Renewable Agriculture and Food Systems: 32(5); 389–402
doi:10.1017/S1742170516000326

Integration of sheep grazing for cover crop termination into market gardens: Agronomic consequences of an ecologically based management strategy

Sean C. McKenzie[1*], Hayes B. Goosey[2], Kevin M. O'Neill[1] and Fabian D. Menalled[1]

[1]Department of Land Resources and Environmental Sciences, Montana State University, 334 Leon Johnson Hall, Bozeman, MT, 59717, USA.
[2]Department of Animal and Range Sciences, Montana State University, 103 Animal Biosciences Building, Bozeman, MT, 59717, USA.
*Corresponding author: smckenzie1986@gmail.com

Accepted 8 July 2016; First published online 29 September 2016 **Research Paper**

Abstract

Cover crops are suites of non-marketable plants grown to improve soil tilth and reduce erosion. Despite these agronomic benefits, the use of cover crops is often limited because they do not provide a direct source of revenue for producers. Integrating livestock to graze cover crops could provide both an expeditious method for cover crop termination and an alternative source of revenue. However, there has been little research on the agronomic impacts of grazing for cover crop termination, especially in horticultural market-gardens. We conducted a 3-year study comparing the effects of sheep grazing to terminate a four species cover crop (buckwheat, sweetclover, peas and beets) with those of mowing on soil quality indicators, cover crop termination efficacy, and subsequent cash-crop yields. In addition, we tested the nutritional quality of the cover crop as forage. Compared with mowing, sheep grazing did not affect soil chemistry, temperature or moisture. Our study demonstrates that sheep grazing removed more cover crop biomass than mowing at termination. The assessment of nutritional indices suggests that the four-species cover crop mixture could provide high-quality forage with a potential value of US\$144.00–481.80 ha^{-1} of direct revenue as a grazing lease. Cash-crop yields did not differ between previously grazed and previously mowed plots in the subsequent growing season. We conclude that integrating sheep grazing into market vegetable garden operations could make cover crops more economically viable without having adverse effects on subsequent cash crops.

Key words: Agroecology, cover crops, ecologically based management, integrated crop–livestock systems, soil tilth, vegetable market-gardens

Introduction

Growing concerns about the need to balance food production with biodiversity and natural resources conservation has led to an increased interest among agroecologists, producers, and the public in reducing the reliance on off-farm synthetic inputs to provide the conditions necessary for sustained agronomic production (Altieri, 1999; Foley et al., 2011). To be successful, this approach to farming requires that the agronomic, economic and ecological conditions remain favorable for crop production (Robertson and Swinton, 2005). The need to reconcile these apparently disparate goals has precipitated a call for the development of ecologically based management systems (Matson et al., 1997; Robertson et al., 2008; Reganold et al., 2011). Such systems are those that augment ecological processes or community structure to support crop production and pest management (Magdoff, 2007; Altieri et al., 2012). One such practice is the use of cover crops, a suite of non-marketable plants grown to improve soil quality (Dabney et al., 2001).

Cover crops can improve physical, chemical and biological soil properties through several mechanisms. For example, cover crop root growth can increase soil macroporosity, thereby increasing saturated hydraulic conductivity, and plant growth can increase evapotranspiration, thereby increasing water storage capacity. Both processes improve water infiltration and may help prevent soil surface sealing (Dabney, 1998; Dabney et al., 2001). Humification of cover crop residues can increase soil organic matter (Reeves, 1994; Hartwig and Ammon, 2002; Lal, 2004), thus increasing cation exchange capacity (CEC), enhance mobilization of recalcitrant macronutrients (Kamh et al., 1999) and provide food for soil microorganisms (Wild, 1993; Hu et al., 1999). If legumes are included in cover crop mixtures, biological nitrogen (N) fixation and subsequent mineralization can further increase plant-available N (Snapp et al., 2005). Cover crops can also be an important component of integrated pest management (IPM) strategies by reducing the *per capita* weed seed production via competitive exclusion (Gallandt et al., 1999), decreasing weed seed survival through microbially mediated seed decay (Dabney et al., 1996; Liebman and Davis, 2000), and minimizing weed emergence either by preventing light transmittance or through allelopathy (Teasdale et al., 1991; Gallandt et al., 1999). Finally, cover crops can provide habitat for beneficial organisms such as parasitoids of phytophagous insects and weed seed predators, enhancing the effectiveness of conservation biological control in highly disturbed agroecosystems (Barbosa, 1998; Landis and Menalled, 1998; Altieri and Nicholls, 1999).

A major drawback to the use of cover crops is that producers do not generate direct revenue during the season in which they are grown (Sulc and Tracy, 2007; Thiessen Martens and Entz, 2011). One approach to overcome this challenge may be integration of livestock grazing for cover crop termination. Integrating livestock may offer producers several benefits besides a method of terminating cover crops. First, livestock production may provide alternative sources of revenue through the production of food (e.g., meat and dairy products) and fiber (e.g., wool) or through grazing leases (Gardner et al., 1991; Franzluebbers, 2007; Thiessen Martens and Entz, 2011). Secondly, livestock grazing could be a component of an integrated weed management program because it may reduce the number of flowering ramets producing seeds (Popay and Field, 1996; Meissner and Facelli, 1999). Finally, livestock grazing may aid in nutrient cycling through inputs of urine and feces (Bakker, 1998; Thiessen Martens and Entz, 2011).

Despite these agronomic benefits, at least two potential adverse outcomes could arise from the integration of livestock grazing. First, trampling by livestock could alter soil physical properties such as macroporosity and compaction (Franzluebbers, 2007). However, if grazing occurs when soils are dry, the compaction is usually limited to the top 10 cm of soil, and naturally attenuated by freeze–thaw and wetting–drying cycles (Bell et al., 2011). Second, grazing represents a potential mass export of nutrients as the animals leave the fields. However, Thiessen Martens and Entz (2011) noted that while grazing ruminants can retain up to 25% of the N they consume, the remaining N, deposited as urine and feces, is often more labile than plant detritus.

Demand for produce from horticultural market-gardens has grown substantially in recent years (Low and Vogel, 2011). Consumer preferences, costs and environmental concerns often prohibit intensive use of off-farm synthetic inputs in these systems. Thus, the development of ecologically based management practices is especially important for market-garden vegetable production systems. While there has been substantial research on the agronomic consequences of cover crops (Dabney, 1998; Dabney et al., 2001; Hartwig and Ammon, 2002; Snapp et al., 2005; Tillman et al., 2012), most of this research has focused on their use in large-scale commodity production. In contrast, there has been substantially less investigation into cover crop use in market-garden vegetable production. Furthermore, there is a paucity of research on the effects of integrating livestock grazing in market-garden vegetable production (but see Franzluebbers, 2007; Kahimba et al., 2008; Thiessen Martens and Entz, 2011: McKenzie et al., 2016).

To fill this knowledge gap, we compared the agronomic effects of sheep-grazing for cover crop termination with those of mowing over two consecutive years in a vegetable production farm. This on-farm study consisted of two phases. In the first phase, we assessed the impacts of sheep grazing as a method of termination on weed pressure and soil quality, as well as the forage quality of the cover crop. In the second phase, we estimated yield in subsequently grown cash crops. We had two trials of our experiment, one trial beginning its first phase in 2012 and the second trial beginning its first phase in 2013. Our research was designed to address four main questions: (1) Does sheep grazing for terminating cover crops remove as much plant biomass as mowing, a common approach to cover crop termination? (2) Does sheep grazing affect soil physical and chemical properties differently than mowing? (3) Can cover crops serve as viable forage for sheep? (4) Do cash crop yields differ between the two management strategies in the subsequent year?

Materials and Methods

Study site

Our study was conducted at Townes Harvest Farm (THF), a 1.2 ha certified organic, irrigated, diversified vegetable farm on the campus of Montana State University—Bozeman (45°40′N, 111°4′W). The farm is divided into six $40 \times 35\ m^2$ units, each following a 6-year rotation beginning with a cover crop season (Year 1) and followed by cash crops in the subsequent five growing seasons (Years 2–6). In a single growing season, each year of the rotation is represented by one unit. THF has a 4-year yield of marketable crops of 10,200 kg (C. Holt, Farm Manager, Personal communication) and has Turner loam (fine loamy over sandy, mixed, superactive, frigid and typic Agriustoll) soil with a clay loam texture, based on our particle size analysis showing 25% sand, 44% silt and 30% clay. THF receives approximately 380–480 mm of annual precipitation and has a mean annual air temperature ranging from 3.9 to 7.2°C (NRCS, 2013). Growing season mean monthly temperatures, total monthly precipitation and 30-year means from US Climate Reference Network Station USC00241044 are in Table 1 (Diamond et al., 2013).

