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Significance of herbicide order in sequential applications to target weeds in a sunn hemp living mulch

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Research Article

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Nomenclature:
Metribuzin; rimsulfuron; common lambsquarters; *Chenopodium album* L.; common purslane; *Portulaca oleracea* L.; hairy galinsoga; *Galinsoga quadriradiata* Cav.; Powell amaranth; *Amaranthus powellii* S. Watson; sunn hemp; *Crotalaria juncea* L.

Keywords:
Cropping system diversification; herbicide reduction; integrated weed management; intercropping; living mulch management; resource use efficiency; soil cover; soil erosion control; sustainable vegetable production

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Abstract

Striking a balance between the weed control capacity of living mulches and their competition with the main crop is complex. At rates that avoid severe injury to living mulch, herbicides may reduce their vigor while simultaneously contributing to weed control. In a 2-yr field study carried out in Freeville, NY, we evaluated the effects of various combinations consisting of two herbicides, applied sequentially at reduced rates, on the growth of a sunn hemp living mulch and weeds (including common lambsquarters, common purslane, hairy galinsoga, and Powell amaranth). When a herbicide with primarily POST activity (Type 1; e.g., rimsulfuron, 0.005 to 0.007 kg ai ha^{-1}) was applied first, performance of sunn hemp (1700 to 3900 kg ha^{-1} dry biomass; 10% to 88% groundcover) was poor and weed growth (25% to 62% groundcover) was high, likely because sunn hemp was severely injured at a young growth stage and was outcompeted by weeds. A follow-up application (approximately 2 wk later) of a herbicide with primarily PRE and residual activities (Type 2; e.g., metribuzin, 0.05 to 0.15 kg ai ha^{-1}), with a surfactant to enhance its POST activity, had little effect on established weeds. However, because sunn hemp was already 20 cm tall at weed emergence, applying a Type 2 herbicide first did not cause severe injury to sunn hemp and reduced weed pressure, thereby also enhancing sunn hemp performance (3,800 to 6,100 kg ha^{-1} dry biomass; 85% to 94% groundcover). Moreover, the follow-up application of a Type 1 herbicide affected the smaller weeds more (4% to 21% groundcover) than the better-established sunn hemp. Our results demonstrate that an appropriate sequence of herbicides at reduced rates may be important to control weeds while maintaining a healthy living mulch stand.

Introduction

As interest in implementing sustainable farming practices has increased during the past few decades, cover crops have also increased in popularity. Cover crops are typically grown during fallow periods after cash crop harvest; however, as living mulches growing alongside cash crops, they can provide additional benefits. Cropping system benefits of living mulches include improved soil health, resource-use efficiency and organic matter return, and reduced soil erosion (Hall et al. 1984; Hartwig and Ammon 2002; Leary and DeFrank 2000; Masiunas 1998; Teasdale et al. 2007). Living mulches can also suppress weeds in both grain and vegetable crops more effectively than cover crop residue (Liebman and Dyck 1993; Teasdale 1996, 1998; Teasdale et al. 2007).

The benefits of living mulches, including as alternatives to interrow cultivation, occur in both annual and perennial living mulch systems (Bhaskar et al. 2018; Grabber and Jokela 2013; Hartwig and Ammon 2002; Liebman and Dyck 1993; Teasdale et al. 2007). Research has often focused on perennial living mulches because they do not require annual seeding (Teasdale 1996), but annual living mulches merit further study because they may be more easily controlled with lower herbicide inputs (Hall et al. 1984; Moomaw and Martin 1976). In herbicide-managed living mulch systems, excessive herbicide injury reduces living mulch biomass and soil cover (Bhaskar et al. 2020; Linscott and Hagin 1975; Robertson et al. 1976). When living mulch injury is not severe, weed suppression by the living mulch can be acceptable, but greater injury usually provides weeds with the competitive advantage (Bhaskar et al. 2020; Echtenkamp and Moomaw 1989; Hughes and Sweet 1979). However, living mulches may not adequately suppress weeds on their own and may need to be accompanied by other management techniques such as the application of herbicides (Brainard et al. 2012; Kunz et al. 2016; Vrabel et al. 1980). Thus, herbicides should augment the level of weed suppression provided by living mulches without markedly affecting their vigor. Herbicides must also limit living mulch growth and thereby diminish competition between the living mulch and the crop. Competition is a primary risk associated with living mulch systems (Brainard and Bellinder 2004; Masiunas 1998; Teasdale 1996; Teasdale et al. 2007), especially under resource-limited conditions (Bhaskar et al. 2018; Brainard et al. 2004; Paine et al. 1995; Pfeiffer et al. 2016).

It is difficult to identify chemical control strategies that compromise neither living mulch function nor crop yield (Echtenkamp and Moomaw 1989; Hughes and Sweet 1979; Martin et al. 1999). One approach to managing these competing goals involves combining different herbicides at low rates that can facilitate quick living mulch recovery. When rates are decreased, herbicide combinations can be used to control a greater number of weed species while maintaining, or even reducing, overall herbicide input. When herbicide combinations have been used to manage living mulch, they have traditionally been sprayed in single applications (Cardina and Hartwig 1980; Hartwig 1976; Linscott and Hagin 1975). Spacing out herbicide applications temporally may provide greater consistency in soil cover (by limiting canopy loss resulting from living mulch injury) and longer-lasting weed control. Sequential applications also provide the opportunity to apply herbicides with different properties at different growth stages. Through appropriate combinations and application timing, potential differences between herbicide effects on weeds and living mulches could be used to give living mulches competitive advantages over weeds.

