



Impact of integrated sheep grazing for cover crop termination on weed and ground beetle (Coleoptera:Carabidae) communities



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ABSTRACT

Cover crops are a suite of non-marketable plant species grown to improve soil quality. They may have additional benefits including reduced weed pressure and enhanced habitat for beneficial arthropods, but they do not provide direct revenue. Integrating sheep grazing for cover crop termination could make the use of cover crops more economically feasible. However, if grazing shifts biological communities to assemblages of less desired species, producers are unlikely to use this method of cover crop termination. We compared weed and carabid beetle (Coleoptera:Carabidae) communities between cover crops terminated by sheep grazing and those terminated by mowing. Our study consisted of two trials of a two-phase experiment. In the first phase (cover crop phase), we seeded a four-species cover crop to enhance nutrient cycling and prevent erosion. The cover crop consisted of buckwheat (*Fagopyrum esculentum*), sweetclover (*Melilotus officinalis*), beets (*Beta vulgaris*), and peas (*Pisum sativum*). The cover crop grew to anthesis, and was terminated by either sheep grazing or mowing. In the second phase (cash crop phase), we sowed three cash crops through the previously grazed or mowed plots to assess legacy impacts of cover crop termination strategies on weed community structure. Both years, weed species richness and biomass were greater prior to than after cover crop termination, but overall weed diversity, species richness, and biomass did not differ between grazed and mowed plots. We found no difference in weed diversity, species richness, biomass, or density in the cash-crop phase between previously grazed and mowed plots. Despite temporal differences in species richness and activity-density, carabid diversity, species richness, and activity-density did not differ between grazed and mowed plots. Overall, our results suggest that grazing and mowing act as similar ecological filters of both weed and carabid beetle communities.

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1. Introduction

Mounting concerns about the adverse effects of high-input, industrially-managed agriculture have precipitated a call for ecologically-based management in agroecosystems (Robertson and Swinton, 2005). In contrast to industrialized approaches, which are largely dependent on synthetic inputs, ecologically-based management primarily relies on augmenting the ecological processes that provide the functions necessary for sustained production including nutrient cycling, pollination, pest suppression, regulation of soil temperature and moisture, and detoxification of noxious chemicals (Altieri, 1999). Thus, agroecologists are

increasingly interested in understanding how agricultural practices alter the biota that provide these functions in production systems (Benton et al., 2003).

In agroecosystems, organisms constitute either the planned or the associated biodiversity (Matson et al., 1997). Planned biodiversity consists of the species that a land manager intentionally includes in the system. Associated biodiversity is the suite of pest, beneficial, and neutral species not deliberately included by the land manager, but that normally live in the system or colonize it from adjacent habitats (Vandermeer et al., 2002). Changes to the associated biodiversity can have important impacts on production, such as changes in pollination efficiency (Carvalho et al., 2011), increased pest pressure (Cardinale et al., 2003), or enhanced pest suppression by natural enemies (Landis et al., 2000). Both planned biodiversity and the associated management practices act as ecological filters of the associated biodiversity, systematically favoring some species while excluding others (Funk et al., 2008). Thus, to secure the provisioning of biologically-based ecosystem

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services, it is imperative to understand how novel land management practices impact associated biodiversity before their implementation.

A cover crop is a suite of non-marketable plants grown to improve soil quality (Dabney et al., 2001). Cover crops provide direct ecosystem services for agriculture such as erosion prevention, competitive exclusion of weeds, and nutrient enhancement, as well as indirect ecosystem services such as conservation biological control (Altieri, 1999; Hartwig and Ammon, 2002). While the ecological and agronomic benefits of cover crops are well documented, less is known about using livestock grazing as a method for cover crop termination (Kahimba et al., 2008; Thiessen Martens and Entz, 2011). Furthermore, while integrating crop and livestock production has been proposed as an ecologically-based management approach to enhance the economic and environmental sustainability of agroecosystems (Hilimire, 2011; Thiessen Martens and Entz, 2011), its impact on associated biodiversity is largely unknown. The scant information that exists primarily focuses on the integration of cover crops and livestock grazing in large-scale row crop production and addresses the effects of its implementation on soil quality (Bell et al., 2011; Thiessen Martens and Entz, 2011).

To assess the extent to which sheep grazing and mowing act as different ecological filters, we conducted a three-year study comparing their effects on two agroecologically important components of the associated biodiversity: weeds and carabid beetles. Despite the recognition of weeds as a major impediment to crop production (Jordan and Votovec, 2004), they can provide a variety of ecological services such as providing habitat and resources for natural enemies of phytophages (Landis et al., 2000) and pollinator communities (Carvalho et al., 2011), enhancing nutrient cycling (Jordan and Votovec, 2004), and maintaining mutualisms with arbuscular mycorrhizal fungi that can infect crops (Votovec et al., 2007). Carabids (Coleoptera: Carabidae) are abundant in northern temperate agroecosystems and are important predators of pests such as aphids, slugs, and other beetles (Lovei and Sunderland, 1996). In addition, most carabid beetle species in the Harpalini and Zabrinini tribes are primarily seed predators during at least one stage in their lifecycle, and may therefore help regulate weed populations (Tooley and Brust, 2002).

Our study consisted of two phases. In the first one (cover crop phase), we grew a four species cover crop and terminated it by either sheep grazing or mowing. In the second phase (cash crop phase), we grew three cash crops in the plots that had a cover crop the previous year and had been terminated through either grazing or mowing. Our hypothesis was that mowing and grazing as methods of cover crop termination act as distinct ecological filters. Mowing would cut biomass several centimeters above the soil and leave the residue *in situ*. By contrast sheep should consume plant species preferentially and remove vegetative residue. Thus, we predicted that mowing would favor prostrate weed species and hygrophilous carabids, while grazing would favor weed species unpalatable to sheep and xerophilous carabids.

2. Materials and methods

Our study was conducted at Townes Harvest Farm, a 1.2 ha certified organic, diversified vegetable farm on the campus of Montana State University—Bozeman, Montana (45°40'N, 111°4'W). The farm follows a six-year rotation beginning with a cover crop season (year 1), followed by cash crops in the subsequent five growing season (years 2–6) (Charles Holt, *Pers. Comm.*). Townes Harvest Farm is underlain with Turner loam (fine loamy over sandy, mixed, superactive, frigid, typic Agriustoll), receives

approximately 380–480 mm of precipitation annually, and has a mean annual air temperature of 3.9–7.2 °C (NRCS, 2013).

