, hr ha^{-1} (± standard error across living mulch treatments, within the same year) in 2012 and 2013 relative to four living mulch treatments and a cultivated control.

Living mulch	2012 Time (hr ha^{-1})	2013 Time (hr ha^{-1})
Buckwheat	108 ab	102 ab
Crimson clover	133 a	121 a
Field peas	101 ab	102 ab
Medium red clover	120 ab	109 a
Cultivated control	72 b	64 b

Column means with the same letter were not significantly different across living mulch treatments, within the same year at $P \leq 0.05$. Standard error for all treatments: 12.2428 in 2012, 9.1343 in 2013.

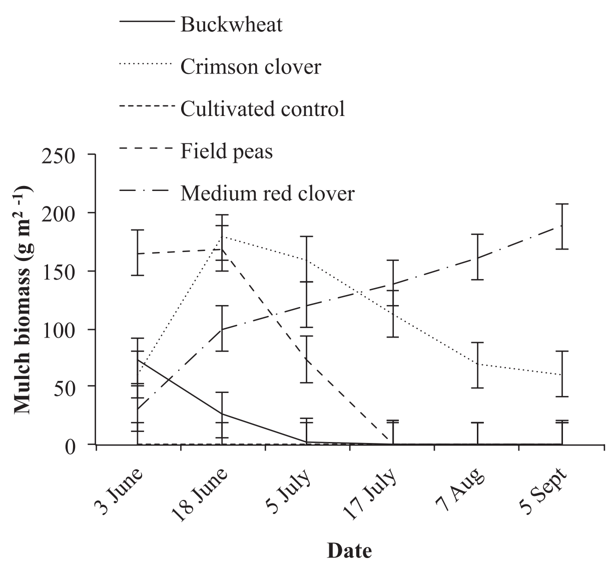

Figure 4. Mulch biomass (g m^{-2}) (± standard error across living mulch treatments) of four living mulch treatments and a cultivated control at four mowing dates, 2013.

data. During both 2012 and 2013, buckwheat and field pea crops were predominantly terminated at the first mowing that occurred at the time of snap bean and bell pepper planting. After the first mowing, buckwheat and field pea crop biomass degraded quickly and suppressed weeds poorly for the remainder of the growing season. Medium red clover and crimson clover crops were resilient to mowing and survived throughout the season. The greatest degree of full season weed suppression was achieved in the medium red clover treatment. In all treatments, pre-mowing weed density and weed biomass were inversely related to living mulch biomass. After the first mowing and subsequent hand cultivation, weed biomass was lower in the cultivated control plots for the remainder of the season as compared with the living mulch plots.

In 2012, buckwheat, crimson clover and field peas had greater biomass at the first mowing as compared with subsequent mowing. At the first mowing, buckwheat biomass was significantly greater than other living mulches, with field pea biomass greater than crimson clover and medium red clover. With respect to overall biomass production, crimson clover produced more biomass mid-season and medium red clover produced the most biomass in the late season (Fig. 3). The trend in 2013 was similar to 2012, with buckwheat and field peas producing the greatest biomass in the early season, followed by crimson clover in the mid-season and medium red clover in the late summer (Fig. 4). A summary of living mulch biomass is shown in Table 5.

In both 2012 and 2013, weed biomass after the first mowing and cultivation of the season was lower in the cultivated control than all other living mulch treatments. At the August 16, 2012 mowing date, the weed biomass in the

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Table 5. Living mulch biomass (g m^{-2}) (± standard error across living mulch treatments, within the same year) in 2012 and 2013 relative to four living mulch treatments and a cultivated control.

Living mulch	2012 Biomass (g m^{-2})	2013 Biomass (g m^{-2})
Buckwheat	79 a	37 c
Crimson clover	58 a	93 ab
Field peas	52 a	65 bc
Medium red clover	62 a	106 a
Cultivated control	0 b	0 d

Column means with the same letter were not significantly different across living mulch treatments, within the same year at $P \leq 0.05$. Standard error for all treatments: 6.5717 in 2012, 7.7315 in 2013.

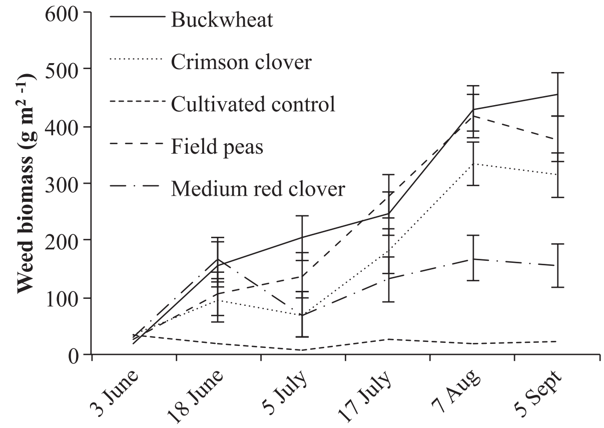

Figure 6. Total weed biomass (g m^{-2}) (± standard error across living mulch treatments) of weeds in four living mulch treatments and a cultivated control at four mowing dates, 2013.