Asymmetric herbicide responses could result from morphological and physiological differences between weeds and living mulches. In annual living mulches, some of these factors are dependent on seedling age and are therefore sensitive to planting time. Living mulch–cash crop competition can be high when living mulches are planted too early relative to the cash crop (Brainard and Bellinder 2004; Brainard et al. 2004; Vrabel et al. 1980). Other benefits associated with living mulches, including weed suppression and soil cover, may be greater when living mulches are planted early (Brainard et al. 2004; Brainard and Bellinder 2004). In some cases, the optimal time for living mulch planting is close to the time of cash crop planting (Vrabel et al. 1980).

In a recently published study (Bhaskar et al. 2020), we tested the effects of several herbicide treatments on weeds in a tomato crop with a sunn hemp living mulch. Each treatment consisted of two temporally separated POST applications, each of which included a single herbicide and rate from the following list: fomesafen (0.012 kg ai ha^{-1}), halosulfuron (0.05 to 0.053 kg ai ha^{-1}), metribuzin (0.08 to 0.15 kg ai ha^{-1}), and rimsulfuron (0.007 to 0.017 kg ai ha^{-1}). Our results indicated that treatments that began with metribuzin, a primarily PRE herbicide with its POST activity enhanced by a surfactant, were the most effective in suppressing weeds by killing newly emerged weed-seedlings and preventing future emergence through residual activity, with minimal adverse impact on crop yield. The use of residual herbicides may reduce herbicide inputs (Moomaw and Martin 1976) and damage to crops and living mulch. Metribuzin was most effective when followed by a herbicide with greater POST activity.

The study presented here builds upon our earlier report by describing the effects of a greater variety of herbicides and rates on a simplified system containing only sunn hemp and weeds. Using two-step herbicide treatments (similar to that reported by Bhaskar et al. 2020), we tested combinations of fomesafen, halosulfuron, imazethapyr, metribuzin, rimsulfuron, and *S*-metolachlor. Based on preliminary greenhouse and field evaluations, we hypothesized that a primarily PRE herbicide such as metribuzin followed by a primarily POST herbicide would provide more effective weed control with lower living mulch injury than other sequences/combinations. We also hypothesized that some herbicide treatments would have disproportionate effects on weeds relative to the living mulch at the relatively low application rates evaluated here. The objective of the study was to identify such treatments, which would represent an important step toward improved control of competitive dynamics in living mulch systems.

Materials and Methods

Field trials were conducted in 2015 and 2016 at the Homer C. Thompson Vegetable Research Farm in Freeville, NY (42.5298°N, 76.3126°W). Soils at this location are Howard gravelly loam (Loamy-skeletal mixed mesic Glosoboric Hapludalf) with a pH range of 6.0 to 6.6. Different fields were used each year. Although cash crops were not planted in this experiment, the sunn hemp is referred to as living mulch because we evaluated management practices for that purpose.

Field Preparation and Planting

To prepare for planting, fields were moldboard-plowed, disked, harrowed, and fertilized with nitrogen, phosphorus, and potassium, each applied at the standard rate of 100 kg ha^{-1} using 13-13-13 (N-P-K). Sunn hemp (Hancock Seed Co., Dade City, FL) was seeded at a row spacing of 23 cm using a grain drill (2010, Model KED-72, Eco-Drill, Kasco Mfg., Shelbyville, IN) on June 4, 2016. In 2015, sunn hemp was replanted on July 6, after the first planting in late May failed to establish following unusually heavy rains. Sunn hemp was seeded at rates of 65 and 90 kg ha^{-1} in 2015 and 2016, respectively, in 1.8-m-wide strips. The variation occurred because the drill lacked a setting appropriate for sunn hemp seeds. For the same reason, final seeding rates exceeded the intended rate of 55 kg ha^{-1} (which was already slightly higher than typically recommended rates because we considered it necessary to achieve rapid and complete establishment). Within the seeded strips, treatments were randomly assigned to 1.8-m by 3.1-m plots. The experiment was set up as a randomized complete block design with three replicates. No irrigation was provided in 2015 because it was a wet year. In 2016, irrigation (total for the season of approximately 60 mm) was provided several times due to severe drought conditions.

Herbicide Treatments

We tested the effects of fomesafen, halosulfuron, imazethapyr, metribuzin, rimsulfuron, and *S*-metolachlor (Table 1) on living mulch and weeds. All herbicide applications included a nonionic surfactant at 0.25% of spray volume to increase POST activity by facilitating flow onto and absorption into plant tissues (Hess and Foy 2000). Treatments consisting of the herbicides listed above were assumed to be inadequate for grass weed control, so sethoxydim (0.27 kg ai ha^{-1}; Table 1) was also applied across the entire field. These sethoxydim applications did not have any visible effects on sunn hemp. Weed data reported here do not differentiate between broad-leaved and grass weeds and may include grasses not killed by the sethoxydim application. No other methods of weed control, including hand-weeding, were used.

Table 1. Application rates and product details of herbicides used in 2015 (July to October) and 2016 (June to September) living mulch (sunn hemp) trials in Freeville, NY.

Herbicide	Rate	Type[a]	Trade name	Manufacturer	Address
	kg ai ha^{-1}				
Fomesafen	0.012	1	Reflex	Syngenta Crop Protection LLC	Greensboro, NC
Fomesafen	0.016	1	Reflex		
Halosulfuron	0.05	2	Sandea	Gowan Co.	Yuma, AZ
Imazethapyr	0.04	2	Pursuit	BASF Corp.	Research Triangle Park, NC
Metribuzin	0.05	2	Sencor	Bayer CropScience LP	Research Triangle Park, NC
Metribuzin	0.1	2	Sencor		
Metribuzin	0.15	2	Sencor		
Rimsulfuron	0.005	1	Matrix	DuPont Crop Protection	Wilmington, DE
Rimsulfuron	0.007	1	Matrix		
S-metolachlor	0.35	1	Dual Magnum	Syngenta Crop Protection LLC	Greensboro, NC
Sethoxydim[b]	0.27	–	Poast	BASF Corp.	Research Triangle Park, NC

[a]At the rates used in this study, herbicides were classified as Type 1 or Type 2 based on the sensitivity of sunn hemp to these applications. Herbicide applications that caused severe injury to sunn hemp are Type 1; herbicide applications that did not cause severe injury are Type 2.
[b]Sethoxydim was applied to all plots because the herbicide treatments were considered to be inadequate for grass weed control. Therefore, sethoxydim is not considered as a treatment.