The cover crop phase followed a single factor, completely-randomized design with two treatment-levels (sheep-grazing and mowing for cover crop termination) and three replicates per treatment-level. Each replicate consisted of a 10 × 15 m rectangular plot with at least a 3 m buffer between plots to avoid contamination of weed seeds between plots due to tillage (Liebman et al., 2014). On June 8, 2012 and on June 25, 2013, we cultivated the soil in all plots and seeded a four-species cover crop consisting of buckwheat (*Fagopyrum esculentum* Moench) sown at 56 kg ha⁻¹, beets (*Beta vulgaris* L.; 23 kg ha⁻¹), sweetclover [*Melilotus officinalis* (L.) Lam.; 11 kg ha⁻¹], and peas (*Pisum sativum* L.; 68 kg ha⁻¹).

Between August 3, 2012 and August 7, 2012, we terminated the cover crops at anthesis by either tractor-mowing or sheep grazing. Similar treatments were used to terminate the cover crops between August 7, 2013 and August 11, 2013. For the sheep grazed plots, we set up temporary electrical fences charged between 3500 V and 6000 V, stocked each plot with 6–11 Rambouillet yearling rams, and allowed them to graze *ad libitum* until the cover crop appeared >90% removed. In each plot, we placed a large watering trough to provide the sheep with water.

On May 24, 2012 and on June 25, 2013, prior to soil cultivation, we collected weed seedling emergence data from four randomly placed 0.44 × 0.75 m quadrats in each plot. Data were collected later in 2013 than in 2012 due to a wetter spring in 2013. At anthesis, but prior to cover crop termination, we took biomass samples of all weed species on July 25, 2012 and on August 1, 2013 for the first and second trials, respectively. Post-treatment biomass samples were also collected on September 7, 2012 and on August 30, 2013. For biomass data, we cut all plant material flush within four 0.44 × 0.75 m quadrats at the soil surface, separated it by species, and combined samples from the four quadrats. We dried all samples at 60 °C to constant mass and weighed them to the nearest 0.1 g.

In 2013 and 2014, three seedbeds were tilled to a depth of approximately 25–35 cm with a 1.07 m-diameter spader (Celli Co., Flori, Italy) through plots previously under cover crop in 2012 or 2013. These seedbeds formed the subplots for the cash crop phase of our experiment. The farm manager planted and harvested kohlrabi (*Brassica oleracea* L. var. *gongyloides* L.), spinach (*Spinacia oleracea* L.), and lettuce (*Lactuca sativa* L.) in these seedbeds, one crop per seedbed. Due to the farmer's space and equipment requirements, the cash crop phase of the study followed a split-plot design with one subplot for each crop within each whole-plot.

To prevent interference between the weed community assessment and crop yield estimations presented in a related study (McKenzie, 2014), each 10 × 15 m whole-plot was divided in half. We randomly selected one half of each whole-plot for weed sampling. Due to heavy rain in spring 2013 and subsequent soil crusting, the 2013 spinach crop failed in half of our experimental plots (Charles Holt, *Pers. Comm.*).

To reflect weed-crop competition at critical growth stages (Zimdahl, 2004), we estimated early season weed pressure on June 25, 2013 and June 12, 2014. Within each previously grazed or mowed plot, we randomly placed two 0.44 × 0.75 m rectangular quadrats with the long edge oriented perpendicular to crop rows in each subplot. For both years, we counted all ramets of each weed species within each quadrat and pooled data from both quadrats for each subplot prior to analysis. Additionally, we took all aboveground plant matter from a representative sample of five ramets of each species. If a species had fewer than five ramets, all ramets were collected. These samples were dried to constant mass at 60 °C in a drying oven, weighed to the nearest 0.001 g, and used to compute an allometric estimate of total biomass by species.

We estimated carabid beetle activity–density, a proxy for species abundance (Thomas et al., 1998), during the cover crop phase of each trial by placing three pitfall traps in the center of each of our six experimental plots. The pitfall traps were 10 cm diameter × 12 cm deep and consisted of two stacked 0.5 L plastic cups placed flush with the soil surface and filled approximately one-third full with a propylene glycol-based antifreeze. Pitfall traps were covered with 25 cm diameter clear plastic plates held to the ground with three equally spaced 10 cm bolts. Each cover had at least 2 cm between the soil surface and the rim of the plastic plates to avoid interfering with ground dwelling arthropod activity.

In 2012, we collected all arthropods caught in the pitfall traps weekly from May 25 to June 1, from June 22 to July 27, and from August 16 to October 5. These three periods represented the carabid community prior to soil cultivation (“precultivation” hereafter), under actively growing cover crop (“pretreatment”), and after cover crop termination (“terminated”), respectively. In 2013, we collected arthropods weekly from May 3 to May 17 and from June 7 to June 21 for the precultivation period. For the pretreatment period, we collected arthropods weekly from June 28 to August 2. Finally, arthropods were collected between August 16 and October 4 for the terminated period. Due to an error, the arthropods were not collected on July 21, 2012, and therefore the samples from July 27, 2012 represented two weeks of collection. To correct for this error, we calculated the mean daily catch rate for each capture period.

At each collection date, the three pitfall traps within each plot were combined, stored in a freezer, and later transferred into 70% ethanol by volume. We identified carabid beetles to species, following Lindroth (1969). The few beetles that could not be positively identified to species were identified to genus, and recorded as morphospecies. Positively identified species names follow Bousquet (2012). Ground beetles were only collected during the cover crop phase.

For the cover crop and cash crop phases of the experiment, we compared weed density, biomass, species richness, diversity, and community structure between grazed and mowed plots. For each plot and sampling period within a trial, diversity was estimated using Simpson's index ($1 - D$) (Simpson, 1949). For the cover crop phase of our study, we compared biomass, species richness, and diversity between grazed and mowed plots and between pretreatment and terminated periods using a repeated measures ANOVA with sampling period as the repeated factor within treatment and treatment blocked by trial. In the cash crop phase, these metrics were compared using a split-plot ANOVA with cover crop termination method as the main plot factor, cash crop as the subplot factor, and trial year as a blocking factor.

For the cover crop phase of each trial, weed community structure was analyzed using non-metric multidimensional scaling (NMDS) ordinations of the pretreatment and terminated biomass data. In the cash crop phase of each trial, we constructed NMDS ordinations of the allometric weed biomass data. Initial data locations in ordination space were determined by principal coordinates analysis (PCO). We constructed the dissimilarity matrix for our PCO using the Bray–Curtis dissimilarity index:

$$BC_{jk} = \frac{\sum_{i=1}^S 2a_{ij} - a_{ik}}{\sum_{i=1}^S a_{ij} + \sum_{i=1}^S a_{ik}} \quad (1)$$

where BC_{jk} is the dissimilarity between sites j and k , a_{ij} and a_{ik} are the total biomass of individuals of species i in sites j and k , respectively, and S is the combined total number of species in both communities (Bray and Curtis, 1957). Prior to constructing the dissimilarity matrix, the raw data were log-transformed to de-

emphasize the effect of dominant species according to:

$$T_{ij} = \ln(M_{ij} + 1) \quad (2)$$

where T_{ij} is the log-transformed abundance (biomass or density) of species i in community j and M_{ij} is the raw abundance of species i in community j .

