

EFFECTS OF ORGANIC AND CONVENTIONAL  
CROPPING SYSTEMS ON PLANT DIVERSITY  
AND PLANT SOIL FEEDBACKS

by

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## ABSTRACT

The reliance on tillage for cover crop termination, weed, and residue management is one of the biggest sustainability challenges facing organic grain farmers. Integrating grazers may be an alternative to tillage for weed management and cover crop termination. We used an on-farm trial to compare tillage-based versus grazed / reduced tillage-based management of organic crops. Our results indicate that using sheep to terminate cover crops and manage weeds can reduce tillage intensity and provide crop yields weed communities similar to standard, tillage-intensive practices. In addition, growers leasing their land under a grazing lease may be able to increase economic returns.

We also implemented a crop rotation study comparing traditional tillage-based organic to reduced-tillage organic with animal-integration, as well as to a no-till conventional system with fertilizer and pesticide inputs. There were no differences in cover crop growth and subsequent winter wheat yielded the same among the three systems. We found little evidence that weed communities differed among the three management systems in the transition to organic period. Generally, shifts in weed communities occurred across all system from one crop to the next, indicating cropping sequence structured weed communities more than divergent tillage and weed management practices

Biologically-mediated plant-soil feedbacks (PSFs) are known to alter plant growth, plant-plant interactions, and plant community dynamics in natural systems. Yet, little is known about the magnitude and importance of PSFs in agro-ecosystems. Therefore, we implemented a greenhouse study that investigated the impact of organic and conventional management systems on crop growth and crop-weed interactions as mediated through PSFs. Results indicated that in general, PSFs and plant growth were more positive when soil inocula was collected from organic farms compared to conventional farms, suggesting that cropping systems modify the relative abundance of mutualistic and pathogenic organisms responsible for the observed PSFs. Also, as feedbacks became more positive, crop-weed competition decreased and facilitation increased. Therefore, in annual cropping systems, PSFs can alter plant growth and crop-weed competition.

## CHAPTER ONE

## BACKGROUND, LITERATURE REVIEW, AND RESEARCH OBJECTIVES

Introduction

Sustainable agriculture can be characterized as a systems-oriented approach that jointly focuses on the provision of ecosystem services, including the production of food, fiber, and energy, while maintaining habitat quality and biodiversity, and securing profits for producers and local communities (Altieri 1999, Tilman et al. 2002). For weed scientists, agronomists, and producers this means moving past prescription-based management of farms through land conversion and intensification (Matson 1997) towards ecologically-based management that looks at agriculture landscapes as complex ecosystems (Cassman 1999, Robertson and Swinton 2005, Philip Robertson et al. 2014). Although organic agriculture perhaps better embraces this approach to sustainability due to its refrained use of nutrient and pesticide inputs (Tilman 1998, Sandhu et al. 2010), organic agriculture faces challenges to sustainability (Peigné et al. 2007, Carr et al. 2011, 2013, Brainard et al. 2013). Chief among them is soil erosion due to excessive reliance on tillage and the ability for organic farms to produce the same amount of food as conventional farms (Connor 2008) while managing nutrients like nitrogen and phosphorous (Entz et al. 2001, Miller et al. 2008). Therefore, improving sustainability in agro-ecosystems must look at farms as a complex of management practices that improve not only agronomic returns, but improve ecological efficiency as well.

## Literature Review

### No-Till

One of the biggest challenges to sustainability facing organic farmers is the reliance on tillage. Tillage poses long-term sustainability challenges including erosion (Greer et al. 2006), reduced aggregate stability (Liebig et al. 2004) and reduced water infiltration (Franzluebbers 2002). Karlen et al. (1994) summarized that no-till systems are characterized by better soil water retention, soil structure, soil carbon, and microbial mass than tilled soils.. In semi-arid environments of the northern Great Plains (NGP), where many regions receive approximately 300mm in annual precipitation, no-till is particularly beneficial in conserving water (Tanaka et al. 2010). While conventional farmers have made strides in adopting no-till operations (Tanaka et al. 2010, Hansen et al. 2012), the reliance on herbicides has led to the selection of herbicide resistant weed biotypes (Powles and Yu 2010), non-target effects on other species, soil and water contaminations due to runoff, and residual carryover in the environment (Liebman et al. 2001).

On the other hand, organic farms heavily rely on tillage for weed control and cover crop termination (Carr et al. 2013). Soil erosion due to tillage has greatly redistributed soil in agricultural landscapes (Van Oot et al. 2005), although some strides have been made in conservation tillage for organic farms (Peigné et al. 2007). In the northern Great Plains, organic farming is dominated by small grain farmers who are interested in reducing erosion associated with tillage, but research is needed to better understand the challenges of organic no-till systems (Carr et al. 2011). These issues have

focused agro-ecological research on ways to develop ecologically-based weed management programs that reduce tillage intensity while minimizing off-farm synthetic inputs (Brainard et al. 2013).

### Cover Crops

Cover crops are unharvested plants grown into or after a main crop and then terminated before a harvested crop is planted and provide an additional tool for ecological management of agricultural systems (Hartwig and Ammon 2002, Carr et al. 2011). Cover crops can be used to reduce soil erosion, sequester excess nutrients and water, suppress weeds, and increase available nutrients (Delgado et al. 2007). For example, Kamh et al. (1999) found that the cover crop *Lupinus albus* (L.) was able to uptake inorganic phosphorous (P) which increased P-availability in the subsequent crop. This is particularly important for organic growers where P tends to one of the more deficient nutrients in their cropping systems (Entz et al. 2001, Miller et al. 2008). Cover crops also provide a rich litter resource that can increase soil organic matter (Hartwig and Ammon 2002) which has been linked with positive responses in the soil biotic community (Wardle et al. 1999, Doran and Zeiss 2000, Ponge et al. 2013). Still, some wheat [*Triticum aestivum* (L.)] growers in the semi-arid sections of the NGP rely on a fallow period for water conservation and reliable yields (Cochran et al. 2006).

In replacing fallow in the water-limited environments of the NGP with legume cover crops, studies have shown similar soil moisture retention to fallow with proper termination timing (Zentner et al. 2004), and increased available N to subsequent crops (McCauley et al. 2012, O'Dea et al. 2013, Miller et al. 2015a). This is crucial for organic

farms, where legume green manure is a critical tool for N management [albeit insufficient for some wheat grain milling standards (Miller et al. 2011)], and an additional strategy for managing weeds (Barberi 2002, Derksen et al. 2002). Nonetheless, cover crop termination still relies on single tool approaches such as tillage or herbicide application and, both approaches have ecological and management shortcomings.

### Crop-Livestock Integration

Integrating grazers into annual crop production represents an alternative to tillage and herbicide application for cover crop termination and weed management (Thiessen Martens and Entz 2011). Although the specialization of farms and ranches to work with either crops or animals as separate entities dominates agriculture in developed nations (Clark 2004, Wilkins 2008), opportunities for farmers to lease their land under grazing leases may relieve costs associated with animal integration (Russelle et al. 2007), including investments in fencing and watering systems (Undersander et al. 2002). Despite the documented benefits of animal-integrated systems (Franzluebbbers et al. 2012), research still needs to tease out differences in mineralization with grazing intensities (Seagle et al. 1992, Shariff et al. 1994), comparing soil compaction from animals with tillage practices (Poffenbarger 2010), and logistic implementation (Thiessen Martens and Entz 2011).

Livestock integrated cropping systems may help alleviate N and especially P deficiencies, manage weeds, and provide stable economic returns for growers (Entz et al. 2002, Russelle et al. 2007, Thiessen Martens and Entz 2011). Franzluebbbers and Stuedemann (2013) found that integrating cattle for cover crop and residue grazing had a

negative impact on corn and soybean yields, but not winter wheat, and was a net economic advantage when considering weight gain in cattle. Further, they found that coupling animal-integration with no-till management led to higher yields, particularly under drought conditions. Nonetheless, grazing integration may lead to soil compaction and reduced water infiltration depending on grazing intensity and prior cropping choices (Franzluebbers and Stuedemann 2008).

Research integrating sheep grazing, as opposed to chemical or mechanical practices for fallow weed management in the NGP has shown that it can be used with minimal effect on crop yield and quality (McKenzie et al. *In Press*, Lenssen et al. 2013), varying effects on soil nutrients (Sainju et al. 2011), and increased carbon and nitrogen storage in soils with moderate grazing intensity (Barsotti et al. 2013). However, this integration can result in an increase in weed pressure, particularly of perennial weeds in the Asteraceae family such as *Taraxacum officinale* F.H. Wigg. (dandelion) (Miller et al. 2015b). Despite this drawback, when targeted grazing is integrated with the use of cover crops, crop rotation, and mechanical control, it may help alleviate weed management challenges in reduced tillage organic systems (Carr et al. 2011).

### Crop Rotations

Increasing cropping diversity with various broad and narrow leaf, as well as warm- and cool-season plants, has known agricultural benefits, including increased crop yields (Anderson et al. 1999, Miller et al. 2002), although this depends on rainfall conditions (Miller and Holmes 2005), improved nutrient cycling and pest management (Anderson 2005b, Cochran et al. 2006, Miller et al. 2006), lowered weed density

(Anderson and Beck 2009), and improved rotation of herbicide families, minimizing the selection of herbicide resistant biotypes and the dominance of single weed species (Derksen et al. 2002). These advantages are further enhanced when coupled with reduced tillage, competitive cultivars, higher seeding rates, and fertilizer management (Blackshaw et al. 2008). If properly integrated, this suite of practices acts as an ecological filter on associated diversity, including weeds, which results in an easier to manage or less competitive weed community (Booth and Swanton 2002).