Table 2. Herbicide treatments used on living mulch (sunn hemp) in 2015 (July to October) and 2016 (June to September) in Freeville, NY. Reference plots are also listed.[a, b, c]

		First application[e]		Second application	
Treatment type[d]	Treatment	Herbicide	Rate	Herbicide	Rate
			kg ai ha^{-1}		kg ai ha^{-1}
	Untreated living mulch check (no herbicide treatments, no hand-weeding)				
	Weedy check (no living mulch, no herbicide treatments, no hand-weeding)				
Type 2 fb Type 2	Metribuzin fb halosulfuron	Metribuzin	0.05	Halosulfuron	0.05
Type 2 fb Type 1	Metribuzin fb rimsulfuron rate I	Metribuzin	0.05	Rimsulfuron	0.005
	Metribuzin fb halosulfuron	Metribuzin	0.05	Halosulfuron	0.05
	Metribuzin fb fomesafen	Metribuzin	0.1	Fomesafen	0.012
	Metribuzin fb rimsulfuron rate II	Metribuzin	0.1	Rimsulfuron	0.007
	Imazethapyr fb rimsulfuron	Imazethapyr	0.04	Rimsulfuron	0.007
	Imazethapyr fb fomesafen	Imazethapyr	0.04	Fomesafen	0.012
Type 1 fb Type 1	*S*-metolachlor fb rimsulfuron	*S*-metolachlor	0.35	Rimsulfuron	0.007
	S-metolachlor fb fomesafen	*S*-metolachlor	0.35	Fomesafen	0.016
Type 1 fb Type 2	Rimsulfuron fb metribuzin	Rimsulfuron	0.007	Metribuzin	0.15
	Fomesafen fb metribuzin	Fomesafen	0.012	Metribuzin	0.15

[a]All herbicide applications included a non-ionic surfactant at 0.25% spray volume.
[b]Abbreviation: fb, followed by.
[c]Sunn hemp was planted at 23-cm row spacing.
[d]At the rates used in this study, herbicides were classified as Type 1 or Type 2 based on the sensitivity of sunn hemp to these applications. Herbicide applications that caused severe injury to sunn hemp are Type 1; herbicide applications that did not cause severe injury are Type 2.
[e]First applications were made approximately 25 d after living mulch emergence (at approximately 75% soil cover); second applications were made approximately 15 d later.

Herbicide treatments included two herbicides applied individually in two separate applications (Table 2). They are referred to as "(first herbicide) fb (second herbicide)," where fb means "followed by" in a sequential application. Based on greenhouse and preliminary field evaluations of living mulch sensitivity, the herbicides were classified into two types. At the rates used, Type 1 [fomesafen (at both rates), rimsulfuron (at both rates), and *S*-metolachlor (single rate)] herbicides were more injurious than Type 2 [halosulfuron, imazethapyr, and metribuzin (at all rates)] herbicides. To illustrate the effects of different combinations of the two herbicide types, results are also presented in terms of the following treatment groups: Type 1 fb Type 1, Type 1 fb Type 2, Type 2 fb Type 1, and Type 2 fb Type 2. We included two controls: an untreated sunn hemp check (living mulch without herbicides) and a weedy check (neither living mulch nor herbicides). Both these check plots received the sethoxydim applications applied to treatment plots.

Herbicides were applied using a CO_2-pressurized backpack sprayer fitted with a four-nozzle [8003 EVS flat fan (TeeJet Technologies®, Spraying Systems Co., P.O. Box 7900, Wheaton, IL)] boom of 1.8-m swath, operating at 200 to 240 kPa pressure and delivering a spray volume of approximately 320 L ha^{-1}. The first set of herbicides was applied when sunn hemp seedlings were 20 cm tall at approximately 25 d after emergence (late June in 2016; late July in 2015), and the second set was made approximately 15 d later.

Data Collection

Percent cover of living mulch, percent cover of weeds, and living mulch height were measured four times at 2- to 3-wk intervals between mid-July and early October in 2015 and mid-July and late August in 2016. In 2016, aboveground biomass and density were measured at the end of August, aimed to coincide with the typical start of vegetable harvests in the region. Due to late planting in 2015, aboveground biomass and density data were collected in early October that year. Biomass and density of living mulch were determined from two randomly selected 50-cm-long segments of

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living mulch row, at least 60 cm away from plot edges. Biomass and density of weeds were determined from two randomly selected 0.25-m^2 (50 cm by 50 cm) areas at least 60 cm away from plot edges. Living mulch and weeds were cut at ground level and oven-dried for 2 wk at 75 C to estimate dry biomass.

Data Analyses

Living mulch (cover, height, density, and biomass) and weed (cover, density, and biomass) parameters were subjected to ANOVA and regression analyses at the 5% level of significance. ANOVA was used to test whether any treatment means differed and linear mixed-effects models followed by a post hoc test, Tukey's honestly significant difference test, were used to determine treatment differences. We also used regression to test whether variation in living mulch parameters were associated with variation in weed parameters. Data were not combined across years due to very different climatic conditions in 2015 and 2016. In regression models, herbicide treatments were included as fixed effects and block was included as a random effect. No data transformations were needed to meet model assumptions. Statistical analyses were performed using JMP Pro 12.0.1 (2013 SAS Institute Inc., Cary, NC) software.