Cover crop phase experimental design

The cover crop phase followed a single factor, completely randomized design with two treatment-levels (sheep-grazed or mowed for cover crop termination) and three replicates per treatment-level. Each replicate consisted of a $10 \times 15\ m^2$ rectangular plot. On June 8, 2012 and on June 25, 2013, the farm manager cultivated the soil in all plots and seeded a cover crop consisting of 56 kg ha^{-1} buckwheat (*Fagopyrum esculentum* Moench), 23 kg ha^{-1} beets (*Beta vulgaris* L.), 11 kg ha^{-1} sweetclover [*Melilotus officinalis* (L.) Lam.] and 68 kg ha^{-1} pea (*Pisum sativum* L).

Between August 3 and 7, 2012, we terminated the cover crops at anthesis by either tractor mowing or sheep grazing. Similar treatments were imposed between August 7 and 11, 2013. For the sheep-grazing plots, we set up temporary electrical fences charged between 3500 and 6000 V, stocked each plot with 6–11 Rambouilet yearling rams and allowed them to graze *ad libitum* until the cover crop appeared >90% removed. In each grazed plot, we placed large watering troughs to provide the sheep with supplemental water. For the mowed plots, the farm manager cut all plant material using a Flex Hitch Rotary Kutter (King Kutter, Winfield, AL) mowing deck with a 1.22 m effective swath width, leaving all plant biomass *in situ*.

Cash crop phase experimental design

In 2013 and 2014, three 1 m wide seedbeds were tilled to a depth of 25–35 cm with a 1.07 m-diameter spader (Celli Co., Flori, Italy) through the previously grazed or previously mowed cover crop plots. The farm manager planted each seedbed with either kohlrabi (*Brassica oleracea* L. var. *gongyloides* L., 15 plants m^{-2}), spinach (*Spinacia oleracae* L., 21 plants m^{-2}), or lettuce (*Lactuca sativa* L., 15 plants m^{-2}). This component of our study followed a split-plot design with one subplot per factor-level within each whole plot, with cover crop termination method as the whole-plot factor and cash crop as the subplot factor. Planting and harvesting dates for cash crops are listed in Table 2.

Soil physical and chemical characteristics

We assessed the impact of cover crop termination strategies on soil quality by measuring several soil physical and chemical parameters. Post-termination soil moisture was measured from September 13 to November 20, 2012 and from August 13 to October 9, 2013 using 7 cm soil moisture data probes (HOBO U30 Station, Onset Computer Corp., Bourne, MA) placed near the center of each plot to a depth of approximately 7 cm. We measured soil temperature by placing four temperature loggers (iButton® model DS1921G, Maxim Integrated, San Jose, CA) approximately 10 cm below the soil surface near the center of each plot. Soil temperatures were measured from June 13 to August 15, 2012 and from June 28 to October 9, 2013. All probes were removed from August 5 to 12, 2013 to accommodate cover crop termination, and were reinstalled on August 13, 2013. Temperatures within a plot from all recovered data loggers were averaged to obtain mean plot temperature through time.

Table 1. Mean monthly temperatures and total precipitation observations for 2012–2014 growing seasons and 30-year normal mean monthly temperature and total precipitation for Bozeman, MT, USA.

	2012 mean monthly temperature (°C)	**2013 mean monthly temperature (°C)**	**2014 mean monthly temperature (°C)**	**30-year normal monthly temperature (°C)**
May	9.8	11.2	10.9	10.9
June	15.9	15.7	13.5	15.2
July	21.3	20.5	20.7	19.5
August	19.9	19.8	18.2	18.9
September	15.6	14.6	14.0	13.7
	2012 mean monthly precipitation (mm)	2013 mean monthly precipitation (mm)	2014 mean monthly precipitation (mm)	30-year normal monthly precipitation (mm)
May	61.0	109.5	47.8	80.8
June	39.1	88.4	95.3	79.0
July	28.7	18.0	15.5	37.1
August	14.5	18.8	71.9	36.3
September	5.3	76.2	46.0	35.6

Data are reported from US Climate Reference Network Station USC00241044 on the Strand Union Building of Montana State University, Bozeman, MT, USA (Diamond et al., 2013).

https://doi.org/10.1017/S1742170516000326 Published online by Cambridge University Press

Table 2. Crop planting and harvest dates for 2013 and 2014 cash crop phases at Towne's Harvest Farm, Bozeman, MT, USA.

	2013 Trial				2014 Trial			
	Treatment	**Crop**	**Planting date**	**Harvest date**	**Treatment**	**Crop**	**Planting date**	**Harvest date**
Plot 1	Grazed	Kohlrabi	June 6, 2013	August 30, 2013	Grazed	Kohlrabi	May 14, 2014	September 3, 2014
		Spinach	April 23, 2013	July 23, 2013		Spinach	April 21, 2014	June 18, 2014
		Lettuce	April 23, 2013	July 8, 2013		Lettuce	May 14, 2014	Multiple harvests
Plot 2	Grazed	Kohlrabi	June 6, 2013	August 30, 2013	Mowed	Kohlrabi	May 14, 2014	September 3, 2014
		Spinach	June 6, 2013	Crop Failed		Spinach	April 21, 2014	June 18, 2014
		Lettuce	May 13, 2013	July 23, 2013		Lettuce	May 14, 2014	Multiple harvests
Plot 3	Mowed	Kohlrabi	June 6, 2013	August 30, 2013	Mowed	Kohlrabi	May 14, 2014	September 3, 2014
		Spinach	April 23, 2013	July 23, 2013		Spinach	April 21, 2014	June 18, 2014
		Lettuce	April 23, 2013	July 8, 2013; July 26, 2013		Lettuce	May 14, 2014	Multiple harvests
Plot 4	Mowed	Kohlrabi	June 6, 2013	August 30, 2013	Grazed	Kohlrabi	May 14, 2014	September 3, 2014
		Spinach	June 6, 2013	Crop Failed		Spinach	April 21, 2014	June 18, 2014
		Lettuce	May 13, 2013	July 16, 2013		Lettuce	May 14, 2014	Multiple harvests
Plot 5	Grazed	Kohlrabi	June 6, 2013	August 30, 2013	Grazed	Kohlrabi	May 14, 2014	September 3, 2014
		Spinach	April 23, 2013	July 23, 2013		Spinach	April 21, 2014	June 18, 2014
		Lettuce	April 23, 2013	July 8, 2013; July 26, 2013		Lettuce	May 14, 2014	Multiple harvests
Plot 6	Mowed	Kohlrabi	June 6, 2013	August 30, 2013	Mowed	Kohlrabi	May 14, 2014	September 3, 2014
		Spinach	June 6, 2013	Crop Failed		Spinach	April 21, 2014	June 18, 2014
		Lettuce	May 13, 2013	July 16, 2013		Lettuce	May 14, 2014	Multiple harvests

We assessed foliar N content, an estimate of resource availability, of the aboveground plant biomass at anthesis in the cover crop phase. Foliar N is a sensitive index of total N because plants uptake N over a larger spatial scale than would be captured by a soil sample (Hausenbuiller, 1985). Furthermore, usually <1% of soil N is NO_3^- at any point in time, whereas immobilized foliar N in detritus and living plant tissue comprises the largest pool of N in terrestrial ecosystems (Foth and Ellis, 1997). Foliar N was estimated as part of the crude protein assay during the cover crop phase (see 'Forage quality' section for details). Samples were initially ground in a plant matter grinder with a 2 mm screen (Wiley® Mill, Thomas Scientific Inc., Swedesboro, NJ) and further ground in a laboratory grinding mill (Cyclone Mill, UDY Corporation, Fort Collins, CO).

To assess soil conditions prior to seeding the cash crop phase, soil compaction and soil nutrient content were measured on April 28, 2013 and on May 12, 2014. Compaction was assessed using a soil penetrometer at four locations per plot and at four depth ranges per sampling location: 0–15, 15–30, 30–45 and 45–60 cm. Values from the four sampling sites were averaged for each depth within each plot. Soil nutrient content was evaluated with two randomly located soil core samples per plot using a hydraulic auger with a 5 cm diameter. For each sample, we separated the soil by depths as above and combined them into one sample per depth and plot. All soil samples were sent to a third party soil analytics laboratory (Agvise Laboratories, Northwood, ND) to be assayed for Olsen P, potassium, calcium, electrical conductivity, CEC, organic matter and pH.