### Ecological Filters

Ecological Filters of Weed Communities. The suite of practices a farmer deploys to manage the cropping system acts as an ecological filter on the associated diversity, including weeds (Vandermeer et al. 2002, Booth and Swanton 2002). Previous studies show that crop seeding, residue management, or crop selection are examples of dispersal, environmental, and biotic filters, respectively, on the regional weed species pool (Keddy 1992, Funk et al. 2008). This is particularly important for land managers interested in understanding the interaction of crop husbandry and cultivation practices on resultant weed abundance and compositions as it can provide predictive tools for practitioners interested in ecological pest management. For example, Ominski et al. (1999) found that *Medicago sativa* L. (alfalfa) planted as a perennial forage before a grain crop may be part of an integrated weed management system to help control annual grassy weeds like *Avena fatua* L. (wild oat) and perennials like *Cirsium arvense* (L.) Scop. (Canada thistle, creeping thistle), although other perennial broadleaf species such as *T. officinale* appears



to increase with this forage. Forages similarly negatively affect grasses like *A. fatua* and *Setaria viridis* (L.) P.Beauv (green foxtail), however biennial crops had seasonal advantages over early season weeds while long season crops like winter triticale tended to provide better late season weed control (Schoofs and Entz 2000). More recently, Smith et al. (2015) showed that specific cover crop species have differing effects on weed community assemblage, although cover crop biomass production appears to better explain changes in weed abundance.

Other management practices such as cultivation, animal integration, and synthetic inputs may also impact weed community responses. Chauhan et al. (2006) summarize that tillage impacts on weeds are usually species specific where weed seeds that require burial may become more prevalent in tilled systems. On the other hand, Menalled et al. (2001) examined at four systems (high input plowed, high input no-till, low input plowed, and organic plowed) where above-ground and seedbank community responses showed more similarities due to the level of chemical inputs than the actual use of tillage. In comparison with conventional, continuous corn (*Zea mays* L.) system in Illinois, animal integration and cover cropping was associated with a change in life history and species composition of the weed community, but the exact contribution of each one of these management practices is unknown (Tracy and Davis 2009). Further, one grassland study indicated that plant communities changed due to inter-annual variability rather than from grazing treatments, at least in a short term period (Loeser et al. 2001), and duration and intensity of grazing may be important factors in determining plant community changes (Popay and Field 1996).

Ecological Filters of the Soil Biotic Community. There is growing interest in manipulating farm management practices to enhance soil biological characteristics in ways that positively impact agroecosystems (Pankhurst 1994, Brussaard et al. 2007). However, while progress has been made in determining the role of soil biota in weed invasiveness (Wolfe and Klironomos 2005), little is known about the impacts of increased cropping system diversification on soil biota and how that drives agricultural productivity. Yet, practices such as tillage, cropping system diversification, and cover cropping alter soil microbial communities (Wortman *et al.* 2013).

Mechanical practices like tillage, commonly used in organic farming systems, have been associated with a decrease in microbial biomass and earthworm populations (Karlen et al. 1994), as well as a decrease in microbial diversity (Lupwayi et al. 1998). Yet, organic farms often have increased weed diversity (Menalled et al. 2001, Pollnac et al. 2009, Harbuck et al. 2009) and higher plant diversity has been linked with increased microbial biomass (Thakur et al. 2015), respiration, and fungal abundance (Zak et al. 2003). On the other hand, agriculture intensification with fertilizers and herbicides, a staple practice in no-tillage conventional farming, has a negative impact on meso- and macro-biota in the short term, and microbiota over time (Postma-Blaauw et al. 2010). Finally, previous studies have demonstrated that diverse crop rotations, a practice commonly used in organic systems, increase the diversity of soil biota (Lupwayi et al. 1998), and this can be directly tied to soil aggregation, organic carbon, and total nitrogen (Tiemann et al. 2015).

### Plant Soil Feedbacks

Research has shown the presence of plant-soil feedbacks (PSFs) in different natural and agriculture plant-soil communities (Postma-Blaauw et al. 2010, Miller et al. 2015b), but little is known about the role agricultural management systems on these feedbacks. Plant-soil feedback refers to the processes by which plants alter belowground ecosystems through root and nutrient exudates, changing and conditioning soil biota and abiotic dynamics, which in turn modify the growth and competitive ability of themselves and subsequent plants (Kulmatiski and Kardol 2008).

Plant-soil feedbacks have the potential of impacting annual plant communities , where yearly shoots and roots are more susceptible to belowground biology like pathogens and resource availability than perennial species (Kulmatiski and Kardol 2008). As such PSFs may play an important role in annual agroecosystems. For example, farmers have known for thousands of years that the long-term practice of rotating crops rather than continuous mono-cropping helps break pest cycles. In these systems, plants have a selective pressure on soil micro-organisms, changing the dynamics in species specific ways due to differing functional roles and rhizosphere structures (van der Heijden et al. 2008). Thus, cropping and management systems result in legacy effects on the soil, where crop and weed community composition has residual carry-over effects in altering the soil community for many years (van der Putten et al. 2013).

Recently, interest has risen regarding the potential role of PSFs in determining crop and weed growth (Smith et al. 2011, Miller and Menalled 2015) as well as crop-weed competitive interactions (Hol et al. 2013). While organically managed systems

typically have a greater abundance and diversity of weeds than conventionally managed ones (Menalled et al. 2001; Pollnac et al. 2009), yield loss in organic fields is not necessarily in proportion with the increased weed abundance (Smith et al. 2010), suggesting that crops in organic systems exhibit greater tolerance to weeds. In this context, Smith et al. (2010) proposed the Resource Pool Diversity Hypothesis (RPDH) to explain how cropping systems and the soil resource pool, a function of soil microbial communities (Reynolds *et al.* 2003), may mediate crop-weed competitive interactions. The RPDH proposes that cropping system diversification results in increased niche differentiation and resource partitioning which, in turn, translates to reduced yield loss from crop-weed competition.

#### Project Justification and Objectives

Reducing tillage on organic farms could increase the sustainability of agro-ecosystems in the NGP. Reducing tillage with livestock integration is well-suited for the agriculture system in the region. At the end of 2013, Montana had 220,000 sheep in the state (National Agricultural Statistics Service 2013), in addition to the over 2.5 million head of cattle and calves, which would provide a unique opportunity for farmers and ranchers to implement grazing leases for cover crop termination and weed management. This research will provide insight into the applicability of grazing for cover crop termination and weed management as well as its impacts on subsequent crop yields on farms transitioning to organic in dryland grain growing regions of the NGP. Farming management systems also have known impacts on weed communities, however little is

known on how animal integrated, reduced-tillage systems will impact weed communities and how that compares with conventional no-tillage systems, and organic tillage-based systems in the NGP.

Despite advances in understanding the ecology of weeds in agricultural systems, weed science has been primarily focused on developing chemical and mechanical methods to minimize weed abundances rather than assessing the mechanisms driving crop-weed competitive interactions (Ward *et al.* 2014). To move forward, weed management needs to be analyzed from a systems-oriented perspective (Barberi 2002), acknowledging that weed biology and ecology play more important roles in agro-ecosystems than previously realized (Petit *et al.* 2011). Therefore, understanding the role of cropping systems on weed communities and soil biology, and the resultant plant-soil feedbacks, will help better apply systems-level approaches to weed management.

The below objectives link applied management techniques and approaches to make NGP farming more resilient, while trying to understand the ecological processes that help define the success of these systems:

Objective 1: Assess the applicability of integrating sheep on dryland organic farms as an approach to reduce tillage intensity.

- 1.1. Assess the agronomic impacts of sheep integration to terminate cover crops and manage weeds with standard organic and conventional operations
- 1.2. Compare weed community responses under diverging crop management systems.

Objective 2: Evaluate the role of plant-soil feedbacks on crop-weed interactions between conventional and organic farms in the NGP.

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## CHAPTER TWO

REDUCING TILLAGE ON ORGANIC DRYLAND FARMS  
IN THE NORTHERN GREAT PLAINS WITH GRAZERS.  
AGRONOMIC AND WEED COMMUNITY RESPONSESIntroduction

Reliance on tillage poses long-term sustainability challenges including increased erosion (Greer et al. 2006) and a general decline in soil quality parameters (Karlen et al. 1994) including reduced aggregate stability (Liebig et al. 2004) and water infiltration (Franzluebbers 2002). While conventional farmers have made strides in adopting no-till operations (Tanaka et al. 2010, Hansen et al. 2012), the excessive reliance on herbicides has led to the selection of herbicide resistant weed biotypes (Powles and Yu 2010), and can have non-target effects such as runoff, toxicity on other species, and long residual carryover in the environment (Liebman et al. 2001). Thus, agro-ecological research has focused on ways to reduce tillage while minimizing chemical spray application and fertilizer inputs (Brainard et al. 2013).

Cover crops can be used to reduce soil erosion, sequester excess nutrients and water, suppress weeds, and, if leguminous species are used, increase available nitrogen (N) (Delgado et al. 2007). By replacing fallow in the water limited environments of the northern Great Plains (NGP) with legume cover crops, similar soil moisture retention with proper cover crop termination timing (Zentner et al. 2004), and increased available N to subsequent crops (Miller et al. 2015a) have been attained. This is crucial for organic



farms, where legume green manure is a critical tool for N management, albeit insufficient for some wheat grain milling standards (Miller et al. 2011), and an additional strategy for managing weeds (Barberi 2002, Derksen et al. 2002). Nonetheless, cover crop termination still relies on single tool approaches such as tillage or herbicide application, and, as discussed above, both approaches have ecological and management shortcomings.

Integrating grazers represents an alternative to tillage and herbicide application for cover crop termination and weed management (Thiessen Martens and Entz 2011). Livestock integrated cropping systems may help alleviate N and especially phosphorous nutrient deficiencies, help manage weeds, and provide stable economic expectations for growers (Entz et al. 2002, Russelle et al. 2007, Thiessen Martens and Entz 2011). Franzluebbbers and Stuedemann (2013) found that integrating cattle for cover crop and residue grazing had a negative impact on corn and soybean yields, but not on wheat yield, and a net economic advantage when considering weight gain in cattle. Further, they found that coupling animal-integration with no-till versus tillage-based management led to higher yields, particularly under drought conditions. Nonetheless, grazing integration has capital investment costs of fencing and watering systems (Undersander et al. 2002) and may lead to soil compaction and reduced water infiltration depending on grazing intensity and prior cropping choices (Franzluebbbers and Stuedemann 2008).