Results and Discussion

Weather and Interannual Variation

At the trial site, the 30-yr average for rainfall from May to August was 404 mm (Northeast Regional Climate Center 2020). In 2015, 451 mm rainfall were recorded during this period, so soil moisture was not deemed limiting. In 2016, rainfall was only 239 mm, which included a prolonged drought (120 mm rainfall from May to July, compared with 395 mm in 2015). In both years, temperatures were low enough by late September to curb the growth of the warm-season sunn hemp. Flowering in sunn hemp was negligible and no seed set was observed.

Major weeds in the experimental plots were common lambsquarters, common purslane, hairy galinsoga, Powell amaranth, and shepherd's purse [*Capsella bursa-pastoris* (L.) Medik.]. In 2015, replanting of sunn hemp during early July, compared with June planting in 2016, likely reduced overall weed pressure in the field by eliminating the impact of a potentially greater weed pressure at the beginning of the season. Maximum weed emergence may have occurred during the typical vegetable planting time in June. In a previous study at the same farm, rye (*Secale cereale* L.) interseeded in broccoli (*Brassica oleracea* L. var. *italica*) a few weeks later than typical planting time had no pronounced effect on weeds because the later weed emergence was weak (Brainard and Bellinder 2004). Above-average rainfall in 2015 also likely moderated the effects of the living mulch and herbicides on weeds. The abundance of soil moisture could have eliminated competition for water between the living mulch and weeds and hastened recovery from herbicide injury.

In 2016, severe drought conditions enhanced the competitive effects of living mulch on weeds, potentially increasing differences between treatments. Soil moisture is an important influence on competitive dynamics in living mulch systems (Bhaskar et al. 2018; Echtenkamp and Moomaw 1989). The difference in seeding rate represents a less likely explanation for interannual variation, given that living mulch stand density was similar between years (Tables 3 and 4). However, eliminating this possibility would require experiments on seeding rates, which would also help improve management recommendations.

Effects on Living Mulch

In 2015, living mulch biomass was relatively consistent across herbicide treatments (3,800 to 5,800 kg ha^{-1}) and did not differ between the herbicide treatments and the untreated check (7,000 kg ha^{-1}), except for the metribuzin fb fomesafen treatment (3,800 kg ha^{-1}; $P = 0.027$; Table 3; Figure 1A). Similarly, living mulch density in 2015 did not differ across herbicide treatments ($P = 0.9$) or herbicide-type combinations ($P = 0.86$). In 2016, most herbicide treatments did not decrease living mulch biomass and cover or increase living mulch mortality (i.e., reduce stand density; Table 4). Taken together, these findings demonstrate that appropriate herbicide applications can avoid living mulch mortality and maintain biomass and cover. It is desirable that herbicides do not cause living mulch mortality because the density of living mulch stands is crucial to their function; gaps in a stand can allow weed outbreaks (Echtenkamp and Moomaw 1989; Hughes and Sweet 1979).

Throughout the 2016 season, in mid-July (18%; $P < 0.0001$), late July (13%; $P < 0.0001$), and early August (15%; $P < 0.0001$), Type 1 (fomesafen, rimsulfuron, or *S*-metolachlor) fb Type 2 (halosulfuron, imazethapyr, or metribuzin) herbicides had lower living mulch cover than all other herbicide-type combinations and the untreated check (Figure 1B). By late August, living mulch in Type 1 fb Type 2 had regrown to provide only 52% cover, which was still lower ($P = 0.0004$) than in the other herbicide-type combinations (93% to 98%). In early August, weed cover in Type 1 fb Type 2 and the weedy check (74% and 92%, respectively) were similar ($P = 0.59$). These results are consistent with other reports of increased weed pressure following severe herbicide damage to living mulch (Bhaskar et al. 2020; Echtenkamp and Moomaw 1989; Hartwig 1977; Hughes and Sweet 1979). When applied first, Type 1 herbicides caused severe injury to the young living mulch with prolonged recovery times. For example, living mulch biomass in fomesafen fb metribuzin (among the herbicides, fomesafen caused the most severe living mulch injury) was only 1700 kg ha^{-1} (Table 4), which was lower than living mulch biomass in treatments with a first application of a Type 2 herbicide ($P = 0.0002$). In some cases, weeds that emerged following Type 1 herbicide applications could have avoided serious injury because these herbicides may have weaker residual soil activity. The resulting increase in weed pressure could have further inhibited living mulch growth.

Living mulch height in 2016 exhibited the same pattern (Table 4; Figure 1B). Type 1 fb Type 1, Type 2 fb Type 1, and Type 2 fb Type 2 were similar to each other and to the untreated check throughout the season, while living mulch in Type 1 fb T ype 2 was shorter ($P = 0.0005$ in mid-July; $P < 0.0001$ in late July; $P < 0.0001$ in early August; $P < 0.0001$ in late August). Reductions in living mulch height are expected from herbicide applications and are positive outcomes because living mulch height has considerable influence on crop yield (Greenland 2000; Hinds et al. 2016; Zandstra and Warncke 1993). Tall living mulches can easily become too competitive with crops by shading both the side and top portions of the crop canopy. In an earlier study (Echtenkamp and Moomaw 1989), crop yields were reduced by 15% in the presence of a shorter chewings fescue [*Festuca rubra* L. ssp. *fallax* (Thuill.) Nyman] but by 46% in the presence of a taller rye plus oats (*Avena sativa* L.) plus vetch (*Vicia villosa* Roth) living

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Table 3. Living mulch (sunn hemp; cover, height, stand density, and biomass) and weed (cover, density and biomass) measurements in 2015 (July to October) in Freeville, NY.[a, b, c]