Forage quality

Prior to terminating the cover crop, we measured its forage quality on July 31, 2012 and on August 2, 2013 by collecting all above ground plant material from four 0.33 m^2 quadrats randomly placed within each plot and combining biomass from all quadrats. Samples were dried at 60°C for 1 week, weighed to the nearest 0.1 g, and ground to pass a 2 mm screen (Wiley® Mill, Thomas Scientific Inc., Swedesboro, NJ). Foliar N samples were further ground in a laboratory grinding mill (Cyclone Mill, UDY Corporation, Fort Collins, CO). Acid and neutral detergent fiber was assayed in an ANKOM 200 Fiber Analyzer (ANKOM Technology, Macedon, NY) following manufacturer protocols (ANKOM Technology, 2011a, b). Crude protein and foliar-N were assayed using a LECO LP528 Nitrogen/Protein Analyzer (LECO®, St. Joseph, MI), correcting for dry matter. To obtain estimates of dry matter, two 1.000 ± 0.010 g samples of ground plant material were placed into tins. The mass of the empty tin as well as the mass of the sample and tin combined were recorded. Samples were dried in a drying oven at 100°C for 72 h, placed in a desiccator, and weighed. Dry matter (DM) was calculated as:

$$\mathrm{DM} = \frac{m_f}{m_0} \times 100\% \tag{1}$$

where m_f is the final mass of the sample after drying, and m_0 is the initial mass of the sample. These metrics were used to obtain dry digestible matter (DDM), dry matter intake (DMI) and relative feed value (RFV) (Undersander and Moore, 2002), which were calculated as:

$$\mathrm{DDM} = 88.9 - (0.779 \times \mathrm{ADF}) \tag{2}$$

$$\mathrm{DMI} = \frac{120}{\mathrm{NDF}} \tag{3}$$

and

$$\mathrm{RFV} = \frac{\mathrm{DDM} \times \mathrm{DMI}}{1.29} \tag{4}$$

Cover crop and weed biomass

We took biomass samples of all cover crop and weed species on July 25, 2012 and on August 1, 2013 at anthesis, but prior to cover crop termination. Post-cover crop termination biomass samples were collected on September 7, 2012 and on August 30, 2013. For biomass data, we again randomly placed four 0.33 m^2 quadrats in each plot, cut all plant material flush to the soil surface within quadrats and separated it by species. For each species, we combined the biomass collected in the four quadrats within a plot. We dried all samples at 60°C to constant mass and weighed them to the nearest 0.1 g.

Cash crop yield

We estimated cash-crop yield by weighing the fresh marketable biomass of all harvest plants within each 5 m crop sampling zone. Due to heavy rain and subsequent soil crusting in the spring of 2013 (Table 1), the spinach crop failed in half of our experimental plots, and those data were excluded from analysis.

Data analysis

We compared daily minimum, mean, and maximum soil temperature between grazed and mowed plots, as well as prior to and after cover crop termination using the conditional *F*-test of a generalized least squares fitted linear mixed effects model with an autoregressive moving average (ARMA) residual covariance structure based on the Julian Date following Zuur et al. (2009). ARMA residual covariance structures were parameterized by comparing Akaike's Information Criterion (AIC) values among candidate models with ARMA structures for $P = 0$, 1, 2 and $q = 0$, 1, 2, and plotting normalized residuals versus their autocorrelation function values. For these models, we treated cover crop termination method and period of the growing season (pre- versus

https://doi.org/10.1017/S1742170516000326 Published online by Cambridge University Press

post-termination) as fixed effects. Each trial year and each experimental plot was modeled with a random intercept with cover crop termination method nested within trial year, plots nested within cover crop termination method and period of the growing season nested within plots. Post-termination mean daily soil moisture was analyzed similarly, except that period was excluded as a fixed effect.

We compared soil chemical properties and compaction between treatments and among soil depths using a nested ANOVA where depth was nested within treatment and treatment was blocked by year. Foliar N at anthesis during the cover crop phase was compared between mowed and grazed plots using a one-way ANOVA with trial year as a blocking factor. Forage quality metrics were analyzed similarly.

We compared the total plant biomass in the cover crop phase at anthesis between grazed and mowed plots as well as between trials using a one way ANOVA blocked by trial year. Once cover crops were terminated, we tested treatment effects on biomass reduction using ANCOVA with pretreatment *Malva neglecta* (Wallr.) biomass as the covariate. ANCOVA was used due to high *M. neglecta* biomass before and after cover crop termination. Prior to the analysis, a Box-Cox power transformation analysis revealed that a log-transformation of biomass was warranted. The log-response (LR) ratio was calculated as:

$$\mathrm{LR} = \ln\left(\frac{M_{\mathrm{f}}}{M_0}\right) = \ln(M_{\mathrm{f}}) - \ln(M_0) \qquad (5)$$

where M_0 is the pretreatment biomass and M_{f} is the post-treatment biomass.

Cash crop yields were compared with a split-plot ANOVA with cover crop termination strategy as the main plot factor and cash crop rows as the subplot factor. As mentioned previously (see "Cash crop yield estimation" section), the spinach crop failed in half of our experimental plots in 2013 and was excluded from analysis. Thus, data from 2013 and 2014 were analyzed separately.

All analyses were conducted in R version 3.0.2 (R Development Core Team, 2013). Autoregressive mixed models were conducted in the nlme package of R (Pinheiro et al., 2015). Mean separations for significant interactions were performed using Tukey's HSD in the TukeyC package of R (Faria et al., 2012). Graphics were constructed in the sciplot (Morales et al., 2012) and ggplot2 (Wickham, 2009) packages of R.

Results

Soil physical and chemical characteristics

Cover crop termination method did not influence maximum [$F_{(1,9)} = 0.09$; $P = 0.761$], mean [$F_{(1,9)} < 0.01$; $P = 0.99$] or minimum daily soil temperature [$F_{(1,9)} = 0.09$; $P = 0.77$, Fig. 1A, C]. Similarly, cover crop termination method did not affect maximum [$F_{(1,9)} < 0.01$; $P = 0.99$], mean [$F_{(1,9)} < 0.01$; $P = 0.99$] or minimum post-termination soil moisture [$F_{(1,9)} < 0.01$; $P = 0.99$; Fig 1B, D]. Maximum [$F_{(1,922)} = 31.62$; $P < 0.001$] and mean [$F_{(1,922)} = 19.72$; $P < 0.001$] but not minimum [$F_{(1,922)} < 0.01$; $P = 0.98$] daily soil temperature differed between the pre-terminated and post-terminated periods. However, differences between pre-termination and post-termination maximum [$F_{(1,922)} = 0.14$; $P = 0.71$], mean [$F_{(1,922)} = 0.40$; $P = 0.53$] and minimum [$F_{(1,922)} = 0.14$; $P = 0.71$] daily soil temperatures did not vary between grazed and mowed plots.

Overall soil compaction differed between previously grazed [1.26 ± 0.14 MPa, mean ± standard error (SE)] and previously mowed (1.59 ± 0.17 MPa, mean ± SE) plots the spring following cover crop termination [$F_{(1,5)} = 8.18$; $P = 0.035$]. Soil compaction also increased with depth [$F_{(3,30)} = 40.02$; $P < 0.001$], with the greatest compaction between 45 and 60 cm below the soil surface ($P < 0.001$) and the least compaction between 0 and 15 cm below the soil surface ($P < 0.001$) (Fig. 2). There was no difference in soil compaction resistance between depths of 15–30 cm and 30–45 cm. However, the general increase in soil compaction with depth did not vary between previously grazed and previously mowed plots [$F_{(3,30)} = 1.52$; $P = 0.23$].

With the exception of soil pH, there was no difference in any of the measured soil chemical properties between previously grazed and previously mowed plots (Table 3). While we found that soil in previously mowed plots was more basic than in previously grazed plots, the difference in pH (0.067) was less than the sensitivity of the test (0.1). All measured soil chemical properties differed between topsoil and subsoil. However, none of those differences in soil chemistry between strata varied between previously grazed and previously mowed plots.

Forage quality

We found no difference in the RFV of the cover crop between grazed and mowed treatments (Table 4). Similarly, there was no interactive effect of treatment and year on RFV. There were no treatments or interactive effects on any of the other forage quality parameters measured.