For the cover crop phase, we tested differences in weed community structure between cover crop termination methods and between the pretreatment and terminated periods using Permutation Multivariate Analysis of Variance (PERMANOVA) of the dissimilarity matrix (Anderson, 2001). We conducted separate PERMANOVAs on the appropriate dissimilarity matrix to test for temporal and treatment effects. In the cash crop phase, we conducted separate PERMANOVAs to test for differences in weed community structure among cash crops and between grazed and mowed plots. All PERMANOVAs were conducted with 9999 Monte-Carlo iterations.

We compared carabid beetle activity–density, species richness, diversity (as indexed by Simpson's $1 - D$), and community structure between grazed and mowed plots, as well as among sampling periods using a repeated measures ANOVA with sampling period as the repeated factor within treatments and trial as a blocking factor. We compared carabid community structure between grazed and mowed plots with NMDS, using PCO based on a Bray–Curtis dissimilarity matrix for initial positions, as described above. Differences in carabid community structure were analyzed among periods and between treatments using PERMANOVA on a Bray–Curtis dissimilarity matrix, as described above. Because period of the growing season was nested within treatment, we conducted separate PERMANOVA analyses for main treatment effects and for temporal effects using the appropriate dissimilarity matrix. Additionally, NMDS and PERMANOVA analyses were conducted separately for each trial.

All statistics and graphics were performed in R version 3.0.2 (R Development Core Team, 2013). Community indices and PERMANOVAs were calculated in the vegan package of R (Oksanen et al., 2007). Ordinations were calculated and graphed using the cluster (Maechler et al., 2012), labdsv (Roberts, 2007) and vegan (Oksanen et al., 2007) packages. All other graphics were created using the ggplot2 (Wickham, 2009) and sciplot (Morales et al., 2012) packages of R. All post-hoc tests for significant interactions found from ANOVA were conducted using Tukey's Honestly Significant Difference (HSD) in the TukeyC package (Jeliahovschi and Allaman, 2011).

3. Results

We sampled a total of 11 weed species in 2012 and 16 weed species in 2013. Three species [redroot pigweed (*Amaranthus retroflexus* L.), common lambsquarter (*Chenopodium album* L.), and common mallow (*Malva neglecta* Wallr.)] comprised over 90% of the total weed biomass sampled in all plots in 2012. In 2013, five species [prostrate pigweed (*Amaranthus blitoides* S. Watson), *A. retroflexus*, *C. album*, *M. neglecta*, and purslane (*Portulaca oleracea* L.)] comprised over 90% of the total weed biomass in all but one plot. Flower-of-an-hour (*Hibiscus trionum* L.) comprised 40% of the total biomass after the cover crop was terminated in one plot, but was absent from all other plots in 2013.

Weed density, biomass, diversity, and species richness did not differ between grazed and mowed plots in either year of the study (Table 1). While there were temporal differences in total weed biomass, with more biomass sampled in the pretreatment period than in the terminated period ($P=0.01$), these differences did not vary between grazed and mowed plots. We found no temporal differences in diversity overall or between grazed and mowed

Table 1
Impacts of sheep grazing and mowing for cover crop termination on weed density, biomass, diversity, and species richness during the cover crop phase in 2012 and in 2013 at Townes Harvest Farm, Bozeman, MT, United States. Values are reported as mean $\pm$ SE.

		Grazed plots			Mowed plots		
		Emergence	Pretreatment	Post-treatment	Emergence	Pretreatment	Terminated
2012	Total weed density (ramets m ⁻²)	324.00 $\pm$ 98.08	–	–	261.67 $\pm$ 71.63	–	–
	Total weed biomass (g m ⁻²)	–	344.91 $\pm$ 144.81	127.32 $\pm$ 66.34	–	283.69 $\pm$ 77.37	147.92 $\pm$ 37.57
	Simpson's diversity (1 – D)	0.57 $\pm$ 0.07	0.38 $\pm$ 0.14	0.43 $\pm$ 0.08	0.48 $\pm$ 0.08	0.54 $\pm$ 0.03	0.39 $\pm$ 0.09
	Species richness	6.33 $\pm$ 0.33	4.67 $\pm$ 0.33	3.00 $\pm$ 0.58	4.67 $\pm$ 0.33	6.67 $\pm$ 1.45	4.67 $\pm$ 0.67
2013	Total weed density (ramets m ⁻²)	11.67 $\pm$ 3.18	–	–	6.33 $\pm$ 1.76	–	–
	Total weed biomass (g m ⁻²)	–	37.50 $\pm$ 10.17	11.39 $\pm$ 3.31	–	53.90 $\pm$ 23.91	57.55 $\pm$ 24.83
	Simpson's diversity (1 – D)	0.61 $\pm$ 0.11	0.56 $\pm$ 0.08	0.49 $\pm$ 0.09	0.51 $\pm$ 0.09	0.54 $\pm$ 0.07	0.40 $\pm$ 0.12
	Species richness	4.00 $\pm$ 0.58	6.67 $\pm$ 1.20	5.00 $\pm$ 0.58	2.67 $\pm$ 0.67	8.33 $\pm$ 0.33	5.00 $\pm$ 1.15

	Treatment			Period			Treatment $\times$ period		
	F	df	P	F	df	P	F	df	P
Total weed density	1.35	1,5	0.30	–	–	–	–	–	–
Total weed biomass	3.85	1,5	0.11	9.45	1,10	0.01	2.84	1,10	0.12
Simpson's diversity	0.35	1,5	0.58	1.69	2,20	0.21	0.96	2,20	0.40
Species richness	1.05	1,5	0.35	6.53	2,20	0.01	3.05	2,20	0.07

plots. Species richness varied by period of the growing season, but patterns did not differ between grazed and mowed plots. Specifically, species richness was higher in the pretreatment period than in either the precultivation ($P=0.03$) or terminated ($P=0.04$) periods.