Treatment	Average LM cover	Average weed cover[d]	LM cover harv.	Weed cover harv.	Average LM height	LM height harv.	LM density	Weed density	LM biomass	Weed biomass
	%[e]				cm		plants m^{-2}		kg ha^{-1}[f]	
Untreated LM check (no herbicide treatments, no hand-weeding)	88 a	6 b	93 a	4 b	104 a	95 a	87 a	20 a	7000 a	180 b
Weedy check (no LM, no herbicide treatments, no hand-weeding)	–	47 a	–	46 a	–	–	–	27 a	–	2180 a
Metribuzin[g, h, i] (0.05)[j] fb halosulfuron (0.05)	88 a	3 b	93 a	2 b	86 ab	85 a	100 a	11 a	5000 ab	60 b
Metribuzin (0.05) fb rimsulfuron (0.005) rate I	81 ab	5 b	84 a	3 b	82 ab	80 a	85 a	19 a	4300 ab	140 b
Metribuzin (0.1) fb fomesafen (0.012)	68 ab	4 b	83 a	3 b	81 ab	85 a	97 a	13 a	3800 b	110 b
Metribuzin (0.1) fb rimsulfuron (0.007) rate II	82 ab	4 b	82 a	3 b	79 b	79 a	100 a	18 a	4300 ab	150 b
Imazethapyr (0.04) fb rimsulfuron (0.007)	83 ab	5 b	87 a	3 b	83 ab	86 a	102 a	13 a	5800 ab	190 b
Imazethapyr (0.04) fb fomesafen (0.012)	76 ab	3 b	91 a	2 b	78 b	80 a	112 a	16 a	4700 ab	130 b
S-metolachlor (0.35) fb rimsulfuron (0.007)	79 ab	8 b	94 a	5 b	88 ab	86 a	87 a	17 a	5300 ab	430 b
S-metolachlor (0.35) fb fomesafen (0.016)	65 ab	8 b	92 a	5 b	80 b	87 a	100 a	28 a	4400 ab	450 b
Rimsulfuron (0.007) fb metribuzin (0.15)	86 a	4 b	86 a	3 b	79 b	76 a	98 a	17 a	4600 ab	320 b
Fomesafen (0.012) fb metribuzin (0.15)	54 b	5 b	21 a	3 b	82 ab	86 a	95 a	16 a	4700 ab	230 b
Standard error	6	0.9	2.4	0.9	5.1	5.4	11.3	5.2	600	300

[a]Values within a column followed by a same letter are not significantly different according to Tukey's test ($\alpha = 0.05$).
[b]Abbreviations: LM, living mulch; harv., harvest during late August, typical vegetable harvest time in the region; fb, followed by.
[c]Sunn hemp was planted at 23-cm row spacing.
[d]Average values are the means of four time points 2 to 3 wk apart, including the late August (harv.) time-point.
[e]Visual estimations (percentages) are in absolute terms, so living mulch and weed cover may not add to 100%.
[f]Oven-dried (2 wk at 75 C) dry matter.
[g]All herbicide applications included a nonionic surfactant at 0.25% spray volume.
[h]First applications were made approximately 25 d after living mulch emergence (at approximately 75% soil cover); second applications were made approximately 15 d later.
[i]Fomesafen, rimsulfuron, and *S*-metolachlor are referred to in the text as Type 1 herbicides; halosulfuron, imazethapyr, and metribuzin are Type 2 herbicides. At the rates used in this study, herbicides were classified as Type 1 or Type 2 based on the sensitivity of sunn hemp to these applications. Herbicide applications that caused severe injury to sunn hemp are Type 1; herbicide applications that did not cause severe injury are Type 2.
[j]Herbicide rates in kg ai ha^{-1} are given within parentheses.

mulch, even though both living mulches produced similar biomass. In our study, however, the reduction in height was associated with reductions in living mulch biomass and cover, which are antithetical to some of the objectives of living mulch systems.

Effects on Weeds

In 2015, weed biomass in herbicide-type combinations (60 to 440 kg ha^{-1}) was not different from weed biomass in the untreated check (180 kg ha^{-1}) but was lower than in the weedy check (2180 kg ha^{-1}; $P < 0.0001$; Table 3). However, weed density was similar in all treatments (11 to 28 plants m^{-2}), including the weedy check (27 plants m^{-2}; $P = 0.5$). In 2016, weed cover decreased ($P < 0.0001$) with increasing living mulch biomass, but there was no relationship between weed density and living mulch biomass ($P = 0.6$). In late August 2016, weed biomass was negatively associated with both living mulch biomass ($P = 0.002$) and living mulch cover ($P = 0.007$). These findings suggest that the living mulch-herbicide treatments stunted weed growth through competitive and chemical stresses rather than killing them.

Negative relationships between weed biomass or cover and living mulch biomass or cover are consistent with reports of greater weed suppression by more vigorous living mulch stands and are considered to be evidence of living mulch efficacy (Bhaskar et al. 2018; Mohammadi 2012; Teasdale et al. 2007). In chemical management of living mulches, a major constraint is that herbicide rates designed to maximize crop yield often cause severe damage to living mulches (Hartwig and Hoffman 1975) and thereby reduce their efficacy. Unless crop-mulch competition is stronger than crop-weed competition (Chase and Mbuya 2008), this problem may be tractable. Herbicide treatments with greater effects on weeds than on the living mulch could help make satisfactory crop yields possible without excessively compromising living mulch function. Some of our results would be consistent with such asymmetrical effects: several herbicide treatments consistently resulted in high living mulch biomass and cover in addition to low weed biomass and cover. However, these experiments did not provide statistical evidence to either support or reject our hypothesis that some herbicide treatments would injure weeds more than they injured the living mulch. More quantitative testing for asymmetry will involve collecting more data from untreated plots to determine whether the presence of herbicides affects the slope of the relationship between weed biomass and living mulch biomass.