Cover crop and weed biomass

Overall total biomass in the cover crop phase did not differ between mowed and grazed plots pooled across both trials of our experiment [$F_{(1,5)} = 0.01$; $P = 0.92$; Fig. 3A, B]. In 2012, grazing reduced total biomass more than mowing [$F_{(1,7)} = 13.33$; $P = 0.008$]. Total biomass in grazed plots was reduced 88.6 ± 6.07% compared with 75.8 ± 10.8% in mowed plots. Cover crop biomass declined more than weed biomass [$F_{(1,7)} = 42.98$; $P < 0.001$]. However, there was no interaction between termination method and plant class [$F_{(1,7)} = 3.33$; $P = 0.11$]. Grazing reduced cover

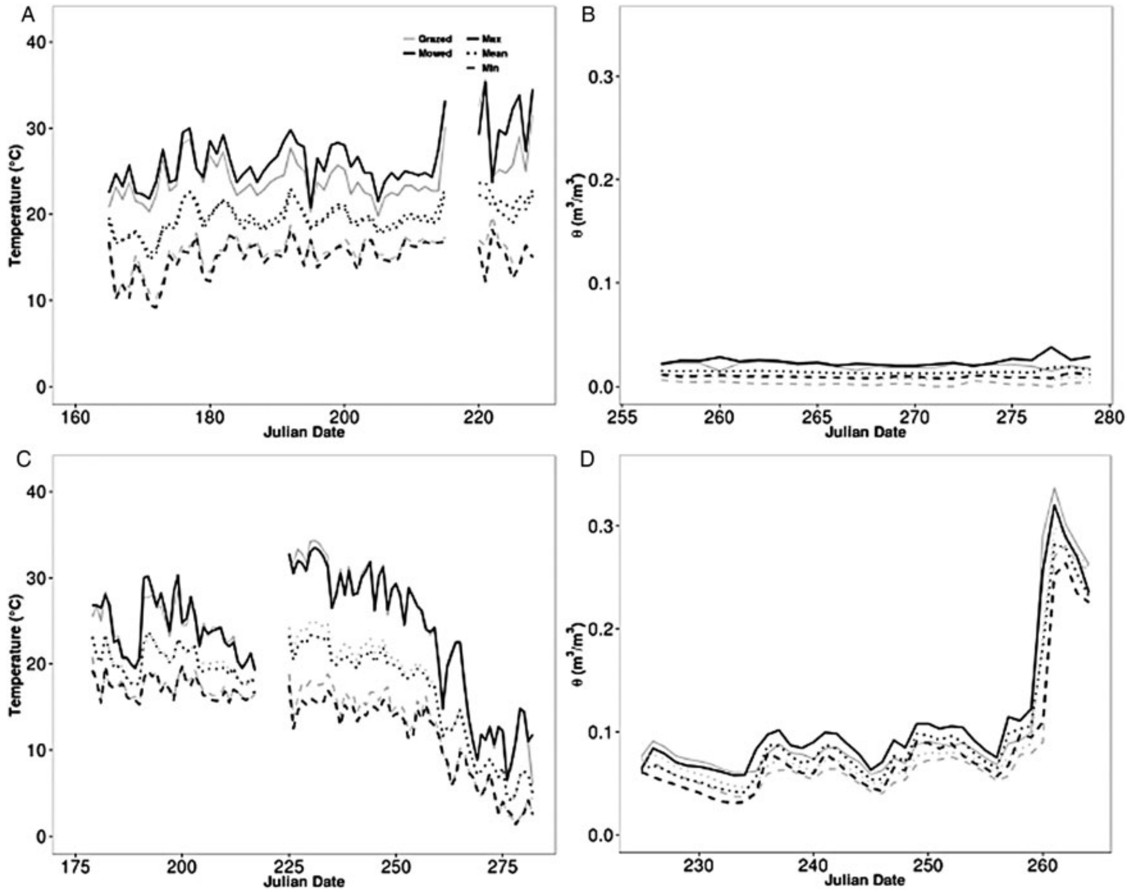

Figure 1. Effects of sheep grazing and mowing on (A) soil temperature in 2012, (B) soil moisture in 2012, (C) soil temperature in 2013 and (D) soil moisture in 2013 during the cover crop phase at Townes Harvest Farm, Bozeman, MT, USA. The legend in the top right panel (A) applies to all other panels (B–D).

crop biomass 97.8 ± 1.1% and weed biomass 56.5 ± 18.8%, while mowing reduced cover crop biomass 89.1 ± 5.1% and weed biomass 34.2 ± 25.4%.

In 2013, cover crop biomass was reduced more than weed biomass [$F_{(1,7)} = 16.89$; $P = 0.005$], but as in 2012, there was no interaction between termination method

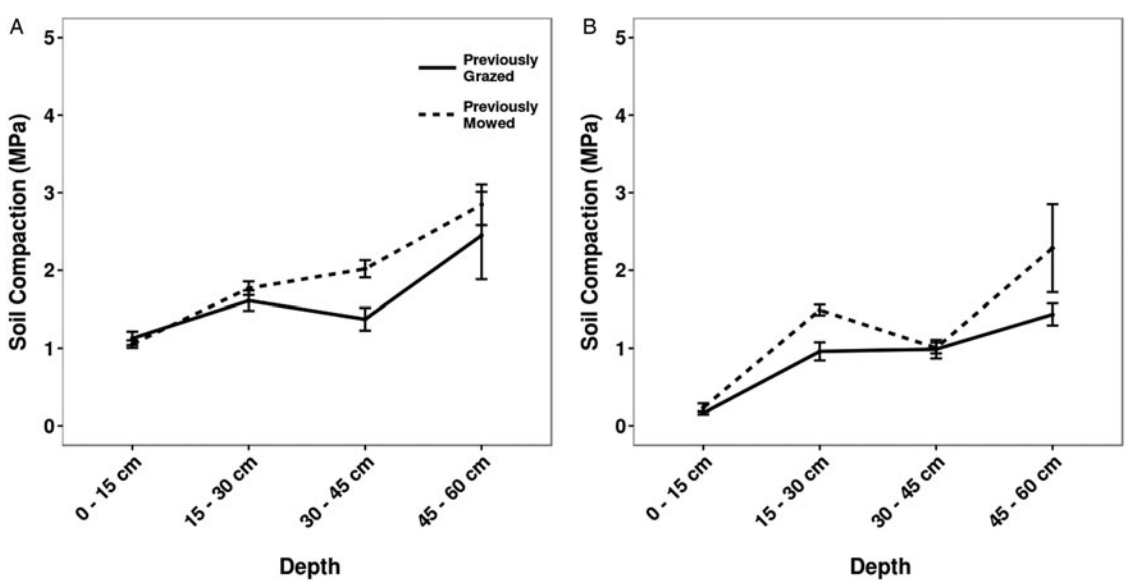

Figure 2. Effects of sheep grazing and mowing on soil compaction at Townes Harvest Farm in (A) 2013 and (B) 2014, Bozeman, MT, USA. Values are reported as mean ± SE. The legend in left panel (A) also applies to the right panel (B).

https://doi.org/10.1017/S1742170516000326 Published online by Cambridge University Press

Table 3. Impacts of sheep grazing and mowing on soil chemistry in the cash crop phase of 2013 and 2014 at Townes Harvest Farm, Bozeman, MT, USA.

		Topsoil (0–15 cm)		Subsoil (15–60 cm)	
		Mowed plots	**Grazed plots**	**Mowed plots**	**Grazed plots**
2013	OM (%)	3.70 ± 0.06	3.60 ± 0.22	2.30 ± 0.03	2.30 ± 0.19
	pH	7.80 ± 0.03	7.80 ± 0.00	7.90 ± 0.03	7.90 ± 0.09
	EC (mmhos)	0.37 ± 0.02	0.37 ± 0.03	0.46 ± 0.05	0.43 ± 0.02
	NO_3 (PPM)	17.00 ± 2.89	16.00 ± 2.09	14.00 ± 2.32	12.00 ± 1.50
	P (PPM)	97.00 ± 3.51	93.00 ± 8.82	73.00 ± 10.10	65.00 ± 8.19
	K (PPM)	850.00 ± 40.20	840.00 ± 18.90	550.00 ± 65.90	540.00 ± 42.10
	Ca (PPM)	3900.00 ± 308.00	4400.00 ± 795.00	6000.00 ± 101.00	5300.00 ± 803.00
	Mg (PPM)	510.00 ± 12.20	500.00 ± 11.80	590.00 ± 18.20	580.00 ± 28.70
	CEC ($cmol_c kg^{-1}$)	26.00 ± 1.72	28.00 ± 3.99	36.00 ± 0.19	33.00 ± 3.81
2014	OM (%)	3.93 ± 0.12	3.73 ± 0.12	2.70 ± 0.10	2.73 ± 0.18
	pH	7.77 ± 0.07	7.67 ± 0.03	7.87 ± 0.03	7.80 ± 0.00
	EC (mmhos)	0.36 ± 0.01	0.33 ± 0.02	0.36 ± 0.01	0.43 ± 0.02
	NO_3 (PPM)	13.67 ± 2.62	12.83 ± 1.67	31.00 ± 3.91	47.50 ± 11.30
	P (PPM)	126.67 ± 5.46	122.33 ± 2.19	106.67 ± 10.93	99.67 ± 13.53
	K (PPM)	937.33 ± 27.42	948.67 ± 37.83	722.67 ± 70.35	692.67 ± 29.81
	Ca (PPM)	3407.33 ± 121.15	3612.00 ± 232.27	5619.33 ± 188.62	4915.67 ± 527.10
	Mg (PPM)	481.67 ± 7.31	482.00 ± 9.81	646.00 ± 17.93	599.33 ± 13.04
	CEC ($cmol_c kg^{-1}$)	23.57 ± 0.69	24.60 ± 1.28	35.43 ± 0.84	31.47 ± 2.70