In 2012, weed community structure did not differ between grazed and mowed plots (pseudo- $F=1.89$; $df=1,5$; $r^2=0.32$; $P=0.30$; Fig. 1A). While weed community structure shifted between the pretreatment and terminated periods (pseudo- $F=6.35$; $df=1,8$; $r^2=0.38$; $P=0.006$), within sampling periods, we did not detect any difference between grazed and mowed plots (pseudo- $F=1.01$; $df=1,8$; $r^2=0.061$; $P=0.40$). As in 2012, weed community structure in 2013 did not differ between grazed and mowed plots (pseudo- $F=1.41$; $df=1,5$; $r^2=0.26$; $P=0.20$; Fig. 1B). In contrast to 2012, in 2013 we did not detect a shift in weed community structure between the pretreatment and terminated periods (pseudo- $F=1.44$; $df=1,8$; $r^2=0.12$; $P=0.24$). Additionally, there was no interactive effect of cover crop termination method and period of the growing season on weed community structure in 2013 (pseudo- $F=1.63$; $df=1,8$; $r^2=0.13$; $P=0.18$).

The observed 2012 temporal shifts in weed community structure appeared to be driven by both the decline in weed species richness noted above, as well as the changes in the relative

abundance of the most dominant weed species. In 2012, *A. retroflexus* comprised $57.9 \pm 22.6\%$ (mean $\pm$ SE) of the total weed biomass prior to cover crop termination in grazed plots and $53.0 \pm 8.7\%$ of the biomass in mowed plots. *M. neglecta*, by contrast, comprised $23.3 \pm 19.9\%$ of the biomass in grazed plots and $35.7 \pm 11.9\%$ of the biomass in mowed plots (Fig. 2A). However, following cover crop termination, *M. neglecta* became the most abundant weed in both grazed and mowed plots, comprising $58.7 \pm 13.9\%$ and $51.2 \pm 18.4\%$ of the biomass in grazed and mowed plots, respectively (Fig. 2B).

We sampled 20 weed species in the 2013 cash crop phase. Three of these species were volunteer crop species including *F. esculentum*, *M. officinalis*, and tomato (*Solanum lycopersicum* L.). The four dominant species, comprising $>85\%$ of the total biomass, were *A. retroflexus* ($23.9 \pm 5.67\%$; mean $\pm$ SE), *M. neglecta* ($23.0 \pm 7.1\%$), Canada thistle (*Cirsium arvense* (L.) Scop.) ($17.7 \pm 7.6\%$), and henbit (*Lamium amplexicaule* L.) ($24.4 \pm 5.0\%$). In the 2014 cash crop phase, we sampled 15 weeds species. *F. esculentum* and *M. officinalis* were the only volunteer crops species that year. In 2014, five species comprised $>85\%$ of the total biomass: *A. retroflexus* ($19.7 \pm 4.7\%$), *C. arvense* ($7.6 \pm 5.1\%$), *L. amplexicaule* ($31.8 \pm 6.4\%$), *M. neglecta* ($20.0 \pm 5.6\%$), and *C. album* ($8.8 \pm 5.2\%$).

Table 2
Legacy impacts of sheep grazing and mowing for cover crop termination on weed biomass, density, diversity, and species richness in the cash crop phase at Townes Harvest Farm, Bozeman, MT, United States. Values are reported mean $\pm$ SE.

		Grazed			Mowed		
		Kohlrabi	Lettuce	Spinach	Kohlrabi	Lettuce	Spinach
2013	Total weed density (ramets m ⁻²)	70.70 $\pm$ 43.40	355.00 $\pm$ 25.90	185.00 $\pm$ 82.80	108.00 $\pm$ 26.40	175.00 $\pm$ 23.20	144.00 $\pm$ 37.50
	Total weed biomass (g m ⁻²)	0.20 $\pm$ 0.17	25.60 $\pm$ 12.50	5.99 $\pm$ 2.76	40.50 $\pm$ 38.90	15.90 $\pm$ 7.54	4.76 $\pm$ 3.85
	Simpson's diversity (1 – D)	0.41 $\pm$ 0.18	0.61 $\pm$ 0.06	0.47 $\pm$ 0.22	0.27 $\pm$ 0.15	0.61 $\pm$ 0.12	0.70 $\pm$ 0.07
	Species richness	3.67 $\pm$ 0.67	8.33 $\pm$ 0.33	7.67 $\pm$ 2.40	6.00 $\pm$ 1.00	8.00 $\pm$ 1.73	7.33 $\pm$ 0.88
2014	Total weed density (ramets m ⁻²)	211.00 $\pm$ 12.40	115.00 $\pm$ 48.10	191.00 $\pm$ 26.70	149.00 $\pm$ 76.00	89.40 $\pm$ 3.15	151.00 $\pm$ 10.40
	Total weed biomass (g m ⁻²)	19.40 $\pm$ 2.80	17.90 $\pm$ 9.79	98.80 $\pm$ 27.50	23.30 $\pm$ 17.20	9.12 $\pm$ 2.72	71.30 $\pm$ 15.50
	Simpson's diversity (1 – D)	0.48 $\pm$ 0.14	0.62 $\pm$ 0.08	0.58 $\pm$ 0.03	0.29 $\pm$ 0.09	0.59 $\pm$ 0.07	0.59 $\pm$ 0.03
	Species richness	6.00 $\pm$ 1.53	7.33 $\pm$ 0.88	8.33 $\pm$ 0.88	4.00 $\pm$ 0.58	6.33 $\pm$ 0.88	5.33 $\pm$ 0.88

	Treatment		Crop		Treatment $\times$ crop	
	F _(1,5)	P	F _(2,20)	P	F _(2,20)	P
Total weed density	4.60	0.08	0.76	0.48	0.64	0.54
Total weed biomass	0.00	0.95	2.26	0.13	0.95	0.40
Simpson's diversity	0.21	0.67	8.04	0.00	2.12	0.15
Species richness	0.54	0.49	9.19	0.00	0.98	0.39