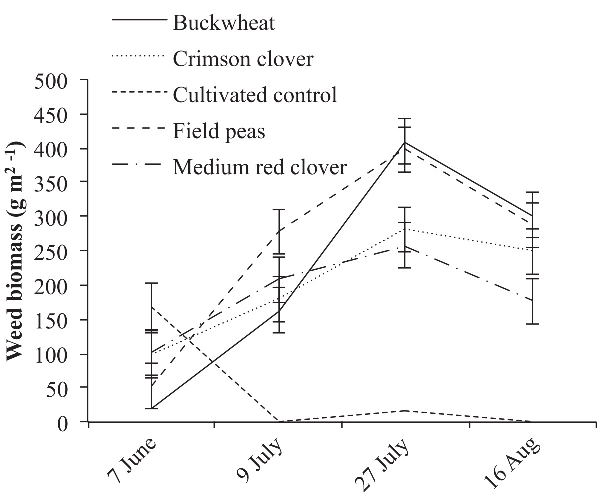

Figure 5. Total weed biomass (g m^{-2}) (± standard error across living mulch treatments) of weeds in four living mulch treatments and a cultivated control at four mowing dates, 2012.

cultivated control plot was less than in the buckwheat, field peas and crimson clover plots (Fig. 5). In 2013, weed biomass was less in the cultivated control relative to mulched treatments at the July 5, 2013 and September 5, 2013 mowing dates. At the August 7, 2013 mowing date, weed biomass was less in the cultivated control plots as compared with the buckwheat, field pea and crimson clover treatments (Fig. 6). Though there are a few instances of significant differences among living mulches, no treatment provided effective full season weed control.

Though difference in density of both grass and broadleaf weeds existed at a few particular mowing dates, all differences in both grass and broadleaf weed density were between the cultivated control and other treatments, with lower weed density in the cultivated control (Table 6). Weed density was less in the cultivated control than in all other treatments at the July 9, July 27 and August 16, 2012 mowing dates. No trends were evident between the living mulch treatments and either biomass or density of grass or broadleaf weeds (broadleaf and grass or sedge data not shown).

Discussion

The objective of this study was to evaluate the effectiveness of living mulch systems in small-scale organic diversified vegetable production, specifically examining whether living mulches can reduce weed pressure or labor inputs in small-scale operations. The overall inverse relationship observed between living mulch growth and weed density supports previous research demonstrating that cover crops and living mulches can effectively suppress weed establishment and growth (Enache and Ilnicki, 1990; Infante and Morse, 1996; Teasdale, 1996). However, reduced vegetable yields in the living mulch treatments relative to the cultivated control demonstrates that competition for resources from both weeds and living mulches impacted overall crop productivity. Yields in living mulch treatments were the most depressed in the broccoli plots, though statistical comparisons were not conducted between vegetables. Previous studies have also shown the potential of competition for light, water and nutrients using these production strategies (Altieri et al., 1985; Brandsaeter et al., 1998; Biazzo and Masiunas, 2000; Brainard et al., 2012). Although initially hypothesized to lower in-season weed management labor inputs, the living mulch systems resulted in greater labor needs for overall management.

Several factors may have limited the success of this system. Relatively high prior weed pressure on this field site may have reduced vegetable yield. In their 1996 study of broccoli overseeded with legume living mulches, Infante and Morse (1996) found that broccoli yield was reduced where initial weed pressure was high while yield

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Table 6. Weed biomass (g m^{-2}) and density (plants m^{-2}) (± standard error across living mulch treatments, within the same year) in 2012 and 2013 relative to four living mulch treatments and a cultivated control.

Living mulch	2012 Biomass (g m^{-2})	2012 Density (plants m^{-2})	2013 Biomass (g m^{-2})	2013 Density (plants m^{-2})
Buckwheat	223 a	233 ab	251 a	281 a
Crimson clover	202 a	347 a	187 bc	213 a
Field peas	254 a	199 ab	237 ab	207 a
Medium red clover	186 a	265 ab	149 c	222 a
Cultivated control	47 b	102 b	30 d	60 b

Column means with the same letter were not significantly different across living mulch treatments, within the same year at $P \leq 0.05$. All data are shown without transformation. Standard error for all treatments: Biomass: 20.8472 in 2012, 13.9579 in 2013; density: 43.2523 in 2012, 29.3023 in 2013.

was comparable with control plots where initial weed pressure was low. Though results from our study demonstrate that a living mulch system is inappropriate for a production field with high existing weed pressure, a similar living mulch system in a field with a lower weed seedbank and less weed competition may result in vegetable yield and management requirements more similar to tilled production.

Drought stress in 2012 is assumed to have significantly impacted results with respect to living mulch performance and vegetable crop yield. Though initial living mulch germination was successful, cover establishment was slow, likely due to limited water availability. Additionally, drought conditions likely exacerbated the competition of vegetable and living mulches for water and nutrients (Coolman and Hoyt, 1993; Brainard et al., 2004). Though water was applied to all vegetable crops, drought conditions combined with hot temperatures made application of adequate water difficult using the available irrigation system.

Management time, including mowing and hand weeding within the crop row, was lowest for the non-mulched, cultivated control plots. The punch-planting technique used for the bell pepper and broccoli transplants necessitated hand-weeding around individual plants, resulting in time-consuming management to limit in-row weed pressure. Bare soil in control plots allowed for much more efficient and physically easier weed control.

Though all living mulch treatments in this experiment resulted in lower vegetable yields as compared with typical cultivated management, modifications to the system from how it was implemented in this study could lead to more comparable vegetable yields and management time requirements. A strip tillage system in which vegetables are planted in a strip of bare soil, buffered by living mulch aisles could be a viable alternative to punch planting and may achieve many of the same cover crop benefits of reduced erosion and soil building with less competition with the primary crop (Brainard et al., 2013). A strip tillage system also offers the benefit of easier in-row management, lowering labor requirements to manage the system. In any living mulch system, it will be important to choose mulch crops that establish quickly for early season weed control but are also able to tolerate mowing. Existing research has focused on mulch control using sub-lethal herbicide applications but organic systems will have to find mulch species that can tolerate mowing. A low or slow growing habit that minimizes competition with the primary crop will also be beneficial. Due to the extreme drought during the first year of this study, living mulches were observed to compete for, rather than conserve, soil moisture. Under different environmental conditions, this aspect of inter-planting could produce significantly different results.

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