Research integrating sheep grazing, as opposed to chemical or mechanical practices for fallow weed management in the NGP has shown that it can be used with minimal effect on crop yield and quality (Lenssen et al. 2013), varying effects on soil nutrients (Sainju et al. 2011), and increased carbon and nitrogen storage in soils with

moderate grazing intensity (Barsotti et al. 2013). However, this integration can result in an increase in weed pressure, particularly of perennial weeds in the Asteraceae family such as *Taraxacum officinale* F.H. Wigg. (dandelion) (Miller et al. 2015b). Despite this drawback when targeted grazing is integrated with the use of cover crops, crop rotation, and mechanical control; it is one tool that can help alleviate weed management challenges in reduced tillage organic systems (Carr et al. 2011).

The suite of practices a farmer deploys to manage the cropping system acts as an ecological filter on the associated diversity, including weeds (Booth and Swanton 2002). The type of crop planted in a field also impacts weeds and soil quality. Ominski et al. (1999) found that alfalfa (*Medicago sativa* L.) planted as a perennial forage before a grain crop may be part of an integrated weed management system to help control weeds like *Avena fatua* L. (wild oat) and *Cirsium arvense* (L.) Scop. (Canada thistle, creeping thistle), although *T. officinale* appears to increase with this forage. Forages such as spring and winter triticale [*Triticosecale* (Wittm. Ex A. Camus)], alfalfa, and sorghum-sudangrass [*Sorghum bicolor* (L.) Moench X *Sorghum Sudanese* (Piper)] similarly negatively affect grasses like *A. fatua* and *Setaria viridis* (L.) P.Beauv (green foxtail), and biennial crops had seasonal advantages over early season weeds while long season crops like winter triticale tended to provide better late season weed control (Schoofs and Entz 2000).

Rotating crops has known agricultural benefits, including increased crop yields (Anderson et al. 1999, Miller et al. 2002), although this depends on rainfall conditions (Miller and Holmes 2005). In addition, rotating crops may improve nutrient cycling and

pest management (Anderson 2005b, Cochran et al. 2006, Miller et al. 2006), lower weed density (Anderson and Beck 2009), and allow for better rotation of herbicide families, minimizing the risk of selecting herbicide resistant biotypes and reducing the dominance of single weed species (Derksen et al. 2002). These advantages are further enhanced when coupled with reduced tillage, competitive cultivars, higher seeding rates, and fertilizer management (Blackshaw et al. 2008).

Previous studies show that crop seeding, residue management, or crop selection are examples of dispersal, environmental, and biotic filters, respectively, on the regional weed species pool (Keddy 1992, Funk et al. 2008). In accordance, Smith et al. (2015) showed that specific cover crop species have differing effects on weed community assemblage, although cover crop biomass production appears to better explain changes in weed abundance. Therefore, understanding the interaction of crop husbandry and cultivation practices on resultant weed abundance and compositions can provide important predictive tools for practitioners interested in ecological pest management.

In this study, we tested the applicability of integrating sheep (*Ovis aries* L.) grazing as cover crop termination and weed management tactics, with the overall goal of reducing tillage intensity on organic farms in the semiarid NGP. We complemented an on-farm study with a research plot trial to assess how legume cover crop termination approach impacted: 1) cash crop yields and quality parameters, and 2) weed abundances and weed community shifts to the subsequent cash crop. Our hypotheses were: (i) methods of cover crop termination and cropping system management differentially impact subsequent crop yield and grain quality parameters, and (ii) cropping system

would act differentially as ecological filters on weed communities. Because this study was conducted at different sites and follows specific protocols, depending on the research question asked, Material and Methods, Results, and Discussion have been split by location for ease in reading.

## On Farm Study

### Materials and Methods

Field Site. An on-farm study was conducted on a United States Department of Agriculture (USDA) certified organic dryland farm located in a primary wheat growing region, 17 km southeast of Big Sandy, Montana (48°02'18, 110°00'51, elevation 960 m). The soils at this location were a sandy clay loam (Aridic Argiborolls). Growing season precipitation and temperature, as well as long-term annual averages over the last 30 years, were recorded at the nearest weather station (approximately 12 km to the northwest; ID USC00240770) operated by the Montana Climate Office and Western Regional Climate Center (Table 2.1). This study was conducted from 2012 to 2014.

Experimental Design. This study focuses on the feasibility of reducing tillage through animal integration to terminate cover crops in dryland organic farms and how this, in turn, impacts subsequent crop agronomics and weed communities. We used two separate fields for this on-farm experiment, one inform 2012 to 2014 (Field A) and another in 2013-2015 (Field B). All seeding and tillage operations were conducted by the host farmer. Field A was planted to Austrian winter peas (*Pisa sativum* L.) in the fall of

2012, and grown as a cover crop before termination in June of 2013. This field harbored a significant population of remnant perennial alfalfa from an earlier cropping cycle. Field B was planted to sweet clover (*Melilotus officinalis* L.) in spring of 2013, and cover crop termination treatments were implemented in June and July of 2014. Tables 2.2 and 2.3 summarize the cropping history and agronomic practices of these two fields since 2008. Both years, the experiment followed the same design: 5 sets of paired plots, each measuring 13 x 13 m were randomly placed in each field. Each set of paired plots had a 4-m border separating two termination treatments: either grazed at first bloom with sheep to reduce tillage events, or tilled with a tandem disk. Field A was planted to safflower (*Carthamus tinctorius* L.) in spring of 2014, and Field B was planted to winter wheat (*Triticum aestivum* L.) in fall of 2014 but failed to establish on the grazed plots due to a seeding error. Thus, no winter wheat data was collected in 2015.

Crop and Weed Sampling. Four 0.5-m<sup>2</sup> frames were randomly placed in each of the paired plots before termination for Austrian winter pea and sweet clover cover crops in 2013 and 2014, respectively, and prior to safflower crop harvest in 2014. Plant material was cut flush to the soil surface, and separated by species. Due to the high abundance of weeds in 2013 pea cover crop, samples were not collected by species but by functional groups (pea, alfalfa, broadleaf weeds, and grasses) although we did make note of presence/absence for each species in each plot. In addition, weed species were inadvertently not indicated for two of the five paired plots in 2013 Austrian winter pea, therefore analyses done on weeds excluded those paired plots. For each species or functional group, we averaged the data collected from frames within a plot. Samples

were dried to a constant weight in an oven at 40°C and weighed to the nearest 0.01 g. Safflower samples were threshed using a large plot Almaco thresher (Almaco, Nevada, Iowa) to obtain seed yield. In order to determine carbon and nitrogen cycled in growing crops and weed, cover crop biomass, safflower chaff, and weeds were separately ground with a Wiley Mill (Thomas Scientific, Swedesboro, New Jersey) and then fine ground (< 0.5mm) with a Udy Cyclone Mill (Udy Corporation, Fort Collins, Colorado). The C:N content was obtained from a 1-g subsample using a LECO CNS combustion analyzer (LECO Corporation, St. Joseph, Michigan).

Agronomic Data Analysis. Crop shoot biomass, residue C and N returned from crops and weeds, seed N harvested, safflower yields, and harvest index were each analyzed for the 2013 Austrian winter pea, 2014 safflower, and 2014 sweet clover using a linear model to test the effect of management system (grazed versus tilled) while accounting for variability among the sets of paired-plots as random effects. We used the summary of regression coefficients to obtain test statistics and to build confidence intervals. Response variables were log-transformed when necessary to satisfy the assumptions of normality and constant variance. We compared each parameter between treatments by using separate linear models for each year and crop: 2013 pea and 2014 safflower in Field A, and 2014 sweet clover in Field B; while accounting for plot to plot variability.

Weed Community Analysis. We compared weed biomass, species richness, Simpson's diversity, and community structure between grazed and tilled plots. Species

richness was calculated as the number of species sampled per plot. Simpson's diversity index was calculated as:

$$D = 1 - \sum_{i=1}^s p_i^2 \quad (\text{Eq. 1})$$

where  $p_i$  is the proportion of species  $i$ , and  $s$  is the number of species. Species richness in 2014 safflower did not follow a normal distribution and was analyzed using a Poisson distribution within a generalized linear model. Summary statistics were formed using the regression table of coefficients.

Assumptions of normality and equality of variances were severely violated under linear regression, when analyzing perennial weed data. Therefore, we used a permutational ANOVA analyzing each year's crop separately for differences in perennial weed biomass. 2014 sweet clover plots were not analyzed because only one plot had one perennial weed, *M. sativa*. In addition, in 2014 safflower, only one tilled plot had *T. officinale* present in 2014 safflower with less than 0.02 kg ha<sup>-1</sup> and only one plot for each grazed and tilled systems had *C. arvensis* present. Therefore we only analyzed differences in abundance of *M. sativa* between tilled and grazed treatments in 2013 Austrian winter pea and subsequent 2014 safflower. Permutations were constrained within each paired-plot to test differences between grazed and tilled treatments. We calculated an  $F$ -value for every permutation, and  $p$ -values were obtained from the percentage of repetitions in which the calculated values of  $F$  exceeded the  $F$ -value obtained from the original data (n=999).

Weed community structure was analyzed using non-metric multidimensional scaling (NMDS) of presence/absence data for the 2013 cover crop to 2014 cash crop

cycle in Field A, and biomass data for the 2014 cover crop data in Field B and 2014 safflower data in Field A. Initial locations in ordination space were determined by principal coordinates analysis (PCO). For presence/absence data, we used the Sorensen dissimilarity matrix (Sørensen 1948) to construct the PCO and NMDS:

$$S_{jk} = 1 - 2a_{jk}/(2a_{jk} + b_j + c_k) \quad (\text{Eq. 2})$$

where  $S_{jk}$  is the dissimilarity between sites  $j$  and  $k$ ,  $a_{jk}$  is the number of species common to both sites,  $b_j$  is the number of species unique to site  $j$ , and  $c_k$  is the number of species unique to site  $k$ .