	Treatment		Depth		Depth × Treatment	
	$F_{(1,5)}$	P	$F_{(1,10)}$	P	$F_{(1,10)}$	P
OM (%)	0.17	0.694	590.70	<0.001***	2.10	0.178
pH	10.00	0.025*	15.00	0.003**	<0.001	>0.999
EC (mmhos)	0.01	0.922	18.70	0.002**	1.39	0.266
NO_3 (PPM)	0.87	0.395	4.99	0.049*	0.57	0.466
P (PPM)	0.80	0.413	45.04	<0.001***	0.27	0.614
K (PPM)	0.13	0.734	132.96	<0.001***	0.21	0.659
Ca (PPM)	0.19	0.684	47.94	<0.001***	5.23	0.045
Mg (PPM)	6.46	0.052•	58.20	<0.001***	0.46	0.513
CEC ($cmol_c kg^{-1}$)	0.27	0.627	46.01	<0.001***	5.09	0.048

Mowed and grazed plots refer to treatment applied in cover crop phase in 2012 and 2013, respectively. Values are reported as mean ± SE. OM, organic matter; EC, electrical conductivity; CEC, cation exchange capacity.
Significance levels: $0.05 \geq P \geq 0.01$*; $0.01 > P \geq 0.001$**; $0.001 > P$***.

and plant class [$F_{(1,7)} = 1.56$; $P = 0.25$]. Grazing reduced cover crop biomass 98.3 ± 1.2% compared with 83.0 ± 7.1% in mowed plots. While grazing reduced weed biomass 65.8 ± 9.4%, mowing increased weed biomass 36.7 ± 76.9% (Fig. 3C, D), principally due to an increase in the biomass of two weed species in one mowed plot. Common mallow (*M. neglecta* Wallr.) biomass in one mowed plot increased from 26.8 g m^{-2} at anthesis to 71.5 g m^{-2} after cover crop termination. Similarly, while we did not detect redroot pigweed (*Amaranthus retroflexus* L.) in that plot at anthesis; its biomass was 23.6 g m^{-2} following cover crop termination.

Cash-crop yields

In 2013, the spinach crop failed in three of the six plots, probably due to heavier than normal rain during spring and subsequent soil crusting (Table 1; C. Holt, Personal communication). Two of these plots had their cover crops terminated by mowing and one plot had its cover crop terminated by grazing. Thus, to avoid introducing bias, we excluded spinach yields from our analysis. Overall in 2013, we found marginally higher yields in mowed plots than in grazed plots [$F_{(1,2)} = 9.98$; $P = 0.087$; Fig. 4A]. There was a marginally significant interactive effect of cash crop species and termination method on yield [$F_{(1,4)} = 6.34$; $P = 0.065$], but no main effect of cash crop species on yields [$F_{(1,4)} = 1.81$; $P = 0.25$]. This is likely the result of a marginal difference between lettuce and kohlrabi yields in mowed plots ($P = 0.055$). In 2014, we found no overall difference in cash-crop yields between previously grazed and previously mowed plots [$F_{(1,2)} = 0.729$; $P = 0.48$; Fig. 4B]. Yields varied among crop species [$F_{(2,8)} = 19.33$; $P < 0.001$], with

Table 4. Forage quality of cover crops at Townes Harvest Farm, Bozeman, MT, USA.

	2012		2013	
	Mowed	Grazed	**Mowed**	**Grazed**
Foliar N (%)	2.19 ± 0.198	2.61 ± 0.439	3.13 ± 0.13	2.93 ± 0.180
Neutral detergent fiber (%)	52.50 ± 1.240	56.20 ± 3.650	53.20 ± 0.641	55.60 ± 4.040
Acid detergent fiber (%)	13.60 ± 0.815	9.25 ± 1.060	11.50 ± 2.3	11.40 ± 1.070
Crude protein (%)	14.50 ± 1.170	13.50 ± 2.580	20.00 ± 0.522	19.80 ± 0.800
Digestible dry matter (%)	78.30 ± 0.636	81.70 ± 0.824	80.00 ± 1.79	80.00 ± 0.834
Dry matter intake (%)	2.29 ± 0.057	2.15 ± 0.131	2.26 ± 0.0275	2.18 ± 0.150
Relative feed value	139.00 ± 3.690	136.00 ± 9.240	140.00 ± 4.86	135.00 ± 8.410

	Treatment		Treatment × Year	
	F(1,8)	*P*	*F*(1,8)	*P*
Foliar N (%)	0.17	0.694	1.38	0.274
Neutral detergent fiber (%)	1.18	0.309	0.05	0.833
Acid detergent fiber (%)	2.35	0.164	2.20	0.176
Crude protein (%)	0.14	0.718	0.06	0.808
Digestible dry matter (%)	2.35	0.164	2.20	0.176
Dry matter intake (%)	1.05	0.335	0.08	0.786
Relative feed value	0.28	0.609	0.03	0.861

Values are reported as mean ± SE.

lower yields of spinach than either lettuce ($P = 0.002$) or kohlrabi ($P = 0.002$). However, these differences in yield by crop species did not vary between previously grazed and previously mowed plots [$F_{(2,8)} = 0.141$; $P = 0.87$].

Discussion

Soil physical and chemical characteristics

Previous research suggests that, if properly applied, soil compaction by livestock grazing is limited to the top 10 cm of soil, ephemeral, and similar to the compaction caused by farm machinery (Greenwood and McKenzie, 2001; Franzluebbers and Stuedemann, 2008; Tracy and Zhang, 2008; Bell et al., 2011). Grazing may increase soil compaction when applied at higher soil moisture content because soil load capacity declines with increasing soil moisture content (Hamza and Anderson, 2005). In our study, we imposed sheep grazing and mowing treatments during a relatively dry period. Thus, we predicted soil compaction would be similar between treatments, but found that soil compaction was lower in previously grazed plots than in previously mowed plots. This may be a consequence of the relatively low stocking rate and short duration of grazing.

During the cover crop phase of our study, there was no difference in soil temperature between grazed and mowed plots. Our study involved a relatively short duration of grazing and in comparison with mowing it removed comparable amounts of living vegetation. As a consequence, while not directly measured, it is possible that both mowed and grazed plots had similar rates of evapotranspiration after cover crop termination. Unsurprisingly, we detected differences in maximum and mean daily soil temperature between the pre-termination and post-termination periods, reflecting an increase in solar radiation reaching the soil surface following termination of the cover crop. However, these differences between periods of the growing season were not modified by cover crop termination treatments. Similarly, we did not detect any differences in soil moisture content between grazed and mowed plots. Our soil probes allowed us to estimate soil moisture in the top 7 cm of the soil, but plants can uptake soil water much deeper than 10 cm (Wild, 1993). Therefore, although plots were grazed during the driest part of the year for Southwestern Montana, our methods may not necessarily reflect the effects of sheep grazing on total plant available water.

Despite the expected differences in soil chemistry between soil strata independent of treatments, and in accordance with previous studies (Marrs et al., 1989; Franzluebbers, 2007), we did not observe differences between grazed and mowed plots with the exception of pH. As noted above, the difference in pH between cover crop termination strategies was less than the sensitivity of the test, and we suggest that readers exercise caution when interpreting this result. The lack of differences in soil nutrient concentrations between grazed and mowed plots agrees with Collins (2003) who noted that for most nutrients, ruminants return up to 90% of what they consume in their excreta. Because crops require a greater quantity of N than any other soil macronutrient, and N is more easily lost from soils than other soil macronutrients (Thiessen Martens and Entz, 2011), its changes may be of the greatest concern for producers.