Management Implications

The results demonstrate that sunn hemp may be an effective tool for weed control when used as a living mulch. The untreated check

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Table 4. Living mulch (sunn hemp; cover, height, stand density, and biomass) and weed (cover, density and biomass) measurements in 2016 (June to September) in Freeville, NY.[a, b, c]

Treatment	Average LM cover	Average weed cover[d]	LM cover harv.	Weed cover harv.	Average LM height	LM height harv.	LM density	Weed density	LM biomass	Weed biomass
	%[e]				cm		plants m^{-2}		kg ha^{-1}[f]	
Untreated LM check (no herbicide treatments, no hand-weeding)	88 a	22 bcd	95 a	31 b	64 ab	106 a	174 a	103 a	5500 a	1100 bc
Weedy check (no LM, no herbicide treatments, no hand-weeding)	–	57 a	–	98 a	–	–	–	160 a	–	4200 a
Metribuzin[g, h, i] (0.05)[j] fb halosulfuron (0.05)	90 a	8 cd	97 a	8 b	65 a	114 a	141 a	81 a	6100 a	1000 bc
Metribuzin (0.05) fb rimsulfuron (0.005) rate I	94 a	14 bcd	99 a	21 b	65 a	107 a	138 a	89 a	5600 a	800 bc
Metribuzin (0.1) fb fomesafen (0.012)	85 a	9 cd	99 a	13 b	55 ab	100 ab	148 a	57 a	3800 ab	700 bc
Metribuzin (0.1) fb rimsulfuron (0.007) rate II	87 a	4 d	98 a	6 b	52 bc	96 ab	131 a	57 a	5600 a	300 c
Imazethapyr (0.04) fb rimsulfuron (0.007)	92 a	15 bcd	99 a	21 b	65 a	108 a	131 a	116 a	5200 a	700 bc
Imazethapyr (0.04) fb fomesafen (0.012)	85 a	21 bcd	97 a	31 b	63 ab	103 ab	112 a	103 a	5200 a	600 bc
S-metolachlor (0.35) fb rimsulfuron (0.007)	86 a	25 bc	92 a	24 b	64 ab	100 ab	146 a	129 a	3900 ab	1500 bc
S-metolachlor (0.35) fb fomesafen (0.016)	88 a	31 b	94 a	30 b	67 a	107 a	130 a	118 a	3900 ab	1600 b
Rimsulfuron (0.007) fb metribuzin (0.15)	38 b	56 a	89 a	28 b	42 cd	84 bc	107 a	69 a	3700 ab	1100 bc
Fomesafen (0.012) fb metribuzin (0.15)	10 c	62 a	15 b	82 a	36 d	68 c	100 a	53 a	1700 b	1600 b
Standard error	2.5	4.5	2.6	6.4	2.9	4.1	21	24	500	200

[a]Values within a column followed by a same letter are not significantly different according to Tukey's test ($\alpha = 0.05$).
[b]Abbreviations: LM, living mulch; harv., harvest during late August, typical vegetable harvest time in the region; fb, followed by.
[c]Sunn hemp was planted at 23-cm row spacing.
[d]Average values are the means of four time points 2 to 3 wk apart, including the late August (harv.) time-point.
[e]Visual estimations (percentages) are in absolute terms, so living mulch and weed cover may not add to 100%.
[f]Oven-dried (2 wk at 75 C) dry matter.
[g]All herbicide applications included a nonionic surfactant at 0.25% spray volume.
[h]First applications were made approximately 25 d after living mulch emergence (at approximately 75% soil cover); second applications were made approximately 15 d later.
[i]Fomesafen, rimsulfuron, and *S*-metolachlor are referred to in the text as Type 1 herbicides; halosulfuron, imazethapyr, and metribuzin are Type 2 herbicides. At the rates used in this study, herbicides were classified as Type 1 or Type 2 based on the sensitivity of sunn hemp to these applications. Herbicide applications that caused severe injury to sunn hemp are Type 1; herbicide applications that did not cause severe injury are Type 2.
[j]Herbicide rates in kg ai ha^{-1} are given within parentheses.

suppressed weeds in both 2015 and 2016, even more effectively than some herbicide treatments (Tables 3 and 4). For instance, in late August 2016, weed cover in the untreated check was 31%, whereas weed cover in the Type 1 fb Type 2 herbicide combination was 55% (Figure 1B). These results suggest that unless designed appropriately, herbicide applications may be redundant or even detrimental to weed control. However, improved weed control is not productive if crops suffer from excessive competition with the living mulch. Combining living mulches with properly designed herbicide regimes may provide the same effective weed control as an untreated living mulch (or more effective weed control under higher weed pressure) while also reducing competition between the living mulch and the cash crop.

The capacity of the living mulch to suppress weeds in the absence of herbicides, along with the effects of herbicides on living mulch and weeds in Type 1 fb Type 2, provide insight into the excellent weed control in Type 2 fb Type 1. In 2016, weed biomass in Type 2 fb Type 1 (600 kg ha^{-1}) was lower than weed biomass in Type 1 fb Type 1 ($P = 0.0009$) and Type 1 fb Type 2 ($P = 0.012$; Table 4). Type 2 fb Type 1 (19%) and Type 2 fb Type 2 (8%) also had the lowest weed cover in late August (Table 4; Figure 1B). At the first herbicide application, living mulch seedlings were larger than weeds because the living mulch had emerged earlier and reached a height of approximately 20 cm by the time of weed emergence. A Type 2 herbicide applied along with a surfactant at the time of weed emergence therefore had more severe effects on weeds than on the living mulch. This injury to young weeds and the residual activity of the primarily PRE herbicides (such as metribuzin), classified as Type 2 may have jointly contributed to a period in which the living mulch could grow under low competition from weeds. This growth period may have helped the living mulch withstand the subsequent Type 1 herbicide application. At the second application, many weeds would still have been smaller than the living mulch due to residual activity from the Type 2 herbicide. Consequently, a second application of a Type 1 herbicide may again have injured weeds more than the living mulch. Thus, our findings corroborate previous work (Bhaskar et al. 2020) and support our hypothesis that treatments consisting of a Type 2 herbicide such as metribuzin followed by a more injurious herbicide would be more effective than other treatments.