In order to de-emphasize bias towards dominant species, we log-transformed raw biomass values:

$$A_{ij} = \ln(\text{Biomass}_{ij} + 1) \quad (\text{Eq. 3})$$

where  $A_{ij}$  is the log-transformed biomass for species  $i$  in site  $j$ . We used the Bray-Curtis dissimilarity matrix (Bray and Curtis 1957, McCune et al. 2002) to construct the PCO and NMDS for weed biomass data:

$$BC_{jk} = 1 - \frac{\sum_{i=1}^S 2|a_{ij} - a_{ik}|}{\sum_{i=1}^S a_{ij} + \sum_{i=1}^S a_{ik}} \quad (\text{Eq. 4})$$

where  $BC_{jk}$  is the dissimilarity between sites  $j$  and  $k$ ,  $a_{ij}$  and  $a_{ik}$  are the total biomass of individual species  $i$  in sites  $j$  and  $k$ , respectively, and  $S$  is the combined total number of species in both communities. Non-metric Multidimensional Scaling attempts to minimize stress, a goodness-of-fit metric that maximizes the rank correlation between the ordination-based distances and distances plotted (McCune et al. 2002, Roberts 2013).

We tested for differences in weed community structure between systems and crop years using Permutation Multivariate Analysis of Variance (PERMANOVA) (Anderson



2005a) on the dissimilarity matrix with each field, analyzed separately. Permutations were stratified to account for the nested structure of plots, with permutations done first to test for a system-by-crop interactions and shifts in community structure between 2013 Austrian winter pea and 2014 safflower with stratifications at the system within paired plot level. We then analyzed 2013 Austrian winter pea and 2014 safflower separately to test for system effects, stratifying the permutation within each paired plot, using the Sorensen index for 2013 Austrian winter pea and Bray-Curtis index for 2014 safflower. The 2014 sweet clover cover crop in Field B was analyzed without a rotation due to one year's worth of data. Two paired plots from 2013 Austrian winter pea in Field A could not be analyzed due to sampling error.

We used 'R' statistical software (R Core Team 2013) for analysis. Ordinations, Simpson's diversity index, and dissimilarity matrices were calculated and graphed using packages 'cluster' (Maechler et al. 2013), 'labdsv' (Roberts 2013), and 'vegan' (Oksanen et al. 2013). Packages 'sciplot' (Morales 2012) and 'ggplot2' (Wickham 2009) were used to build graphs.

## Results

Agronomics. For field A, 2013 cover crop shoot biomass and residue C and N returned did not differ between grazed and tilled treatments (Table 2.4). In the 2014 subsequent safflower crop, there were no differences in crop and weed biomass, residue C and N returned, or grain yield parameters (Table 2.5).

For field B, C and N returned from weeds did not differ between grazed and tilled treatments (Table 2.4). There was  $1.12 \text{ Mg ha}^{-1}$  more sweet clover biomass (95% CI = 0.020 – 2.21) by chance in tilled treatments than grazed which translated to higher residue C and N returned for tilled treatments as well (Table 2.4).

Weed Community. In field A 2014 safflower, weed species richness or Simpson's diversity did not differ between grazed and tilled plots (z-value = -0.59, df = 4, p = 0.56; t-value = -0.50, df = 4, p = 0.64; respectively). *Medicago sativa* grew as one of the most abundant weeds in this field both years (Fig. 2.1a). Nonetheless, there were no differences between grazed and tilled treatments in terms of *M. sativa* biomass in 2014 after termination treatments (F-value > 0.077 = 0.80).

Method of cover crop termination did not alter weed communities in the crop phase. Weed community structure shifted between the 2013 Austrian winter pea to the 2014 safflower plots (pseudo-F = 7.60; df = 1,12;  $r^2 = 0.32$ ; p = 0.017), and marginal evidence that differences between grazed and tilled systems depended on the crop phase (pseudo-F = 3.37; df = 1,12;  $r^2 = 0.14$ ; p = 0.066) (Fig. 2.2a). Dominant weed species that differed in the 2013 Austrian winter pea plots were *Chenopodium album* L. (lambs quarters), and *Lactuca serriola* L. (prickly lettuce), while 2014 safflower uniquely had *Amaranthus retroflexus* L. (redroot pigweed) and *Vicia americana* Muhl. Ex Willd. (American vetch) which helps explain the difference in community structure between crops. Still, in 2014 safflower, there were no differences in weed community structure between grazed and tilled systems (pseudo-F = 0.79; df = 1,8;  $r^2 = 0.09$ ; p = 0.51).

In the 2014 field B, seeded with sweet clover, there were no differences between grazed and tilled systems in terms of weed biomass (t-value = 1.17, df = 4, p = 0.31), species richness (t-value = 0.78, df = 4, p = 0.48), or Simpson's diversity (t-value = -0.36, df = 4, p = 0.74). Prior to treatments, there was marginal evidence, however, that weed community structure differed in 2014 between grazed and tilled treatments (Fig. 2.2b; pseudo-F = 1.37; df = 1,8;  $r^2 = 0.15$ ; p = 0.07). This is likely due to the higher abundance of dominant weeds like *Descurania pinnata* (Walt.) Britt. (western tansymustard;  $59 \text{ kg ha}^{-1} \pm 26$ ), *Kochia scoparia* L. (kochia;  $33 \text{ kg ha}^{-1} \pm 30$ ), *Salsola kali* L. (Russian thistle;  $21 \text{ kg ha}^{-1} \pm 13$ ), and *Thlaspi arvense* L. (pennycress;  $55 \text{ kg ha}^{-1} \pm 25$ ) in the grazed plots compared to tilled.

### Discussion

In this on-farm study, we did not detect any differences in biomass, C:N cycling, or yields in 2013 Austrian winter pea and the subsequent safflower, suggesting that sheep grazing and tillage have similar agronomic impacts when used to terminate cover crops. Austrian winter pea and safflower crop establishment was poor and easily outcompeted by *M. sativa* both years, and *S. kali* in particular in 2014. Although higher crop density planting is an effective strategy to manage weeds in organic systems (Derksen et al. 2002), safflower requires a balance between adequate warmth and growing degree days, and adequate soil moisture which may be difficult to achieve in the limited growing season of the NGP (Johnston et al. 2002). Weeds likely grew in high abundances in field A not only due to poor crop establishment, but due to the low competitive ability of Austrian winter peas (Miller et al. 2005). Also, the lack of crop residue due to cultivation

of this field may have made winter peas susceptible to winter kill with little stubble to retain snow (Chen et al. 2006). Nonetheless, grazed and tilled treatments did not differ in overall weed abundances following grazing or tillage, and community characteristics did not differ between treatments in either year indicating that grazing and tillage, two different ecological filters (Funk et al. 2008), resulted in similar weed community structure. A key caveat is that this study only investigated weed communities in the subsequent cropping year to grazing and tillage, whereas grazing has been noted to have long-term impacts on the weed composition and abundance (Renne and Tracy 2013). Indirectly, this became a study in organic termination of alfalfa, often an issue for farmers integrating perennial forages in rotation (Entz et al. 1995). Still, grazed and tilled treatments did not differ in alfalfa abundance before and after the two treatments.

The 2014 sweet clover in the second field trial differed in terms of crop biomass and weed community structure, even before grazed and tilled treatments were implemented which suggests randomization should have been restricted and blocked by initial weed and crop biomasses. Further, winter wheat planted in these plots as a subsequent crop showed variable emergence on the grazed treatments only (Fig. 2.S1) due to mechanical issues with lack of drill penetration during planting. In transitioning to conservation tillage practices in the NGP on organic farms, soil compaction may be an important issue (Peigné et al. 2007) and requires innovation and investment in proper seeding equipment (Huggins and Reganold 2008), and better understanding of timing and grazing intensity on near-surface soil compaction (Liebig et al. 2012).

Cover crop termination through tillage or grazing comes at a cost but grazing leases may cover some of the expenses. We estimated 504 kg ha<sup>-1</sup> of Austrian winter pea forage on average in 2013, although when combined with the volunteer alfalfa and other weeds, we had an estimated 1750 kg ha<sup>-1</sup> of available forage. Estimating the total monthly forage dry matter intake to be 171 kg per lamb (Lacey 1991), stocking rates would be approximately 10 lambs ha<sup>-1</sup> month<sup>-1</sup>, or 2 animal unit months (AUM) to fully terminate the crop. Assuming the landowner will not provide services, the pasture lease rate should be about 70 percent of the average land lease rate, making the grazing lease approximately \$14/AUM based on 2011 non-irrigated rates in Montana (Mosley 2012). Thus in 2013, growers could expect approximately \$27 ha<sup>-1</sup> under a grazing lease. In 2014, there was approximately 2770 kg ha<sup>-1</sup> of available dry forage sweet clover, or the equivalent of 3.2 AUMs. In 2014, growers could expect approximately \$44 ha<sup>-1</sup> under a grazing lease. The average price for non-alfalfa hay in Montana in 2013 was worth \$138 Mg<sup>-1</sup> (National Agricultural Statistics Service, 2013), adding a potential value of \$241 ha<sup>-1</sup> in 2013, and \$382 in 2014. Nonetheless, due to the weediness of the cover crop fields, it is unlikely that growers could expect premium prices for the hay, although some weeds provide good forage (Dutt et al. 1982, Hageman et al. 1988). Buyers may be reluctant to buy hay with high risk of seed contamination on their property. Thus grazing leases may provide a cheap alternative for ranchers to buying hay, and help farmers alleviate setbacks from weedy fields. In addition, in nutrient-limited systems like some organic farms, grazing would keep more nutrients on farm in the form of animal wastes, versus complete loss with a hayed crop (Thiessen Martens and Entz 2011).

## Research Plot Study

### Materials and Methods

Field Site. This study was conducted at a dryland field site at Montana State University's Fort Ellis Research and Extension Center approximately 6 km east of Bozeman, MT (45°40'02, 110°58'40, elevation: 1495 m). The soil is a Blackmore silt loam (a fine-silty, mixed, superactive, frigid Typic Arguistoll). Growing season precipitation and temperature, as well as long-term annual averages over the last 30 years, were recorded at the nearest weather station (approximately 5 km to the southwest; ID USC00241044) operated by the Montana Climate Office and Western Regional Climate Center (Table 2.6). This study was conducted from 2013 to 2014.