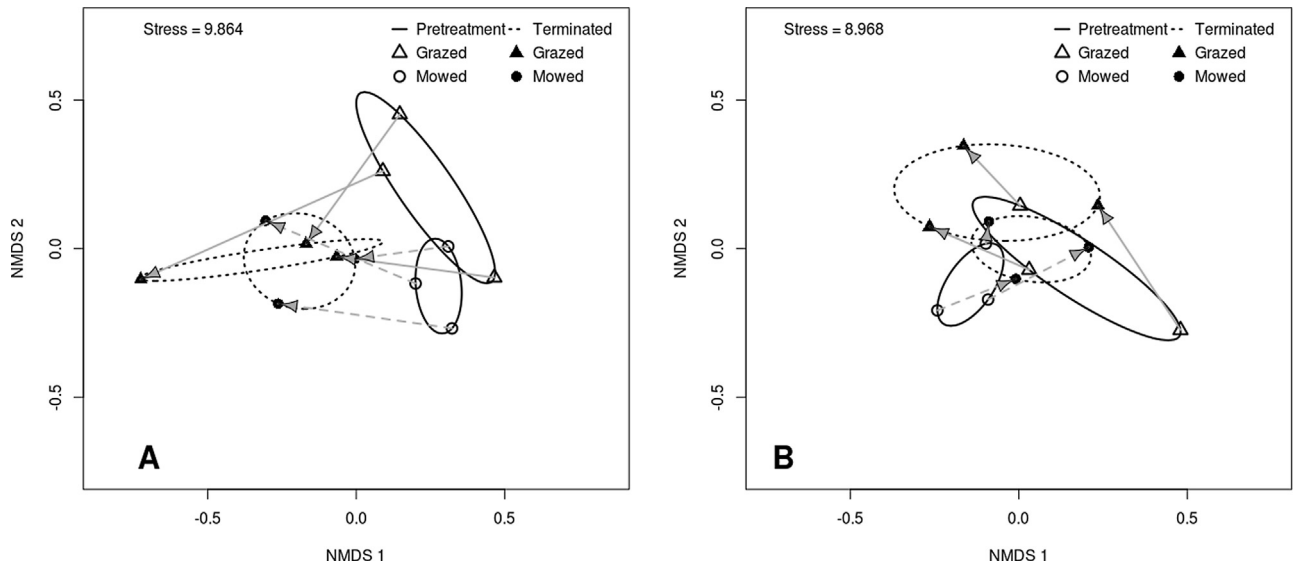


Fig. 1. Non-metric multidimensional scaling (NMDS) ordination of weed community structure in sheep grazed and mowed plots during the cover crop phase in 2012 (A) and 2013 (B) at Townes Harvest Farm, Bozeman, MT, United States. Solid ellipses inscribe communities in the pretreatment period and dotted ellipses inscribe communities in the terminated period. Solid arrows denote the shift in community structure for grazed plots and dashed arrows denote the shift in community structure for mowed plots.

Pooled across trials, there was no overall difference in weed density, biomass, diversity, or species richness between previously grazed and mowed whole-plots (Table 2). However, while there was no difference in total weed biomass or total weed density among crops, diversity and species richness differed among crops. Specifically, we found lower diversity in kohlrabi subplots than in either spinach ($P=0.01$) or lettuce subplots ($P=0.004$) and fewer weed species in kohlrabi subplots than in either spinach ($P=0.007$) or lettuce subplots ($P=0.002$). However, the observed differences in weed density among cash-crops did not vary by cover crop termination method.

PERMANOVA and NMDS of the community dissimilarity matrices revealed that during the 2013 cash-crop phase, overall weed community structure did not differ between previously

grazed and mowed whole-plots (pseudo- $F=1.91$; $df=1,4$; $r^2=0.32$; $P=0.11$; Fig. 3A). By contrast, weed community structure differed among cash crop subplots (pseudo- $F=2.22$; $df=2,12$; $r^2=0.22$; $P=0.02$). However, these differences in weed community structure by cash crop did not vary by cover crop termination method (pseudo- $F=0.97$; $df=2,12$; $r^2=0.10$; $P=0.48$). Similarly, we found no difference in weed community structure between previously grazed and mowed plots during the 2014 cash crop phase (pseudo- $F=2.47$; $df=1,4$; $r^2=0.38$; $P=0.20$; Fig. 3B). As in 2013, weed community structure differed among cash crop rows (pseudo- $F=2.51$; $df=2,12$; $r^2=0.24$; $P<0.001$), but these differences did not vary between previously grazed and mowed plots (pseudo- $F=1.33$; $df=2,12$; $r^2=0.13$; $P=0.19$).

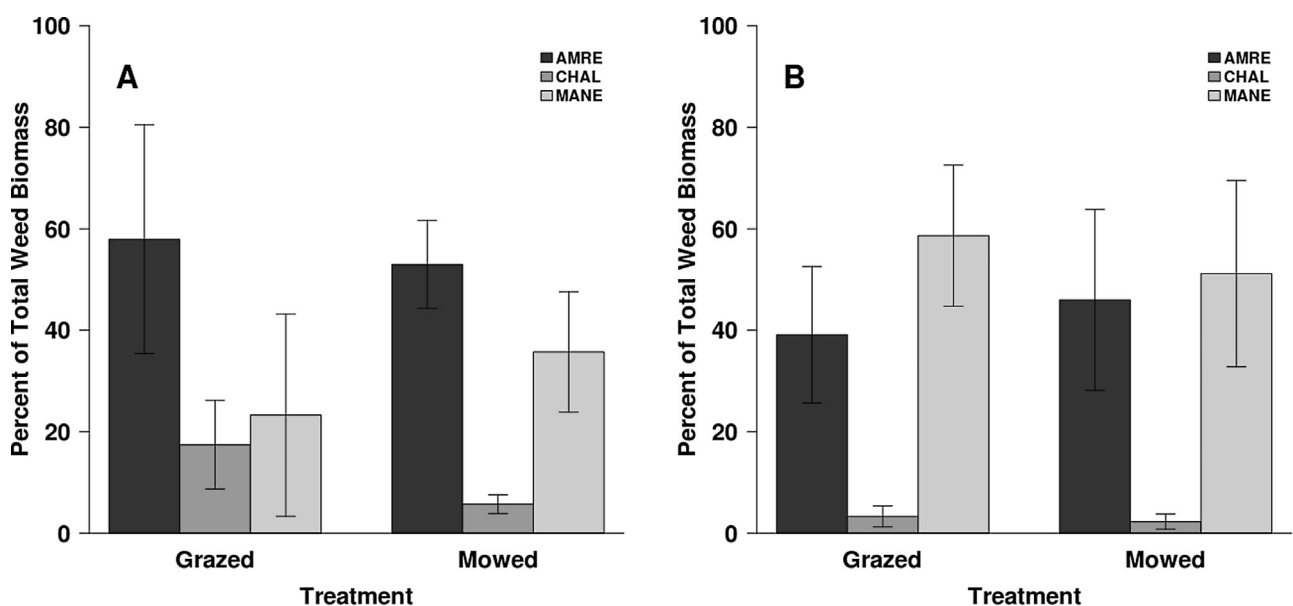


Fig. 2. Impact of sheep grazing and mowing on relative abundance of the most dominant weed species (A) prior to cover crop termination and (B) after cover crop termination in 2012 at Townes Harvest Farm, Bozeman, MT, United States. Species codes are as follows: AMRE = *Amaranthus retroflexus*, CHAL = *Chenopodium album* and MANE = *Malva neglecta*.