Our results are consistent with the interpretation that Type 2 herbicides provide mild POST control of living mulch and weeds in addition to stronger soil residual activity against weeds. Some herbicide treatment combinations appeared to preferentially target weeds, successfully averting losses in living mulch cover, density, and biomass. Herbicides also have the potential to reduce living mulch height, although no treatment in this study reduced height without associated losses in living mulch biomass, cover, or weed

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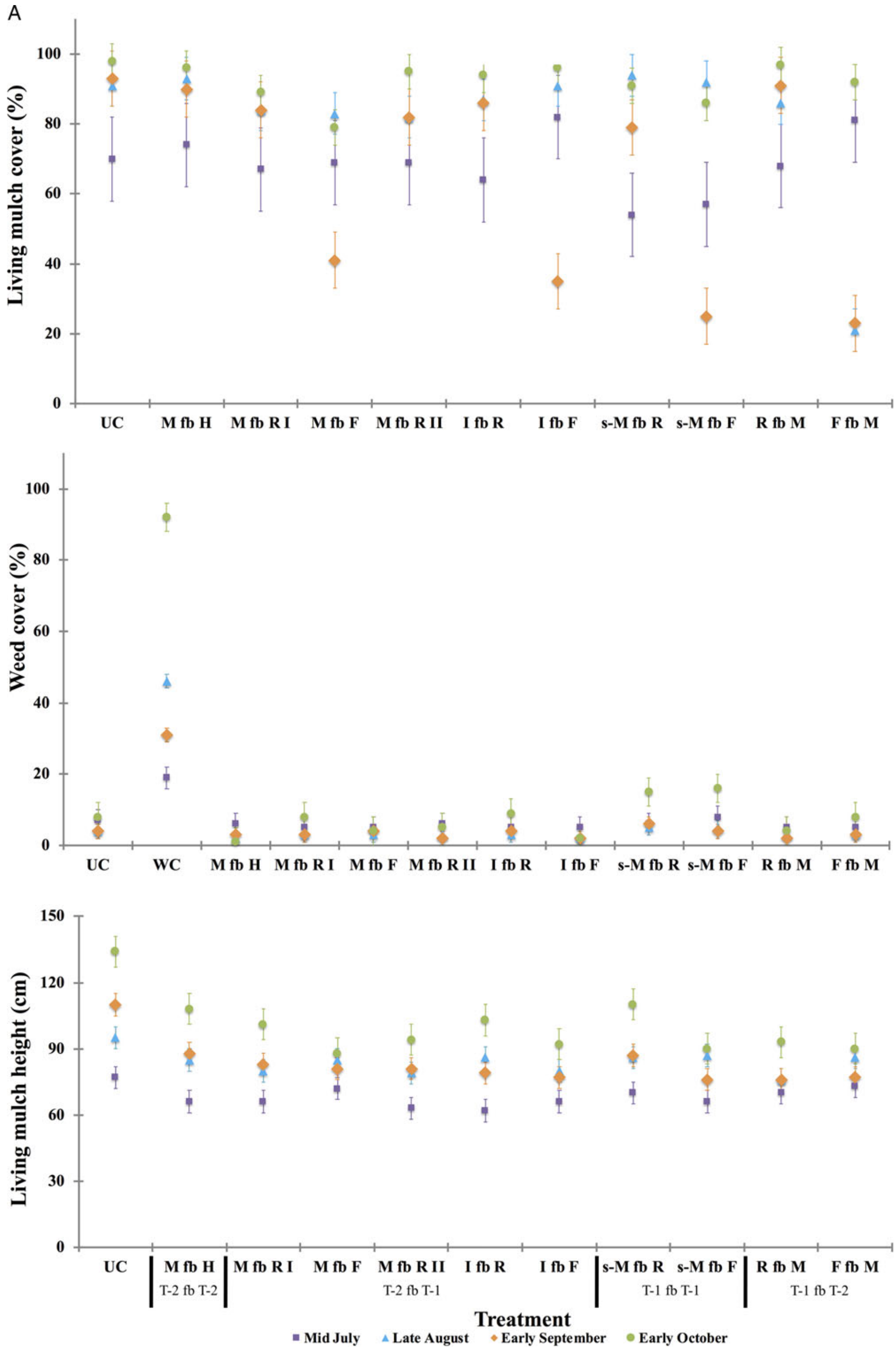