Experimental Design. Before 2004, the entire site was planted to a perennial grass pasture for at least ten years, containing a mixture of smooth brome grass (*Bromus inermis* L.), intermediate wheatgrass [*Thinopyrum intermedium* (Host) Barkworth & D.R. Dewey], and Canada bluegrass (*Poa compressa* L.). From 2004-2008, wheat was grown in a randomized split-plot design with summer fallow management treatments (grazed, herbicide, or tillage) applied at the whole plot level, and continuous spring wheat, spring wheat-fallow, or winter wheat-fallow applied to the split-plots (Lenssen et al. 2013). In 2009, the wheat-fallow rotations were replaced with either a continuous alfalfa (*M. sativa*) crop, or a three year rotation of spring wheat-pea (*P. sativum*)/barley (*H. vulgaris*) hay mixture-fallow, maintaining the same fallow treatments (Barsotti et al. 2013, Miller et al. 2015b). In spring of 2012, all plots were planted to glyphosate tolerant canola

(*Brassica napus* L.) and managed with herbicide in order to help minimize past cropping system effects on weed communities.

In July 2012, the entire site was disked when the canola was in full bloom, then tilled with a 3-m spring tine cultivator with 18-cm shovels and trailing roller baskets, and rolled in September to smooth the planting surface. The current study is a split-plot design with three management treatments applied at the whole plot level: conventional no-till (CNT), tilled-organic (TO), and grazed-organic (GO) for a total of 9 whole plots. Both organic treatments began the organic transition process in July 2012, making crops harvested in 2015 eligible for USDA organic certification. Each whole plot was split equally into 5 sections 0.12 ha in size (13 x 90 m) and randomly assigned a crop treatment out of a 5-yr cropping sequence of safflower (*C. tinctorius*) undersown with sweet clover (*M. officinale*) (Y1), sweet clover green manure (Y2), winter wheat (*T. aestivum*) (Y3), lentil (*Lens culinaris* Medik.) (Y4), and winter wheat (Y5). In 2013, the sweet clover green manure split-plots were planted instead to Austrian winter pea (*P. sativum*) in fall of 2012 since clover is biennial and would have required a prior year of growth. Whole plots were separated by a 10-m alley and split-plots were separated by a 1-m border. This study focuses on the agronomics of terminating cover crops (Y2) and subsequent impacts on the winter wheat crop (Y3), and the shifts in weed communities among all crop phases under three management systems.

The conventional no-till system did not use tillage implements, reflective of typical conventional farm management practices in the northern Great Plains, but did use fertilizer inputs when necessary (Tables 2.7 and 2.8). Weeds were managed pre-seed,

post-harvest, and in-crop with glyphosate mixed with dicamba and with selective herbicides. The two organic systems received no inputs in the forms of synthetic fertilizers or pesticides. The tilled-organic system is reflective of typical dryland organic farms where tillage is the main mechanism for weed control, cover crop termination, and seedbed preparation. The goal of the grazed-organic system is to minimize the number of tillage events, using sheep to terminate cover crops, and as the primary residue and weed control method. Cash crops in both organic systems were seeded at twice the density (narrower crop rows) as the conventional system, a typical organic management practice to help control weeds. Tables 2.7 and 2.8 summarize the different agronomic practices used for crop and residue management, seeding dates, and seeding rates for 2013 and 2014, respectively. Two of three reps in the 2014 grazed-organic safflower / sweet clover split-plots were ultimately grazed due to excess weed competition (mainly *T. arvense* and *Capsella bursa-pastoris* (L.) Medik.) in the seedling stage. The first rep had been badly outcompeted by weeds from the outset and so the safflower crop was cultivated out and re-seeded to buckwheat (*Fagopyrum esculentum* Moench) and sweet clover (Table 2.8).

Crop and Weed Sampling. All split-plots were sampled for crop and weed biomass by species at peak biomass of cash crops or termination of the cover crop (starting in June before cover crop termination and lasting through July for all other crops). Each split-plot was stratified into four sections for sampling and two 0.5 x 1.0 m frames were randomly placed lengthwise across crop rows in each of the four sections, for a total of 8 subsamples per split-plot to estimate aboveground biomass by species. For each species, we combined the data collected from all frames within each split-plot to



form the experimental unit. Samples were dried to a constant weight in an oven at 40° C and weighed to the nearest 0.01 g. Plots were generally harvested with a commercial-scale combine (4.2 m wide) by taking a full width swath from the center of the split-plots to estimate yield.

Winter wheat biomass samples were threshed using an Almaco plot thresher (Almaco, Nevada, Iowa) to separate grain from chaff. In order to determine carbon and nitrogen cycled through plant growth, cover crop biomass, winter wheat chaff, and weeds were ground with a Wiley Mill (Thomas Scientific, Swedesboro, New Jersey) and fine ground (< 0.5mm) with a Udy Cyclone Mill (Udy Corporation, Fort Collins, Colorado). The C:N content was obtained from a 1-g subsample using a LECO CNS combustion analyzer (LECO Corporation, St. Joseph, Michigan). Wheat grain protein concentration was determined by multiplying N concentrations by a factor of 5.7 (Jones 1941). All wheat grain yield values were standardized to 12% moisture. Weed shoot biomass was not analyzed for C:N since it comprised less than 10% of total split-plot sample.

Split-plots were also sampled early in the season, both years, before the crop canopy was formed, to assess perennial weeds [*T. officinale* (dandelion), *M. sativa* (alfalfa), and *C. arvensis* (creeping thistle)] cover and density for the above by species. Split-plots were stratified in sections as described above, and five 0.5m x 1.0m frames were randomly placed in each section, for a total of 20 subsamples per split-plot. Frames were again placed lengthwise across crop rows and subsample data was combined at the split-plot level prior to analysis.

Agronomic Data Analysis. We compared crop shoot biomass, crop residue C and N returned to the split-plots, grain N yield, grain yield, harvest index, grain protein, and test weight among the three management systems with a linear mixed-effects regression model. This model tested the fixed effect of system while accounting for block variability as a random intercept. We used a likelihood ratio test to calculate chi-square statistics comparing the full model with the explanatory variable in question against a model without that variable. Confidence intervals and planned comparison were made using least squares means and Satterthwaite's approximation of degrees of freedom. Response variables were log-transformed when necessary to satisfy the assumptions of normality and constant variance, which were visually evaluated in residual error plots.

Weed Community Analysis. We compared weed biomass, species richness, and Simpson's diversity among three management systems using a linear mixed effects model that accounted for both the repeated measures structure and blocking variability by nesting the fixed effect of farming system in block as random intercepts. This model included the interaction between crop and system, using drop-in-deviance tests for model simplification (Bates 2010). Species richness was analyzed using a Poisson distribution and was calculated as the number of species sampled per split-plot. Simpson's diversity index was calculated within each split-plot as:

$$D = 1 - \sum_{i=1}^s p_i^2 \quad (\text{Eq. 4})$$

where  $p_i$  is the proportion of species  $i$ , and  $s$  is the number of species (Simpson 1949).

Weed biomass and Simpson's diversity were analyzed for every 2013 crop treatment with

its subsequent 2014 crop, and values were log-transformed when visual evaluation of residual plots indicated a violation in assumptions of normality and equal variance.

Changes in weed community structure across systems and crops were analyzed using non-metric multidimensional scaling (NMDS) of biomass data. Initial locations in ordination space were determined by principal coordinates analysis (PCO). In order to de-emphasize bias towards dominant species, we log-transformed raw biomass values as:

$$A_{ij} = \ln(\text{Biomass}_{ij} + 1) \quad (\text{Eq. 5})$$

where  $A_{ij}$  is the log-transformed biomass for species  $i$  in site  $j$ . We used the Bray-Curtis dissimilarity matrix (Bray and Curtis 1957, McCune et al. 2002) to construct the PCO and NMDS calculated as:

$$BC_{jk} = 1 - \frac{\sum_{i=1}^S 2|a_{ij} - a_{ik}|}{\sum_{i=1}^S a_{ij} + \sum_{i=1}^S a_{ik}} \quad (\text{Eq. 6})$$

where  $BC_{jk}$  is the dissimilarity between sites  $j$  and  $k$ ,  $a_{ij}$  and  $a_{ik}$  are the total biomass of individual species  $i$  in sites  $j$  and  $k$ , respectively, and  $S$  is the combined total number of species in both communities. Non-metric Multidimensional Scaling attempts to minimize stress, a goodness-of-fit metric that maximizes the rank correlation between the ordination-based distances and distances plotted (McCune et al. 2002, Roberts 2013).

We tested for differences in weed community structure between systems and crop phases using Permutation Multivariate Analysis of Variance (PERMANOVA) (Anderson 2005a) on the dissimilarity matrix. Each unique rotation from 2013-2014 was analyzed separately. Permutations were stratified to account for the nested structure of split-plots within system, with PERMANOVA tests done separately for overall system effects

stratified within block, and system-by-cropping sequence effects stratified within split-plots.

Winter pea grown in 2013 was not assessed for perennials, (none were evident) and only percent cover was taken on perennials in 2014 sweet clover. Fitting larger mixed effects models was difficult due to some split-plots having no perennial weeds present and the inability to converge models that incorporated the split-plot design and repeated measures. Therefore, we analyzed each crop and year separately using a generalized linear model (GLM). We first attempted to fit each model under a Poisson distribution and tested for model validity with goodness-of-fit tests and plots of deviance residuals versus fitted means (Zuur 2009). Since overdispersion was almost always suspected when fitting a Poisson distribution based on the above tests, we used a quasi-Poisson GLM. If deviance residual plots, goodness-of-fit tests, as well likelihood ratio tests of the log-likelihoods of negative binomial regression models versus Poisson regression models indicated further over-dispersion, we fit a negative binomial GLM. For testing model parameters, we used drop-in-deviance tests for Poisson GLMs and likelihood ratio tests for negative binomial GLMs. We attempted to fit a linear regression model for the percent cover data, but the assumptions of normality and constant variance were severely violated. In order to satisfy these regression assumptions, we used a logit transformation, as recommended by Warton and Hui (2011) that prevented undefined values from sample proportions equal to 0 or 1:

$$\ln \frac{y+\epsilon}{1-y+\epsilon} \tag{Eq. 7}$$

where  $y$  is the percent cover response, and  $\epsilon$  is the minimum non-zero percentage.