Table 3
Impacts of sheep-grazing and mowing on carabid beetle activity–density, diversity, and species richness during the cover crop phase in 2012 and 2013 at Townes Harvest Farm, Bozeman, MT, United States. Values are reported mean $\pm$ SE.

		Grazed			Mowed		
		Precultivation	Pretreatment	Terminated	Precultivation	Pretreatment	Terminated
2012	Total activity density (beetles day ⁻¹)	5.95 $\pm$ 1.63	8.33 $\pm$ 2.91	0.38 $\pm$ 0.05	6.00 $\pm$ 0.87	5.69 $\pm$ 0.56	0.90 $\pm$ 0.13
	Simpson's diversity (1 – D)	0.89 $\pm$ 0.00	0.89 $\pm$ 0.01	0.61 $\pm$ 0.06	0.86 $\pm$ 0.02	0.83 $\pm$ 0.08	0.79 $\pm$ 0.02
	Species richness	9.33 $\pm$ 0.33	9.67 $\pm$ 1.20	2.67 $\pm$ 0.33	7.33 $\pm$ 1.33	8.33 $\pm$ 2.67	5.00 $\pm$ 0.58
2013	Total activity density (beetles day ⁻¹)	3.62 $\pm$ 0.50	3.24 $\pm$ 0.91	0.81 $\pm$ 0.25	3.10 $\pm$ 1.44	2.76 $\pm$ 1.08	1.10 $\pm$ 0.05
	Simpson's diversity (1 – D)	0.89 $\pm$ 0.00	0.89 $\pm$ 0.01	0.61 $\pm$ 0.06	0.86 $\pm$ 0.02	0.83 $\pm$ 0.08	0.79 $\pm$ 0.02
	Species richness	9.67 $\pm$ 1.76	4.33 $\pm$ 1.76	4.00 $\pm$ 1.00	8.33 $\pm$ 2.96	5.00 $\pm$ 0.58	6.33 $\pm$ 0.33

	Treatment		Period		Treatment $\times$ period	
	$F_{(1,5)}$	P	$F_{(2,20)}$	P	$F_{(2,20)}$	P
Total activity density (beetles day ⁻¹)	0.96	0.37	13.54	<0.001	0.62	0.55
Simpson's diversity (1 – D)	2.18	0.20	2.25	0.13	1.16	0.33
Species richness	0.03	0.86	6.99	0.00	1.66	0.22

We collected a total of 2,132 carabid beetles from 33 species in 2012 and 2,127 beetles from 39 species in 2013. In 2012, over 80% of all beetles collected were members of six species: *Pterostichus melanarius* (Illiger) ($n = 972$; 45.6% of all carabids), *Poecilus scitulus* (LeConte) ($n = 263$; 12.3%), *Amara patruelis* (Dejean) ($n = 165$; 7.7%), *Amara thoracica* (Hayward) ($n = 160$; 7.5%), *Harpalus amputatus* (Say) ($n = 140$; 6.6%), and *Bembidion ruficollis* (Kirby) ($n = 109$; 5.1%). In 2013, over 80% of all beetles collected were members of five species: *P. melanarius* ($n = 1149$; 53.9%), *A. patruelis* ($n = 235$; 11.0%), *H. amputatus* ($n = 136$; 6.4%), *A. thoracica* ($n = 105$; 4.9%), and *Bradycellus congener* (LeConte) ($n = 95$; 4.5%).

Pooled across trials, we did not detect any differences in activity–density, species richness, or diversity of carabid beetles between grazed and mowed plots (Table 3). However, both activity–density and species richness varied by period of the growing season. Carabid activity–density was higher in the precultivation ($P < 0.001$) and pretreatment ($P = 0.001$) periods than in the terminated period. However, activity–density did not differ between the precultivation and pretreatment periods ($P = 0.93$). Species richness was higher in the precultivation period than in the terminated period ($P = 0.004$). Species richness in the pretreatment period did not differ with that in the precultivation

($P = 0.25$) or the terminated periods ($P = 0.12$). These temporal changes in total activity–density and species richness did not differ between mowed and grazed plots. In contrast to activity–density and species richness, we did not detect any temporal changes in diversity.

Overall, carabid beetle community structure in 2012 did not differ between grazed and mowed plots (pseudo- $F = 0.38$; $df = 1,4$; $r^2 = 0.09$; $P = 0.90$; Fig. 4A). By contrast, we observed strong temporal shifts in carabid beetle community structure among periods of the growing seasons in 2012 (pseudo- $F = 11.34$; $df = 2,12$; $r^2 = 0.63$; $P < 0.001$). However, these temporal dynamics did not differ between mowed and grazed plots (pseudo- $F = 0.48$; $df = 2,12$; $r^2 = 0.03$; $P = 0.92$). Similarly, in 2013 overall carabid beetle community structure did not differ between grazed and mowed plots (pseudo- $F = 0.55$; $df = 1,4$; $r^2 = 0.12$; $P = 0.80$; Fig. 4B), but there were temporal shifts in carabid beetle community structure (pseudo- $F = 18.46$; $df = 2,12$; $r^2 = 0.69$; $P < 0.001$). As in 2012, these temporal dynamics in carabid beetle community structure did not differ between mowed and grazed plots (pseudo- $F = 1.43$; $df = 2,12$; $r^2 = 0.05$; $P = 0.21$).

The observed temporal shifts in carabid beetle community structure are likely a result of a marked fluctuation in the activity–