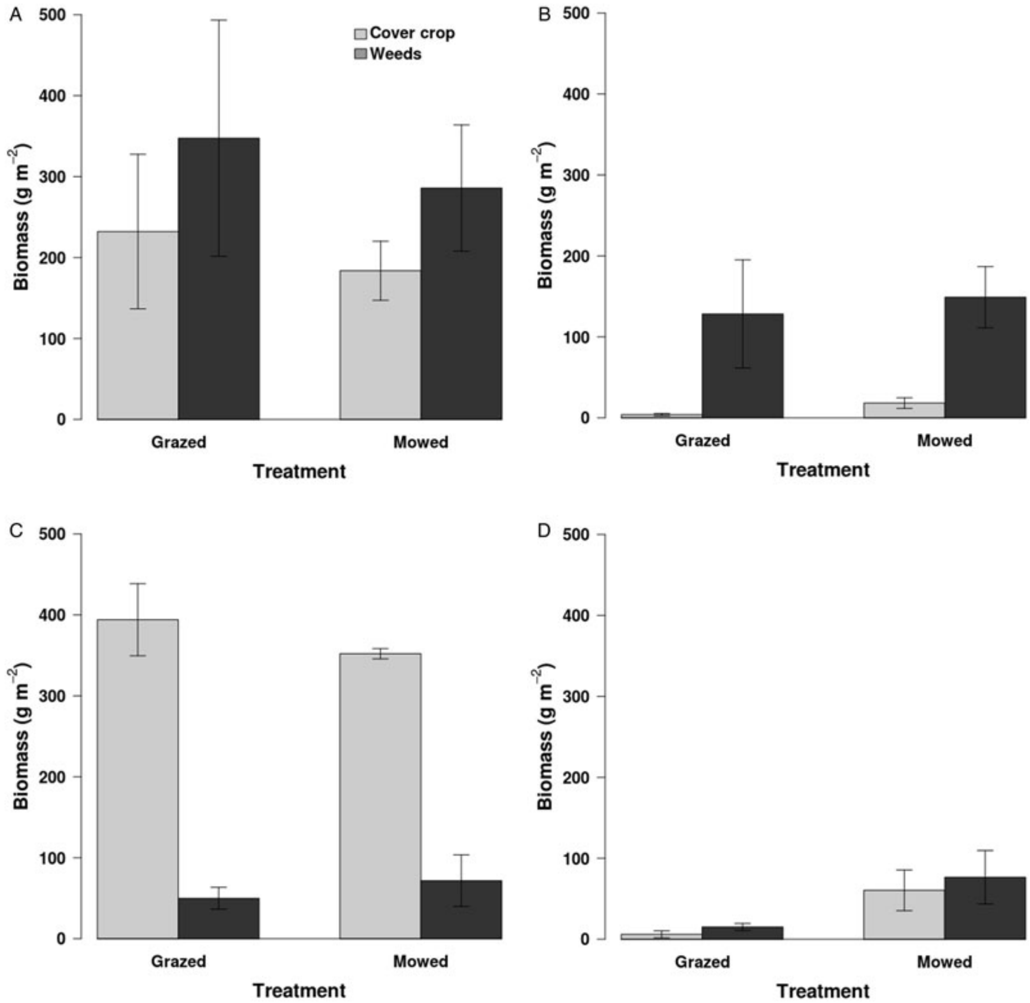

Figure 3. Impacts of termination approach (sheep grazing or mowing) on cover crop and weed biomass in (A) 2012 prior to cover crop termination, (B) 2012 after cover crop termination, (C) 2013 prior to cover crop termination and (D) 2013 after cover crop termination at Townes Harvest Farm, Bozeman, MT, USA. Values are reported as mean ± SE. The legend in the top right panel (A) applies to all other panels (B–D).

Thiessen Martens and Entz (2011) reported that sheep can retain up to 25% of the N they consume, but the N deposited in their feces and urine is often more labile than mineralized plant detritus. Thus, repeated grazing may result in declines in total N over longer temporal scales. The short-term nature of our study precludes us from evaluating the mid- and long-term consequences of sheep grazing on the movement of N and other nutrients.

Forage quality

We did not detect any differences in forage quality of cover crops, as measured by RFV, between treatment plots. Additionally, we did not find an effect of year or an interactive effect of year and treatment on forage quality. These results suggest that the forage quality of our cover crop was spatially homogeneous and temporally consistent.

The values we obtained for acid detergent fiber, a metric of indigestible fiber, were lower than a maximum value of 290 g kg^{-1} (29%) for premium quality alfalfa (*Medicago sativa* L.) forage (Bath and Marble, 1989; Buxton, 1996). Forbes (2007) notes that optimal forage crude protein concentrations for sheep nutrition range between 130 and 160 g kg^{-1} (13–16%). In 2012, crude protein concentrations were within this range for both treatments. However, in 2013, crude protein values were greater than this optimal range. Excess protein has a few potential adverse health effects on sheep including increased risk of heat stress, pizzle rot in rams and urolithiasis (Pugh and Baird, 2012). However, Kyriazakis and Oldham (1993) found that sheep can discriminate among available forages to optimize their crude protein intake. Thus, it is unlikely that sheep grazing cover crops would suffer the deleterious effects of excess crude protein intake, especially if they graze the cover crop for less than 1 month.

Both years the forage quality, as measured by RFV, fit within the top two categories as defined by the American Forage and Grassland Council (Hopper et al., 2004).

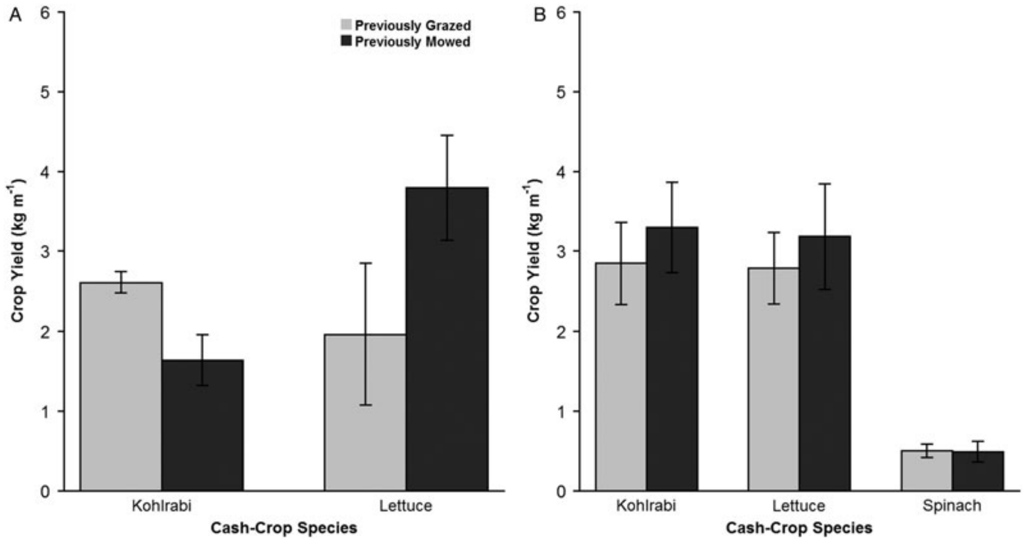

Figure 4. Impacts of sheep grazing and mowing on subsequent cash-crop yields (A) in 2013 and (B) in 2014 at Townes Harvest Farm, Bozeman, MT, USA. Values are reported as mean ± SE. The legend in left panel (A) also applies to the right panel (B).

Alfalfa forage of such standards commanded US\$77.76 and 69.37 Mg^{-1}, respectively (Hopper et al., 2004). Based on these values, the cover crop in the first trial represents US\$435.59 ± 74.60 and 409.69 ± 76.79 ha^{-1} worth of potential forage for mowed and grazed plots, respectively. In the second trial, the cover crop represented US\$276.18 ± 29.57 and 255.30 ± 27.81 ha^{-1} worth of potential forage for mowed and graze plots, respectively. Thus, a producer who terminated his/her cover crop by grazing with his/her own livestock grazing may save a substantial amount of money on high-quality fodder that he/she would otherwise have to buy if he/she terminated the cover crop by mowing.

In a study conducted in the Imperial Valley of California, alfalfa growers granted grazing leases to sheep ranchers *in lieu* of harvesting hay for US\$0.06–0.11 head^{-1} day^{-1} (Bell and Guerrero, 1997). At these rates and a stocking rate of 400–730 head ha^{-1}, a grazing lease would be worth US \$24.00–80.30 ha^{-1} day^{-1}. Assuming a 6-day lease—the duration of grazing in our study—a producer could potentially sell a grazing lease for US\$144.00–481.80 ha^{-1}. Hence, a grazing lease could at least partially off-set the cost of cover crop husbandry. These estimates do not represent a complete economic analysis, but this would be a valuable avenue for future research.