Grazed-organic safflower / sweet clover split-plots in the 2014 cropping year in replications 2 and 3 were not analyzed due to repeated grazing (Table 2.8) and two replication split-plots from 2014 winter wheat following 2013 lentil in grazed organic systems were not analyzed due to sampling error. This left one replication for the above treatments, so analyses of weed biomass, species richness, or Simpson's diversity did not include grazed-organic 2014 safflower / sweet clover or 2014 winter wheat following 2013 lentil.

We used 'R' statistical software (R Core Team 2013) for analysis. Ordinations, Simpson's diversity index, and dissimilarity matrices were calculated and graphed using packages 'cluster' (Maechler et al. 2013), 'labdsv' (Roberts 2013), and 'vegan' (Oksanen et al. 2013). Packages 'sciplot' (Morales 2012) and 'ggplot2' (Wickham 2009) were used to build graphs. Mixed effects models were fit using package 'lme4' (Bates et al. 2014), and package 'lmerTest' (Kuznetsova et al. 2014) was used for least squares means comparisons, confidence interval estimates, and inferences about regression coefficients. Negative binomial models were fit using package 'pscl' (Jackman 2015).

## Results

Agronomics. The 2013 Austrian winter pea did not show differences among systems in terms of crop shoot biomass or residue C and N returned to split-plots (Table 2.9), as would be expected due to site-wide common management practice at the outset of this experiment. In the subsequent 2014 winter wheat, wheat biomass, grain yield, and protein levels did not differ among the three systems (Table 2.10). Despite similar wheat

biomass production among systems, 27 kg ha<sup>-1</sup> (t-value = 2.27, p = 0.064) more residual N and 1.0 Mg ha<sup>-1</sup> (t-value = 2.86, p = 0.029) more residual biomass C was present in grazed organic split-plots compared to conventional no-till, as well as 27 kg ha<sup>-1</sup> (t-value = 2.31, p = 0.060) more residual biomass N returned in tilled-organic compared to conventional no-till. 20 kg ha<sup>-1</sup> (t-value = 2.23, p = 0.067) more N was taken up in wheat grain in the tilled-organic system than in the conventional no-till. Test weight in tilled-organic systems was approximately 4.7 kg HI<sup>-1</sup> (95% CI = 1.57 – 7.80) and 5.5 kg HI<sup>-1</sup> (95% CI = 2.37 – 8.60) lower than grazed-organic and conventional no-till systems, respectively. Harvest index was approximately 0.06 (95% CI = 0.03 – 0.10) and 0.04 (95% CI = 0.01 – 0.07) greater in conventional no-till than in grazed-organic and tilled-organic split-plots, respectively.

The 2014 sweet clover crop produced 1.23 Mg ha<sup>-1</sup> (95% CI = -0.07 – 2.54) more biomass in the conventional no-till system compared to grazed-organic split-plots (Table 2.9). This translated into 0.47 Mg ha<sup>-1</sup> and 0.43 Mg ha<sup>-1</sup> more residual C returned to the soil from conventional no-till compared to grazed-organic and tilled-organic, respectively, but no differences were found among the three systems in terms of biomass N.

Weed Community. We sampled a total of 56 weed species across all crops and treatments at Fort Ellis between 2013 and 2014. For 2013 safflower and subsequent 2014 sweet clover, there were no differences among tilled organic, grazed organic, or conventional no-till systems, in terms of total weed biomass, species richness, or Simpson's diversity (Table 2.11). There was marginal evidence that 2014 sweet clover

had a higher number of weed species than 2013 safflower [z-value = -1.82,  $p = 0.069$ ], however, neither weed biomass nor Simpson's diversity differed between crops. There was a shift in weed community structure from 2013 safflower to 2014 sweet clover (pseudo-F = 5.15; df = 1,12;  $r^2 = 0.24$ ;  $p = 0.009$ ), but no differences among systems (pseudo-F = 1.09; df = 2,6;  $r^2 = 0.27$ ;  $p = 0.303$ ), and no interaction between crop-year and system (pseudo-F = 0.54; df = 2,12;  $r^2 = 0.05$ ;  $p = 0.68$ ) (Fig. 2.3a). The 2013 safflower was dominated by *Malva neglecta* Wallr. (common mallow;  $156 \text{ kg ha}^{-1} \pm 53$ ), *A. fatua* ( $54 \text{ kg ha}^{-1} \pm 51$ ), and *A. retroflexus* ( $38 \text{ kg ha}^{-1} \pm 19$ ) in addition to weeds also found in 2014 clover which was dominated by *C. album* ( $118 \text{ kg ha}^{-1} \pm 31$ ), *C. bursa-pastoris* ( $214 \text{ kg ha}^{-1} \pm 73$ ), and *T. arvense* ( $146 \text{ kg ha}^{-1} \pm 31$ ).

Across the three systems, weeds grew 13.6 times (95% CI = 6.6 – 27.9) more biomass in the 2013 Austrian winter peas compared to the subsequent 2014 winter wheat (t-value = -8.32, df = 8,  $p < 0.0001$ ), with marginal evidence of greater species richness in the 2013 pea crop (z-value = -1.90,  $p = 0.058$ ). Nonetheless, weed biomass was still relatively low both years (Table 2.11). Simpson's diversity depended on the interaction between farming system and crop-year [ $\chi^2(2) = 9.39$ ,  $p = 0.0091$ ], with higher diversity found in the grazed and tilled organic winter wheat phases compared to organic pea systems, but the conventional no-till system showed the opposite trend with more diversity in the 2013 pea crop than the 2014 winter wheat (Table 2.11). The weed community structure shifted from 2013 Austrian pea to 2014 winter wheat (pseudo-F = 6.63; df = 1,12;  $r^2 = 0.26$ ;  $p = 0.005$ ) with no interaction with farming system (pseudo-F = 0.149; df = 2,12;  $r^2 = 0.12$ ;  $p = 0.26$ ) (Fig. 2.3b). There was no evidence weed

communities differed between systems (pseudo-F = 1.64; df = 2,6;  $r^2 = 0.35$ ;  $p = 0.11$ ).

The dominant weed species in 2013 for all three systems was *T. arvense* ( $185 \text{ kg ha}^{-1} \pm 43$ ), while 2014 conventional no-till winter wheat shifted towards *C. bursa-pastoris* ( $10 \text{ kg ha}^{-1} \pm 9$ ), *A. retroflexus* ( $953 \text{ g ha}^{-1} \pm 912$ ), and *L. serriola* ( $2.76 \text{ kg ha}^{-1} \pm 1.78$ ).

While both organic systems continued to be dominated by *T. arvense*, tilled systems had volunteer peas in one split-plot (*P. sativum*) ( $312 \text{ g ha}^{-1}$ ) from the previous year's crop that went to seed, and tilled systems had *Asperugo procumbens* L. (catchweed;  $5.88 \text{ kg ha}^{-1} \pm 3.79$ ).

There was no interaction between system and crop for species richness or simpson's diversity in 2013 winter wheat and subsequent 2014 lentil (Table 2.11). There was an interaction between system and crop for weed biomass [ $\chi^2(2) = 9.32$ ,  $p = 0.0095$ ] in 2013 winter wheat and subsequent 2014 lentil (Table 2.11). 2013 tilled organic winter wheat had 3.64 times (95 % C.I. = 0.93 – 14.22) and 3.55 times (95% C.I. = 0.91 – 13.85) more weed biomass than 2013 conventional no-till and 2013 grazed organic systems, respectively, but in 2014 lentil, weed biomass was greatest in conventional no-till systems with 3.33 times (95% C.I. = 0.85 – 13.01) more biomass than the tilled organic system. There were no differences in species richness between 2013 or 2014 crop phases or among systems, but 2014 lentils had higher Simpson's diversity than 2013 winter wheat crops (t-value = 3.40, df = 11.99,  $p = 0.0052$ ). There was no interaction between system and crop when analyzing weed community structure (pseudo-F = 1.50; df = 2,12;  $r^2 = 0.11$ ;  $p = 0.34$ ) (Fig. 2.3c). There was, however, a strong shift in community structure from 2013 winter wheat to 2014 lentil (pseudo-F = 7.82; df = 1,12;  $r^2 = 0.29$ ;  $p$



= 0.007) and slight evidence that the farming systems differed from one another (pseudo-F = 1.93; df = 2,6;  $r^2 = 0.39$ ;  $p = 0.052$ ), regardless of crop phase. All three systems were comprised mainly of *T. arvense* ( $192 \text{ kg ha}^{-1} \pm 30$ ) and *M. sativa* ( $186 \text{ kg ha}^{-1} \pm 33$ ) in 2013, and these weeds continued into the 2014 crop. However, conventional no-till split-plots differed from the other systems with a moderate amount of *C. arvense* ( $2.86 \text{ kg ha}^{-1} \pm 1.83$ ) in both years and a much greater abundance of *C. album* ( $590 \text{ kg ha}^{-1} \pm 343$ ), in addition to *C. bursa-pastoris* ( $67 \text{ kg ha}^{-1} \pm 65$ ) and *L. serriola* ( $141 \text{ kg ha}^{-1} \pm 113$ ) in the 2014 lentil crop. Tilled organic winter wheat split-plots had a higher abundance of *Bromus tectorum* L. (cheatgrass;  $8.83 \text{ kg ha}^{-1} \pm 6.82$ ) and *A. procumbens* ( $3.9 \text{ kg ha}^{-1} \pm 1.97$ ).