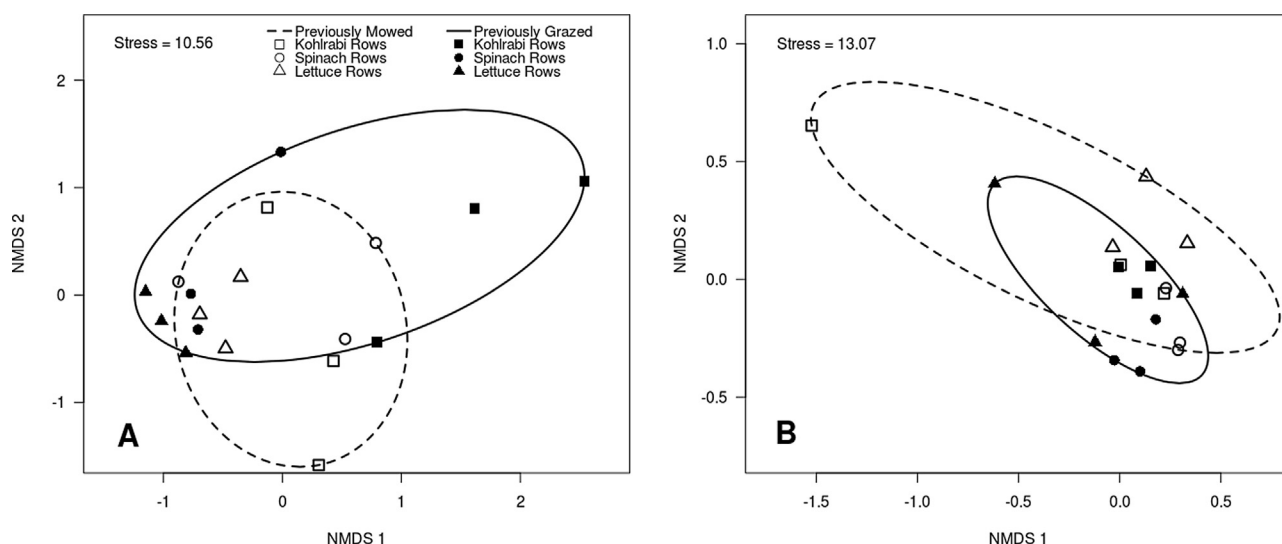


Fig. 3. Non-metric multidimensional scaling (NMDS) ordination of weed community structure in previously sheep grazed and previously mowed plots during the cash crop phase (A) in 2013 and (B) in 2014 at Townes Harvest Farm, Bozeman, MT, United States. Solid ellipses inscribe communities in previously grazed plots, whereas dashed ellipses inscribe communities in previously mowed plots. The legend in the left panel (A) also applies to the right panel (B).

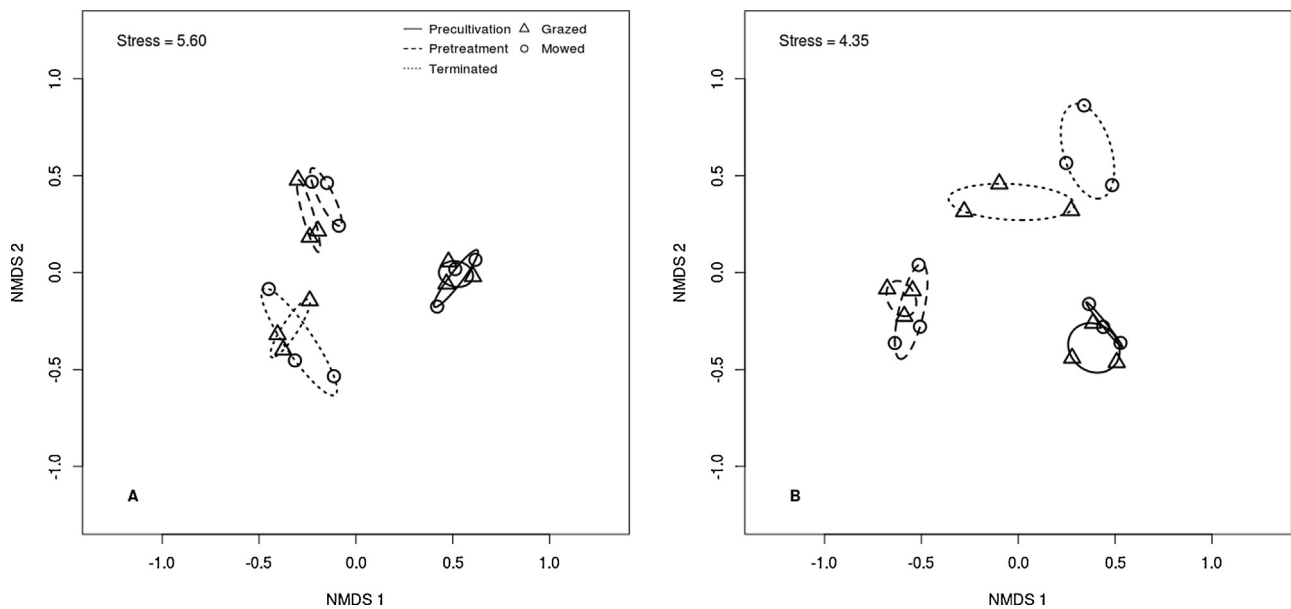


Fig. 4. Non-metric multidimensional scaling (NMDS) ordination of the impacts of sheep grazing and mowing during cover crop phase on carabid beetle community structure (A) in 2012 and (B) in 2013 at Townes Harvest Farm, Bozeman, MT, United States. The legend in the left panel (A) also applies to the right panel (B). Solid ellipses inscribe beetle communities in the precultivation period, dashed ellipses inscribe those in the pretreatment period, and dotted ellipses inscribe those in the terminated period.

density of *P. melanarius*. Both years, the activity–density of this species increased precipitously in the pretreatment period, but declined following cover crop termination. We noted a concomitant decline in *A. patruelis* activity–density with the increase in *P. melanarius* activity–density both years in both grazed and mowed plots. Conversely, as *P. melanarius* activity–density declined following cover crop termination, *A. thoracica* activity–density increased (Fig. 5).

4. Discussion

In contradiction to our hypothesis, neither weed nor carabid beetle community structure differed between plots in which cover crops were terminated by sheep grazing or those terminated by mowing, suggesting that these management practices act as similar ecological filters of these two suites of associated biodiversity. Furthermore, the lack of differences was consistent through both the cover crop and cash crop phases of this study. Thus, our results suggest that integrating targeted sheep grazing as an approach to terminate cover crops in horticultural vegetable production systems does not have immediate or short-term legacy impacts different than those of mowing.

In accordance with previous studies (Davis et al., 2005; Lososová et al., 2003), we observed that weed community structure differed among crop rows during both the 2013 and 2014 cash crop phases. Tracy and Davis (2009) compared weed biomass and species composition among two integrated cattle/grain production systems [oats (*Avena sativa* L.), followed by winter forage cover crop mixture and corn (*Zea mays* L.), followed by corn residue] and one non-integrated cropping systems (continuous corn monoculture). They found that while cover crops and crop residues produced for forage reduced weed biomass and altered weed community composition compared with continuous corn monoculture, cattle grazing had no effect on either weed biomass or community composition. Similarly, Loeser et al. (2001) reported that livestock grazing had negligible short-term impacts on plant community structure in semi-arid grasslands. These studies concur with our findings that livestock grazing does not alter weed community structure in the subsequent growing season and

that other aspects of management are stronger ecological filters of weed diversity.

One particular concern with our study was that it only investigated short-term changes in weed community structure. Renne and Tracy (2013) noted that disturbance events such as grazing can have long-term impacts on the seedbank or can interact with future disturbances to alter weed community structure. Indeed, weed species richness, seed production, and density all increased when livestock grazed on previously disturbed sites compared with undisturbed sites (Renne and Tracy, 2013). Similarly, Miller et al. (2015) found that sheep grazing during fallow for weed and crop residue management favored perennial weed species, especially dandelion (*Taraxacum officinale* L.).