Figure 1. Living mulch (sunn hemp) cover (top), weed cover (center), and living mulch height (bottom; ± SE) at different times in 2015 (July to October; A) and 2016 (June to September; B) in Freeville, NY. Sunn hemp was planted at 23-cm row spacing. Abbreviations: T, type; fb, followed by (in a sequential application); UC, untreated living mulch check (no hand-weeding, no herbicide treatments); WC, weedy check (no living mulch, no hand-weeding, no herbicide treatments); M fb H, metribuzin followed by halosulfuron (0.05 and 0.05 kg ai ha^{-1}, respectively); M fb R I, metribuzin followed by rimsulfuron rate I (0.05 and 0.005 kg ai ha^{-1}, respectively); M fb F, metribuzin followed by fomesafen (0.1 and 0.012 kg ai ha^{-1}, respectively); M fb R II, metribuzin followed by rimsulfuron rate II (0.1 and 0.007 kg ai ha^{-1}, respectively); I fb R, imazethapyr followed by rimsulfuron (0.04 and 0.007 kg ai ha^{-1}, respectively); I fb F, imazethapyr followed by fomesafen (0.04 and 0.012 kg ai ha^{-1}, respectively); s-M fb R, *S*-metolachlor followed by rimsulfuron (0.35 and 0.007 kg ai ha^{-1}, respectively); s-M fb F, *S*-metolachlor followed by fomesafen (0.35 and 0.016 kg ai ha^{-1}, respectively); R fb M, rimsulfuron followed by metribuzin (0.007 and 0.15 kg ai ha^{-1}, respectively); F fb M, fomesafen followed by metribuzin (0.012 and 0.15 kg ai ha^{-1}, respectively). First herbicide applications were made approximately 25 d after living mulch emergence (at approximately 75% soil cover); second applications were made approximately 15 d later. Herbicide applications were classified as Type 1 or Type 2: at the rates used in this study, herbicide applications that caused severe injury to sunn hemp are Type 1; those that did not cause severe injury are Type 2. Fomesafen, rimsulfuron, and *S*-metolachlor applications are Type 1; halosulfuron, imazethapyr, and metribuzin applications are Type 2.

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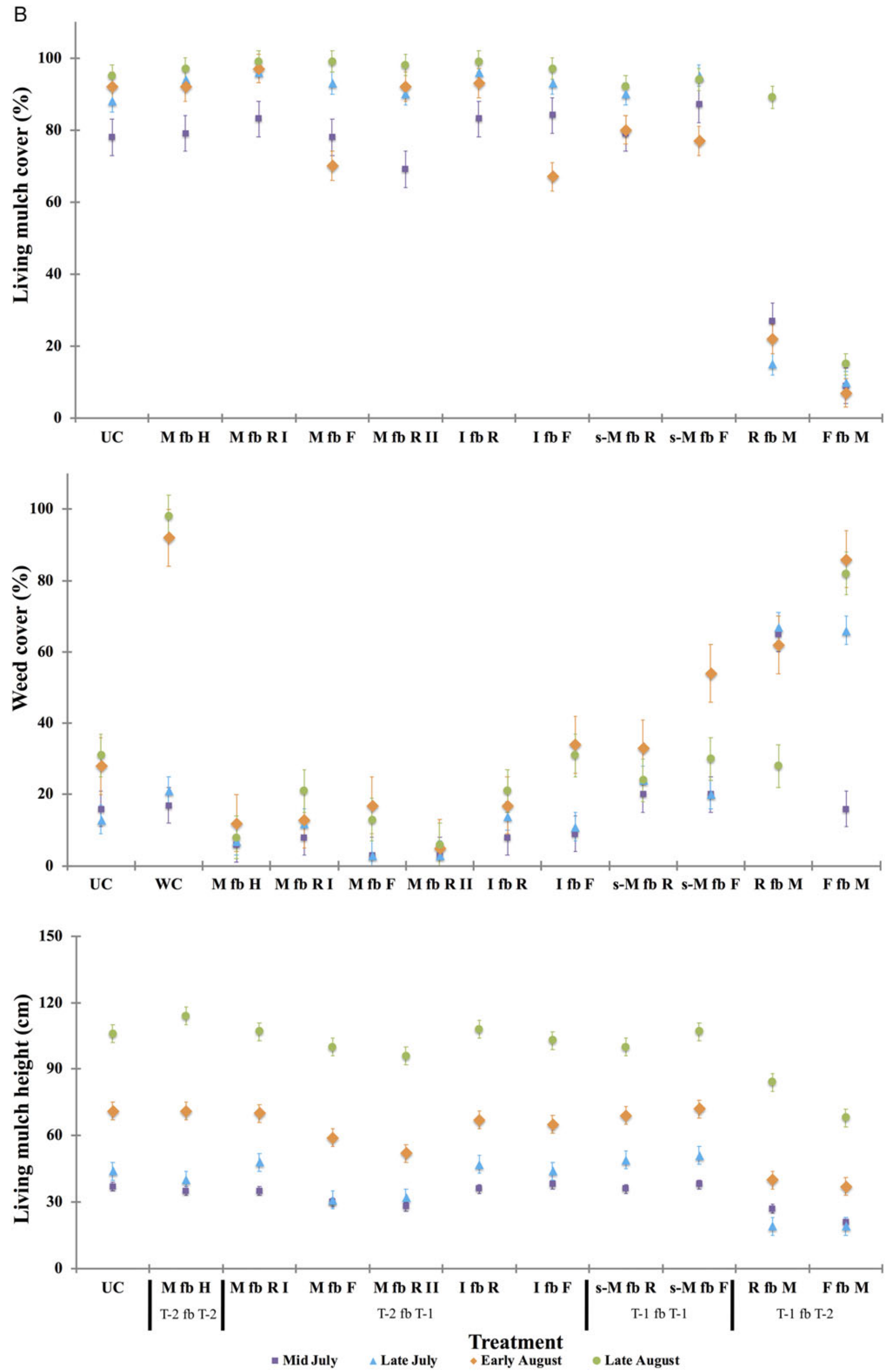

Figure 1. (*continued*)

suppression. Overall, the Type 2 fb Type 1 herbicide treatments appear to have the greatest potential to maintain healthy living mulch stands. In a planted field, variations on this treatment program could give producers finely tuned control over the interactions among crops, living mulches, and weeds. Findings from this study demonstrate that herbicide applications at reduced rates are a viable strategy for the management of living mulches and may promote sustainability by increasing the feasibility of living mulch systems.

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