For 2013 lentil – 2014 winter wheat crop rotation, there was higher weed abundance (t-value = -3.37, df = 10.06,  $p = 0.0070$ ) and marginal evidence of a difference in Simpson's diversity (t-value = -2.00, df = 12,  $p = 0.069$ ) in the lentil crop compared to the subsequent winter wheat (Table 2.11). Similarly, there was no interaction between farming system and crop in terms of weed community structure (pseudo-F = 1.87; df = 2,10;  $r^2 = 0.13$ ;  $p = 0.20$ ), but there was a strong shift across crops (pseudo-F = 6.31; df = 1,10;  $r^2 = 0.21$ ;  $p = 0.009$ ) (Fig. 2.3d). Still, for both years, there was no evidence of an overall difference in weed community structure among the three systems (pseudo-F = 1.65; df = 2,6;  $r^2 = 0.35$ ;  $p = 0.19$ ). The shift in weed community structure appears to be mainly due to higher abundances of multiple weeds in the 2013 lentil crop including *A. retroflexus* ( $137 \text{ kg ha}^{-1} \pm 43$ ), *A. fatua* ( $82 \text{ kg ha}^{-1} \pm 54$ ), *C. album* ( $214 \text{ kg ha}^{-1} \pm 71$ ), *C. bursa-pastoris* ( $34 \text{ kg ha}^{-1} \pm 15$ ), *M. neglecta* ( $172 \text{ kg ha}^{-1} \pm 68$ ), *T. arvense* ( $114 \text{ kg ha}^{-1} \pm$

46), and *Solanum triflorum* Nutt. (cutleaf nightshade;  $26 \text{ kg ha}^{-1} \pm 9$ ), among others; while only *C. bursa-pastoris* ( $74 \text{ kg ha}^{-1} \pm 42$ ) and *T. arvense* ( $77 \text{ kg ha}^{-1} \pm 46$ ) continued at relatively high abundance in the subsequent 2014 winter wheat crop.

In the 2013 winter wheat - 2014 safflower rotation, weed biomass was 5.25 times lower (95% C.I. = 1.57 – 17.57) in 2013 winter wheat compared to 2014 safflower, ignoring the single buckwheat split-plot in the analysis, regardless of farming system. Species richness was lower in grazed organic systems, regardless of crop, and Simpson's diversity was lowest in tilled and grazed 2013 organic winter wheat split-plots when compared with the 2013 wheat grown in the conventional no-till system (Table 2.11). There was a strong shift in weed communities associated with year (pseudo-F = 3.53; df = 2,10;  $r^2 = 0.32$ ;  $p = 0.019$ ) and this did not depend on an interaction with farming system (pseudo-F = 1.365; df = 1,10;  $r^2 = 0.062$ ;  $p = 0.32$ ) (Fig. 2.3e). There was a marginal evidence that weed community structure was different among farm management systems (pseudo-F = 2.13; df = 2,6;  $r^2 = 0.42$ ;  $p = 0.057$ ). All three systems were dominated by *T. arvense* in 2013 winter wheat ( $142 \text{ kg ha}^{-1} \pm 82$ ) and 2014 safflower ( $62 \text{ kg ha}^{-1} \pm 27$ ) and buckwheat ( $44 \text{ kg ha}^{-1}$ ), however only the conventional no-till split-split-plots had *B. tectorum* ( $6.9 \text{ kg ha}^{-1} \pm 5.8$ ) and *C. bursa-pastoris* ( $5.7 \text{ kg ha}^{-1} \pm 2.2$ ) both years, and *C. arvense* ( $9.3 \text{ kg ha}^{-1} \pm 3.0$ ) and *Sisymbrium altissimum* L. (tumble mustard;  $91 \text{ kg ha}^{-1} \pm 30$ ) at relatively high abundance. Tilled organic split-plots uniquely had *A. fatua* in 2013 and 2014 ( $6.7 \text{ kg ha}^{-1} \pm 4.3$ ), and winter wheat persisted in both organic systems as a weed in 2014 safflower ( $35 \text{ kg ha}^{-1} \pm 17$ ) and the one buckwheat split-plot ( $29 \text{ kg ha}^{-1}$ ).

Perennial Weeds. *Taraxacum officinale* was present in only one conventional no-till safflower split-plot in 2013 (Fig. 2.4a), however subsequent sweet clover in 2014 saw an increase in this weed in all systems with no differences across systems (ESS F-test on 2 and 6 df,  $p = 0.32$ ). There were no differences in *C. arvense* density among farming systems in 2013 safflower [ $\chi^2(2) = 2.83$ ,  $p = 0.24$ ], and although *C. arvense* was only detected in two conventional no-till split-plots in 2014 clover (Fig. 2.4b), there was no evidence that the odds of finding this perennial weed in one system differed from the others (ESS F-test on 2 and 6 df,  $p = 0.34$ ). Lastly, only one tilled organic safflower split-plot had *M. sativa* present (Fig. 2.4c) with only one plant sampled, which was not detected in 2014.

Early season cover estimates of perennials were not taken in 2013 Austrian winter pea split-plots, however only conventional no-till systems had one perennial, *C. arvense*, present from biomass samples. In subsequent winter wheat, we detected *C. arvense* in all three systems (Fig. 2.4b), however there were no differences in density (Drop in Deviance F-value<sub>(2,6)</sub> = 3.05,  $p = 0.16$ ). *Medicago sativa* was never sampled in any of these split-plots (Fig. 2.4c), and *T. officinale* was only present in grazed organic systems in 2014 winter wheat (Fig. 2.4a), indicating a strong difference in *T. officinale* abundance among the three systems (Drop in Deviance F-value<sub>(2,6)</sub> = 7.77e+10,  $p < 0.0001$ ).

Only one split-plot of each grazed organic and conventional no-till systems had *T. officinale* present in 2013 winter wheat (Fig. 2.5a), and we did not detect this perennial in subsequent lentil split-plots. Despite a general decline in abundance in 2014 (Fig. 2.4c), *M. sativa* density did not differ among the three farming systems (Drop in Deviance F-

value<sub>(2,6)</sub> = 2.20, p-value = 0.23). We found *C. arvensis* in all three conventional no-till split-plots and one tilled organic split-plot in 2013 (Fig. 2.4b) indicating a slight difference among systems (Drop in Deviance F-value<sub>(2,6)</sub> = 6.49, p = 0.055), however this perennial weed's abundance declined in 2014 split-plots, and was only found in conventional no-till split-plots.

There was some evidence that farming systems differed in *C. arvensis* abundance in 2013 lentils (Drop in Deviance F-value<sub>(2,6)</sub> = 6.49, p = 0.055), however abundances declined in 2014 winter wheat overall (Fig. 2.4b), and there were no differences between the three systems (Drop in Deviance F-value<sub>(2,6)</sub> = 0.28, p = 0.77). *Taraxacum officinale* was found in only one conventional no-till split-plot in 2013 lentils indicating a strong difference among systems (Drop in Deviance F-value<sub>(2,6)</sub> > 1000, p < 0.0001), however we did not detect this perennial in subsequent 2014 winter wheat split-plots (Fig. 2.4a). We did not sample any *M. sativa* in 2013 or 2014 (Fig. 2.4c).

In 2013 winter wheat, *C. arvensis* density was approximately 8 times higher in conventional no-till compared to grazed organic systems (95% CI = 7.99 – 8.00), and none was found in tilled organic systems (Fig. 2.4b). Nonetheless, in 2014 safflower, all three systems had *C. arvensis* present at varying levels with no evidence that systems differed (Drop in Deviance F-value<sub>(2,6)</sub> > 0.90, p < 0.47). *Taraxacum officinale* was detected in one conventional no-till winter wheat split-plot in 2013 (Fig. 2.4a), however *T. officinale* was found in multiple conventional no-till and grazed organic split-plots in 2014 safflower indicating a slight difference among farming systems (Drop in Deviance F-value<sub>(2,6)</sub> > 7.18, p < 0.047), with tilled organic systems having none present. Although

conventional no-till and tilled organic split-plots only had *M. sativa* present in 2013 winter wheat (Fig. 2.4c), there was little evidence that systems differed (Drop in Deviance F-value<sub>(2,6)</sub> > 1.45,  $p < 0.34$ ), and none was sampled in subsequent safflower split-plots.

### Discussion

A key caveat is that this study only investigated agronomics and weed communities in the first two years of a transitional organic study. Nonetheless, finding few differences in terms of yield and weeds and this transition period indicate that farmers may have alternative choices in management choices.

Austrian winter pea grown in 2013 did not have differences in crop biomass prior to termination, as expected, due to common site-wide management at the study outset in 2011-2012. Although there were no differences in wheat biomass or grain yield among systems, the harvest index was higher for conventional no-till wheat. This is likely due to the quicker mineralization of nutrients through urine and feces from grazing (Shariff et al. 1994) and tillage (Vaisman et al. 2011), giving a boost in plant biomass growth early in the season. Yet available water may have decreased under the two organic systems later in the growing season during grain maturation, a typical issue for Plains dryland farmers (Nielsen et al. 2005), resulting in similar yields across all treatments and a lower harvest index for the grazed treatment. Still the grain nitrogen levels were highest in the tilled organic split-plots, which might be due to less N put into shoot biomass compared to the grazed organic and conventional no-till split-plots, and the increased mineralization and more immediate availability of N from the previous cover crop associated with tillage

versus herbicide or grazed termination (Vaisman et al. 2011). In addition, other research has demonstrated that tillage based systems may favor better mineralization of nitrogen versus no-till systems favoring better conservation of soil water (Burgess et al. 2014), which may explain the higher yields as well as test weight associated with the reduced-tillage (grazed-organic) and no-till conventional systems. Less available water in the tilled system could have helped boost nitrogen and protein levels (Jones and Olson-Rutz 2012).

Although yields were similar for all three systems in 2014 winter wheat, preliminary 2015 yield data for the subsequent winter wheat crop indicates greater response differences under the different management systems (grazed-organic < tilled-organic = conventional no-till, data not shown). These results indicate that organic producers can expect similar or better yields and grain quality in transitioning to organic, yet shortcomings of these systems may be more apparent after this short period, especially in terms of soil quality parameters (Miller et al. 2008), and particularly in reduced tillage organic systems, an increase in weed pressure (Carr et al. 2013).