The observed changes in carabid community structure could be the result of a number of drivers such as differences in the phenology among carabid species (Sergeeva, 1994), habitat alteration as a result of agronomic practices (Goosey et al., 2015; Lovei and Sunderland, 1996), interspecific competition (Niemelä, 1993), or an interaction of these factors. Gardner et al. (1997) found that sheep grazing in heather (*Calluna* spp.) moorlands reduced canopy height and biomass. These environmental changes, in turn, directed carabid assemblages toward species with preferences for sparse vegetation. Petit and Usher (1998) reported that intensive sheep grazing of adjacent hedgerows in Scottish agroecosystems was associated with a shift to communities dominated by carabid species preferring open vegetation and characteristic of grasslands. Conversely, ungrazed hedgerows were dominated by carabid species that prefer densely vegetated habitats and are typically found in forests. In our study, the similarity between grazed and mowed plots suggests that these methods of cover crop termination act as similar ecological filters of carabid diversity.

The ecological and agronomic benefits derived from the use of cover crops are well documented (e.g., Hartwig and Ammon, 2002; Thiessen Martens and Entz, 2011), but their use has been limited. Integrating livestock for cover crop termination could provide an alternative source of revenue for producers directly through the production of fiber (wool) or meat, or indirectly through grazing

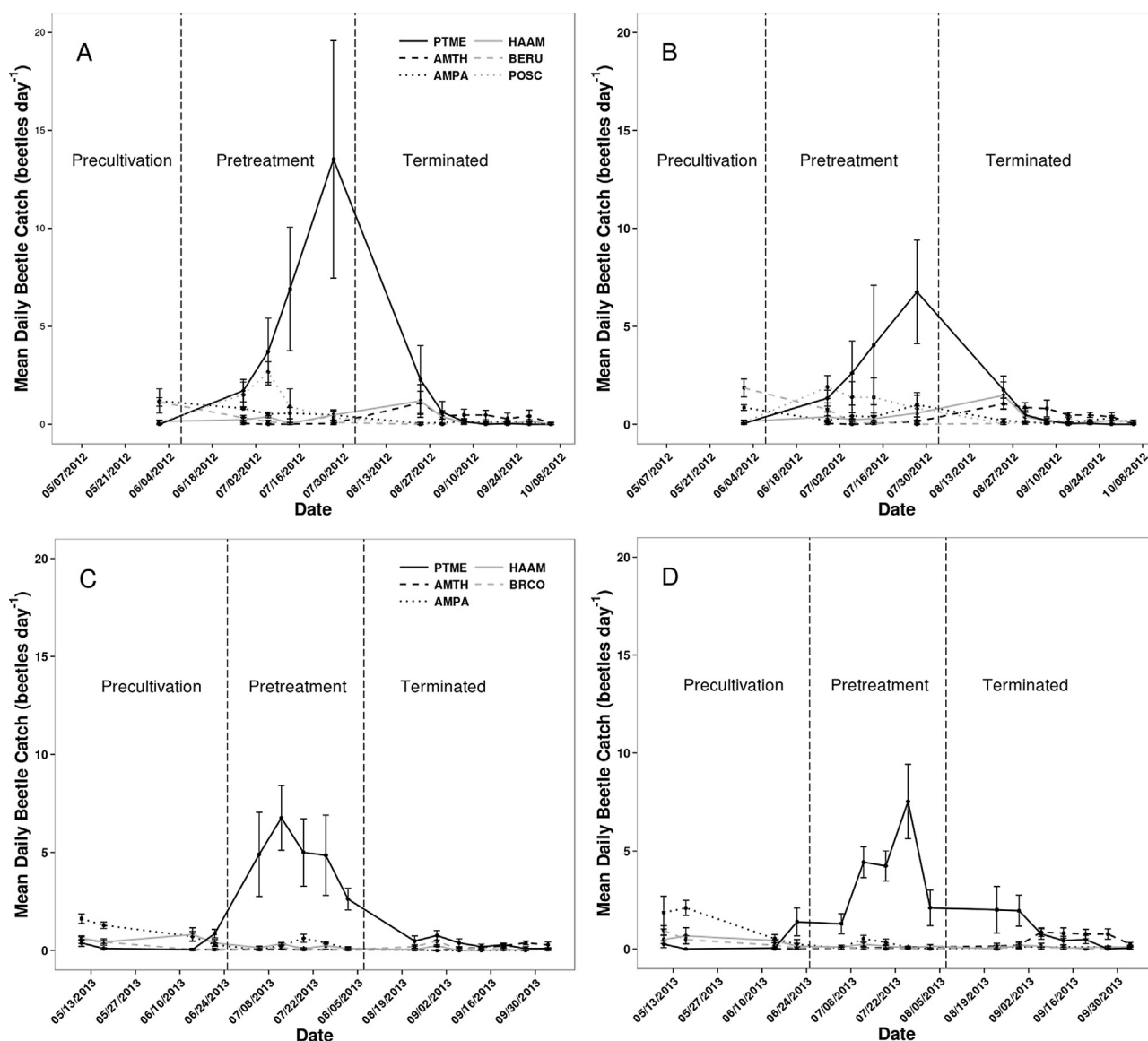


Fig. 5. Dynamics of activity–density of dominant carabid beetle species during the cover crop phase in (A) 2012 grazed plots (B) 2012 mowed plots, (C) 2013 grazed plots and (D) 2013 mowed plots at Townes Harvest Farm, Bozeman, MT, United States. The legend in the top left panel (A) also applies to the top right panel (B). The legend in the bottom left panel (C) also applies to the bottom right panel (D). Species codes are as follows: PTME = *Pterostichus melanarius*; AMTH = *Amara thoracica*; AMPA = *Amara patruelis*; HAAM = *Harpalus amputatus*; POSC = *Poeciliscus scitulus*; BRCO = *Bradycellus congener*; BERU = *Bembidion ruficollis*.

leases, thus making the use of cover crops more economical (McKenzie, 2014; Sulc and Tracy, 2007; Thiessen Martens and Entz, 2011). Overall, our results suggest that producers are unlikely to experience changes in associated biodiversity if they switch from terminating cover crops with mowing to termination by sheep grazing. Furthermore, integrating sheep grazing for cover crop termination may help land managers reduce their need for off-farm synthetic inputs and their reliance on fossil fuels, thus potentially reducing input costs and enhancing the environmental sustainability of production.

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