Cover crop and weed biomass

The effect of cover crop termination method on cover crop and weed biomass was not uniform. In 2012, sheep grazing reduced total plant biomass more than did mowing. However, in 2013 we found no differences between mowed and grazed plots. Despite these differences, in both years cover crop biomass declined more than weed biomass. In the 2012 trial, weed biomass was greater than cover crop biomass prior to termination with *A. retroflexus* and *M. neglecta* as the dominant species. *Malva neglecta* has a prostrate growth form and thus may have avoided termination through either grazing or mowing (Sean McKenzie, personal observation). Despite the erect stems of *A. retroflexus*, many stems of this species were able to re-sprout following termination (Sean McKenzie, personal observation). The dominant cover crop species was *F. esculentum*, which has erect stems. In contrast to *A. retroflexus*, *F. esculentum* stem did not re-sprout after being mowed or grazed. These results suggest that grazing and mowing are equally effective at terminating a cover crop, but the efficacy of these cover crop termination methods may be temporally variable and may depend on the species composition of the weed community and the cover crop, as well as the species of livestock used for cover crop termination. In addition, some cover crop and weed species—including *M. officinalis* and *A. retroflexus*—are considered toxic to livestock, which may preclude grazing for cover crop termination when such species comprise a substantial proportion of the total biomass. For a detailed discussion of the effects of these cover crop termination methods on plant community dynamics see our companion study (McKenzie et al., 2016).

Cash-crop yields

Similar to previous studies (Franzluebbers, 2007; Bell et al., 2011; Hilimire, 2011; Thiessen Martens and Entz, 2011), we did not find any detriments to crop yields from integrating livestock into our cropping system. In addition, our results concur with the observation of Franzluebbers (2007), that using livestock to terminate cover crops does not impact subsequent crop yields. To our knowledge, this is the first study to quantify the legacy effects of integrating livestock for cover crop termination on cash-crop yield in horticultural vegetable market-gardens, and thus precludes any direct comparisons with previous studies in such systems.

Conclusion

Our study indicated that integrating livestock for cover crop termination can enhance the economic feasibility of cover crop use without negatively impacting growing conditions or agronomic outputs. This may be especially important in horticultural vegetable market-gardens, where consumer preferences, costs and environmental concerns prohibit or at least discourage the use of off-farm inputs for nutrient and pest management. Our study is one of a very few studies (e.g., Lowy, 2009; McKenzie et al., 2016) to investigate the impacts of integrating livestock into horticultural market-gardens. While we found no negative legacy impacts of using sheep grazing to terminate cover crops, future research should investigate longer-term legacy effects, as well as the impacts of repeated grazing.

Acknowledgements. We would like to extend our deepest gratitude to Charles Holt, farm manager at Townes Harvest Farm (THF) and David Baumbauer, Director of Horticulture at Montana State University (MSU), for allowing us to conduct our research at THF and accommodating our research needs. Many thanks to the other members of the Weed Ecology Laboratory at MSU, Subodh Adhikari, Dr. Judit Barraso, Erin Burns, Krista Ehlert, Stephen Johnson, Dr. Zachariah Miller and Nar Ranabadht, as well as our undergraduate technicians Torrin Daniels, Christian Larsen, Madison Nixon, Wyatt Holmes, Janki Patel, Lori Saulsbury, Alexandra Thornton and Emmett Wester for their assistance with data collection and processing. Thanks to Hilary Parkinson, plant identification diagnostician for Schutter Diagnostic Laboratory at MSU, for her assistance with plant identification. Finally, we are grateful to the Montana Agricultural Experiment Station, the Western Sustainable Agriculture Research and Extension Program (grant no. SW11–086) the NIFA Organic Research and Extension Initiative (grant no. MONB00314) and the NIFA Organic Transitions program (grant no. MONB00128) of the USDA for funding this research.

References

Altieri, M.A. 1999. The ecological role of biodiversity in agroecosystems. Agriculture, Ecosystems and Environment 74(1): 19–31.

Altieri, M. and Nicholls, C. 1999. Biodiversity, ecosystem function, and insect pest management in agricultural systems. In W. Collins and C. Qualset (eds). Biodiversity in Agroecosystems. CRC Press, Boca Raton, FL, USA. p. 69–84.

Altieri, S.M.A., Ponti, L., and Nicholls, C.I. 2012. Soil fertility, biodiversity and pest management. In G.M. Gurr, S.D. Wratten, and W.E. Snyder (eds). Biodiversity and Insect Pests: Key Issues for Sustainable Management. John Wiley and Sons Ltd., New York, NY, USA. p. 72–84.

ANKOM Technology 2011a. Acid Detergent Fiber in Feeds – Filter Bag Technique (for A2000 and A2000I).

ANKOM Technology 2011b. Neutral Detergent Fiber in Feeds – Filter Bag Technique (for A2000 and A 2000I).

Bakker, J.P. 1998. The impact of grazing on plant communities. In M.F. WallisDeVries, S.E.V. Wieren, and J.P. Bakker (eds). Grazing and Conservation Management, Conservation Biology Series. Kluwer Academic Publishers, London, UK. p. 137–184.

Barbosa, P.A. 1998. Agroecosystems and conservation biological control. In P.A. Barbosa (ed.). Conservation Biological Control. Academic Press, San Diego, CA, USA. p. 39–54.

Bath, D.L. and Marble, V.L. 1989. Testing Alfalfa for its Feeding Value. Cooperative Extension, University of California, Division of Agriculture and Natural Resources, Oakland, CA. Leaflet 21457. WREP 109.

Bell, C.E. and Guerrero, J.N. 1997. Sheep grazing effectively controls weeds in seedling alfalfa. California Agriculture 51 (2):19–23.

Bell, L.W., Kirkegaard, J.A., Swan, A., Hunt, J.R., Huth, N.I., and Fettell, N.A. 2011. Impacts of soil damage by grazing livestock on crop productivity. Soil and Tillage Research 113(1):19–29.

Buxton, D.R. 1996. Quality-related characteristics of forages as influenced by plant environment and agronomic factors. Animal Feed Science and Technology 59(1):37–49.

Collins, J.L. 2003. Agricultural phosphorus in an integrated crop/livestock system in the Texas High Plains. Doctoral Dissertation, Texas Tech University, Lubbock, TX, USA.

Dabney, S.M. 1998. Cover crop impacts on watershed hydrology. Journal of Soil and Water Conservation 53(3):207–213.

Dabney, S.M., Schreiber, J.D., Rothrock, C.S., and Johnson, J.R. 1996. Cover crops affect sorghum seedling growth. Agronomy Journal 88(6):961–970.

Dabney, S.M., Delgado, J.A., and Reeves, D.W. 2001. Using winter cover crops to improve soil and water quality. Communications in Soil Science and Plant Analysis 32(7–8):1221–1250.

Diamond, H.J., Karl, T.R., Palecki, M.A., Baker, C.B., Bell, J. E., Leeper, R.D., Easterling, D.R., Lawrimore, J.H., Meyers, T.P., Helfert, M.R., Goodge, G., and Thorne, P.W. 2013. U.S. climate reference network after one decade of operations: Status and assessment. Bulletin of the American Meteorological Society 94(4):485–498.

Faria, J.C., Jelihovschi, E.G., and Allaman, I.B. 2012. Conventional Tukey Test. Universidade Estadual de Santa Cruz, Ilheus, Bahia, Brazil.

Foley, J.A., Ramankutty, N., Brauman, K.A., Cassidy, E.S., Gerber, J.S., Johnston, M., Mueller, N.D., O'Connell, C., Ray, D.K., West, P.C., Balzer, C., Bennett, E.M., Carpenter, S.R., Hill, J., Monfreda, C., Polasky, S., Rockström, J., Sheehan, J., Siebert, S., Tilman, D., and Zaks, D.P.M. 2011. Solutions for a cultivated planet. Nature 478(7369):337–342.

Forbes, J.M. 2007. Voluntary Food Intake and Diet Selection in Farm Animals. CAB International, Oxon, UK.

Foth, H.D. and Ellis, B.G. 1997. Soil Fertility. 2nd ed. John Wiley and Sons Ltd., New York, NY, USA.

Franzluebbers, A.J. 2007. Integrated crop–livestock systems in the Southeastern USA. Agronomy Journal 99(2):361–372.

Franzluebbers, A.J. and Stuedemann, J.A. 2008. Soil physical responses to cattle grazing cover crops under conventional and no tillage in the Southern Piedmont USA. Soil and Tillage Research 100(1):141–153.

Gallandt, E.R., Liebman, M., and Huggins, D.R. 1999. Improving soil quality: Implications for weed management. Journal of Crop Production 2(1):95–121.

Gardner, J.C., Faulkner, D.B., and Hargrove, W.L. 1991. Use of cover crops with integrated crop-livestock production systems. In W.L. Hargrove (ed.). Cover Crops Clean Water. Soil and Water Conservation Society, Ankeny, IA, USA. p. 185–191.

Greenwood, K.L. and McKenzie, B.M. 2001. Grazing effects on soil physical properties and the consequences for pastures: A review. Australian Journal of Experimental Agriculture 41 (8):1231–1250.

Hamza, M.A. and Anderson, W.K. 2005. Soil compaction in cropping systems: A review of the nature, causes and possible solutions. Soil and Tillage Research 82(2):121–145.

Hartwig, N.L. and Ammon, H.U. 2002. Cover crops and living mulches. Weed Science 50(6):688–699.

Hausenbuiller, R.L. 1985. Soil Science: Principles and Practices. 3rd ed. Wm. C. Brown Publishers, Dubuque, IA, USA.

Hilimire, K. 2011. Integrated crop/livestock agriculture in the United States: A review. Journal of Sustainable Agriculture 35(4):376–393.

Hopper, J.A., Peterson, H.H., and Burton, R.O., Jr 2004. Alfalfa hay quality and alternative pricing systems. Journal of Agricultural and Applied Economics 36(3):675–690.

Hu, S.J., van Bruggen, A.H.C., and Grünwald, N.J. 1999. Dynamics of bacterial populations in relation to carbon availability in a residue-amended soil. Applied Soil Ecology 13(1):21–30.

Kahimba, F.C., Sri Ranjan, R., Froese, J., Entz, M., and Nason, R. 2008. Cover crop effects on infiltration, soil temperature, and soil moisture distribution in the Canadian Prairies. Applied Engineering in Agriculture 24(3):321–333.

Kamh, M., Horst, W.J., Amer, F., Mostafa, H., and Maier, P. 1999. Mobilization of soil and fertilizer phosphate by cover crops. Plant and Soil 211(1):19–27.

Kyriazakis, I. and Oldham, J.D. 1993. Diet selection in sheep: The ability of growing lambs to select a diet that meets their crude protein (nitrogen × 6.25) requirements. British Journal of Nutrition 69(3):617–629.

Lal, R. 2004. Soil carbon sequestration impacts on global climate change and food security. Science 304(5677):1623–1627.

Landis, D.A. and Menalled, F.D. 1998. Ecological considerations in the conservation of effective parasitoid communities in agricultural systems. In P.A. Barbosa (ed.). Conservation Biological Control. Academic Press, San Diego, CA, USA. p. 101–121.

Liebman, M. and Davis, A.S. 2000. Integration of soil, crop and weed management in low-external-input farming systems. Weed Research 40(1):27–47.

Low, S.A. and Vogel, S. 2011. Direct and Intermediated Marketing of Local Foods in the United States. US Department of Agriculture, Economic Research Service, Washington, DC, USA.

Lowy, P. 2009. Integrating Poultry and Sheep on Vegetable Cropping Land for Increased Economic Return and Enhanced Fertility. Sustainable Agriculture Research and Education Project Database; Farmer/Rancher Project, Northeast.

Magdoff, F. 2007. Ecological agriculture: Principles, practices, and constraints. Renewable Agriculture and Food Systems 22(2):109–117.

Marrs, R.H., Rizand, A., and Harrison, A.F. 1989. The effects of removing sheep grazing on soil chemistry, above-ground nutrient distribution, and selected aspects of soil fertility in long-term experiments at Moor House National Nature Reserve. Journal of Applied Ecology 26(2):647–661.

Matson, P.A., Parton, W.J., Power, A.G., and Swift, M.J. 1997. Agricultural intensification and ecosystem properties. Science 277(5325):504–509.

McKenzie, S.C., Goosey, H.B., O'Neill, K.M., and Menalled, F. D. 2016. Impact of integrating sheep grazing for cover crop termination on weed and ground beetle (Coleoptera: Carabidae) communities. Agriculture Ecosystems and Environment 218(2):141–149.

Meissner, R.A. and Facelli, J.M. 1999. Effects of sheep exclusion on the soil seed bank and annual vegetation in chenopod shrublands of South Australia. Journal of Arid Environments 42(2):117–128. doi:10.1006/jare.1999.0515

Morales, M., R Core Development Team, and Murdoch D. 2012. sciplot: Scientific graphing functions for factorial designs. R package version 1.1-0. Available at Web site http://CRAN.R-project.org/package=sciplot

Natural Resources Conservation Service (NRCS) 2013. Web Soil Survey. Available at Web site http://websoilsurvey.nrcs.usda.gov/app/WebSoilSurvey.aspx

Pinheiro, J., Bates, D., DebRoy, S., Sarkar, D., and R Core Team 2015. nlme: Linear and nonlinear mixed effects models. R package version 3.1-122. Available at Web site http://CRAN.R-project.org/package=nlme

Popay, I. and Field, R. 1996. Grazing animals as weed control agents. Weed Technology 10(1):217–231.

Pugh, D.G., and Baird, N.N. 2012. Sheep & Goat Medicine. W.B. Saunders Company, Philadelphia, PA, USA.

R Development Core Team 2013. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.

Reeves, D.W. 1994. Cover crops and rotations. In J.L. Hatfield and B.A. Stewart (eds). Advances in Soil Science: Crops Residue Management. Lewis Publishers, CRC Press, Boca Raton, FL, USA. p. 125–172.

Reganold, J.P., Jackson-Smith, D., Batie, S.S., Harwood, R.R., Kornegay, J.L., Bucks, D., Flora, C.B., Hanson, J.C., Jury, W.A., and Meyer, D. 2011. Transforming US agriculture. Science 332(6030):670–671.

Robertson, G.P. and Swinton, S.M. 2005. Reconciling agricultural productivity and environmental integrity: A grand challenge for agriculture. Frontiers in Ecology and the Environment 3(1):38–46.

Robertson, G.P., Allen, V.G., Boody, G., Boose, E.R., Creamer, N.G., Drinkwater, L.E., Gosz, J.R., Lynch, L., Havlin, J.L., Jackson, L.E., Pickett, S.T.A., Pitelka, L., Randall, A., Reed, A.S., Seastedt, T.R., Waide, R.B., and Wall, D.H. 2008. Long-term agricultural research: A research, education, and extension imperative. BioScience 58 (7):640–645.

Snapp, S.S., Swinton, S.M., Labarta, R., Mutch, D., Black, J.R., Leep, R., Nyiraneza, J., and O'Neil, K. 2005. Evaluating cover crops for benefits, costs and performance within cropping system niches. Agronomy Journal 97(1):322–332.

Sulc, R.M. and Tracy, B.F. 2007. Integrated crop–livestock systems in the U.S. corn belt. Agronomy Journal 99(2):335–345.

Teasdale, J.R., Beste, C.E., and Potts, W.E. 1991. Response of weeds to tillage and cover crop residue. Weed Science 39(2): 195–199.

Thiessen Martens, J. and Entz, M. 2011. Integrating green manure and grazing systems: A review. Canadian Journal of Plant Science 91(5):811–824.

Tillman, P.G., Smith, H.A., and Holland, J.M. 2012. Cover crops and related methods for enhancing agricultural biodiversity and conservation biocontrol: Successful case studies. In G M. Gurr, S.D. Wratten, and W.E. Snyder (eds). Biodiversity and Insect Pests: Key Issues for Sustainable Management. John Wiley and Sons Ltd., New York, NY, USA. p. 309–327.

Tracy, B.F. and Zhang, Y. 2008. Soil compaction, corn yield response, and soil nutrient pool dynamics within an integrated crop-livestock system in Illinois. Crop Science 48(3):1211–1218.

Undersander, D. and Moore, J.E. 2002. Relative forage quality. Focus on Forage 4(5):1–2.

Wickham, H. 2009. ggplot2: Elegant Graphics for Data Analysis. Springer, New York.

Wild, A. 1993. Soils and the Environment. Cambridge University Press, Cambridge, UK.

Zuur, A., Ieno, E.N., Walker, N., Saveliev, A.A., and Smith, G.M. 2009. Mixed Effects Models and Extensions in Ecology with R. Springer Science & Business Media, New York, NY, USA.