Generally, weed communities shifted from one crop to the next, but management systems did not cause divergence much in the first two years of the transition to organic period. There was evidence that conventional no-till weed communities diverged in 2014 lentil following winter wheat, but the lentil crop was inadvertently not managed with in-crop or pre-seed herbicides, losing a key management tool for lentils (Boerboom and Young 1995), which may have led to a spike in weed growth. Further, conventional no-till plots were implemented on the research farm where weeds had the densest legacy

from prior experimentation at this site, therefore this high weed pressure may largely be a residual legacy effect. There was also marginal evidence that weed communities diverged among management systems in 2014 safflower following winter wheat. This may be a product of the use of herbicides in the conventional systems, which has been shown to help select herbicide-susceptible weeds weed communities on organic farms (Hyvönen et al. 2003). Still weed communities did not differ between grazed organic and tilled organic systems, despite the fact that these management tactics can act as different ecological filters (Funk et al. 2008).

Grazing has been noted to have long-term impacts on the weed seedbank later realized in above-ground weed growth (Renne and Tracy 2013). However, other research has shown little correlation between above-ground and seedbank weed communities, and that yearly variation impacted weed seedbank communities more than management systems (Harbuck et al. 2009). This is in line with our results where weed community structure typically shifted from one year to the next, regardless of management system, possibly due the type of crop or biomass of each crop grown in competition with the weeds (Tracy and Davis 2009, Smith et al. 2015). In fact, we observed weed suppression in winter wheat, even after a weed-infested lentil crop from the prior year, which highlights the importance of crop choice and other cultural practices like row spacing (Blackshaw et al. 2008, Drews et al. 2009). Although there was only one replication of buckwheat planted in 2014, it showed promise as a possible crop to interseed with sweet clover as an alternative to safflower, with reduced weed biomass following 2013 winter wheat. Prior studies have shown buckwheat to be a good weed suppression tool (Bulan et

al. 2015), however it is not suitable for emergency grazing due to causing photo-toxic effects in sheep.

Perennial weeds were not typically problematic in the first couple years of this study. Interestingly though, *T. officinale* did appear to increase in periods of no tillage (from 2013 safflower to 2014 sweet clover) for all systems. The largest abundance of this weed, however, was found in 2014 winter wheat following Austrian winter pea in grazed organic systems. This supports prior research that shows an increase in *T. officinale* with reduced tillage intensity and grazing integration (Sans et al. 2011, Miller et al. 2015b) and continued monitoring of this weed is warranted to determine its relative impact on crop growth as these management systems continue to be implemented. *Cirsium arvense* on the other hand showed more variable trends, increasing under reduced tillage systems in some crop phases, and decreasing in others. Still, this weed is of paramount concern in both organic and conventional systems where tillage, or the lack thereof (i.e. no-till), are not good tools for managing this perennial weed (Menalled et al. 2009, Gruber and Claupein 2009).

It is necessary to evaluate the economics of alternative crop management practices as well. Cover crop termination through tillage or herbicide applications comes at a cost and grazing leases may cover some of the expenses of cover crop cultivation. We estimated 2.75 Mg ha<sup>-1</sup> of Austrian winter pea forage on average in 2013. Estimating the total monthly forage dry matter intake to be 171 kg per lamb (Lacey 1991), stocking rates would be approximately 16 lambs ha<sup>-1</sup> month<sup>-1</sup>, or 3.2 animal unit months (AUM) to fully terminate the crop. Assuming the landowner will not provide services, the pasture



lease rate should be about 70 percent of the average land lease rate, making the grazing lease approximately \$14/AUM based on 2011 non-irrigated rates in Montana (Mosley 2012). In 2013, growers could expect approximately \$44 ha<sup>-1</sup> under a grazing lease. In 2014, there was approximately 3 Mg ha<sup>-1</sup> of available dry forage sweet clover, or the equivalent of 3.5 AUMs. In 2014, growers could expect approximately \$48 ha<sup>-1</sup> under a grazing lease. The average price for non-alfalfa hay in Montana in 2013 was worth \$138 Mg<sup>-1</sup> (National Agricultural Statistics Service, 2013), reflecting a potential value of \$379 ha<sup>-1</sup> in 2013, and \$411 in 2014. Thus grazing leases may provide a cheap alternative for ranchers to buying hay, and help farmers alleviate set-backs from weedy fields. In addition, in nutrient-limited systems like some organic farms, grazing would keep more nutrients on farm in the form of animal wastes, versus complete export with a hayed crop (Thiessen Martens and Entz 2011) and can provide other alternatives for crop termination on conventional farms which requires further expenses in herbicide application (Entz et al. 2002).

Table 2.1. Precipitation and temperature data for Big Sandy, MT.

Big Sandy	Precipitation (mm)			Mean Temperature Maximum (C)			Mean Temperature Minimum (C)		
	2013	2014	LTA*	2013	2014	LTA*	2013	2014	LTA*
Oct - April	87	95	103	6.7	4.9	6.6	-5.7	-8.0	-7.9
May	135	38	55	21.4	20.8	21.3	6.0	4.9	4.7
June	105	82	68	25.2	22.5	25.3	10.3	8.5	8.8
July	43	84	35	29.4	30.9	31.2	13.3	13.7	11.8
August	36	78	32	30.4	28.7	30.1	13.0	13.7	10.4
September	43	25	32	25.3	22.4	23.7	9.8	7.0	5.2

\* LTA = Long-term average, 1981–2000 mean precipitation, temperature maximum, and temperature minimum for Big Sandy, Montana located 12 km from the site (Western Regional Climate Center, Desert Research Institute, Reno, NV, USA)

Table 2.2. Cropping history in the two fields used in Big Sandy, MT, to assess the impact of cover crop termination method on crop agronomy and weed communities.

	2008 Crop	2009 Crop	2010 Crop	2011 Crop	2012 Crop	2013 Crop	2014 Crop
<b>Field A</b>	Kamut ( <i>Triticum turanicum</i> )	Feed Barley ( <i>Hordeum vulgare</i> L.)/ Alfalfa ( <i>M. sativa</i> )	Alfalfa / Grass hay	Alfalfa plow down	Kamut	Fall seeded Peas green manure ( <i>P. sativum</i> )	Safflower ( <i>C. tinctorius</i> )
<b>Field B</b>	Sweet clover ( <i>M. officinale</i> ) / Pea green manure	Kamut	Pea green manure	Barley / Radish ( <i>Raphanus sativus</i> L.) / Sweet Clover	Sweet Clover failed/replant to Pea green manure	Safflower/ Sweet Clover	Sweet Clover green manure

Table 2.3. Crop Management in the two fields used in Big Sandy, MT, to assess the impact of cover crop termination method on crop agronomy and weed communities.

	2013 Austrian winter pea		2014 Yellow sweet clover	
	Tilled Organic	Grazed Organic	Tilled Organic	Grazed Organic
Seeding date	September 2012		Seeding date	8 May 2013
Seeding rate	100 kg ha <sup>-1</sup>		Seeding rate	Sweet clover (8 kg ha <sup>-1</sup> ) interseeded with safflower (28 kg ha <sup>-1</sup> )
Row spacing	30 cm		Row spacing	18 cm
Cover Crop Termination	Tilled 17 June 2013	178 rams ha <sup>-1</sup> from 17-21 June 2013	Cover Crop Termination	Tilled 8 July 2014 296 rams ha <sup>-1</sup> from 23 June-2 July 2014
Other management	Tilled 19 July and 15 Aug 2013	355 sheep ha <sup>-1</sup> from 20-22 July 2013	Other management	888 sheep ha <sup>-1</sup> from 6-8 Aug 2014

Safflower	2014 Safflower		2015 Winter Wheat	
	Tilled Organic	Grazed Organic	Tilled Organic	Grazed Organic
Seeding date	May 21, 2014			
Seeding rate	28 kg ha			**Data Not Collected
Row spacing	18 cm			
Pre-planting cultivation	Tilled 30 April and 20 May 2014			
Harvest Date	16 Sep 2014			

\*\* Wheat seeding error caused unacceptable establishment in grazed plots.

Table 2.4. Cover crop shoot biomass and biomass C and N (Mean  $\pm$  SE) returned to soil at Big Sandy, MT, 2013-2014

	2013 Austrian Winter Pea						t-value	t-test df	P
	Grazed			Tilled					
Cover Crop Shoot Biomass (Mg ha <sup>-1</sup> )	4.87	$\pm$	0.80	4.47	$\pm$	0.62	-0.75	4	0.49
Weed Shoot Biomass (Mg ha <sup>-1</sup> )	1.25	$\pm$	0.07	1.83	$\pm$	0.26	3.14	4	0.035
Residue N returned from weeds(kg ha <sup>-1</sup> )	30.2	$\pm$	1.3	43.8	$\pm$	6.2	3.03	4	0.039
Residue C returned from weeds (kg ha <sup>-1</sup> )	530	$\pm$	22	759	$\pm$	95	2.88	4	0.045
Residue N returned from crops (kg ha <sup>-1</sup> )	12.6	$\pm$	1.4	10.8	$\pm$	1.0	-1.77	4	0.15
Residue C returned from crops (kg ha <sup>-1</sup> )	213	$\pm$	34	190	$\pm$	26	-0.94	4	0.40
	2014 Sweet Clover						t-value	t-test df	P
	Grazed			Tilled					
Cover Crop Shoot Biomass (Mg ha <sup>-1</sup> )	2.62	$\pm$	0.33	3.73	$\pm$	0.33	2.83	4	0.047
Weed Shoot Biomass (kg ha <sup>-1</sup> )	151.20		69.75	71.31		16.31	-0.32	4	0.76
Residue N returned from weeds(kg ha <sup>-1</sup> )	3.8	$\pm$	1.7	1.6	$\pm$	0.4	-2.27	3	0.29
Residue C returned from weeds (kg ha <sup>-1</sup> )	81	$\pm$	32	34	$\pm$	9	-1.42	3	0.25
Residue N returned from crops (kg ha <sup>-1</sup> )	47.2	$\pm$	6.4	67.1	$\pm$	8.2	2.69	4	0.054
Residue C returned from crops (kg ha <sup>-1</sup> )	1179	$\pm$	152	1673	$\pm$	154	2.72	4	0.053

Table 2.5. Safflower agronomic parameters (Mean  $\pm$  SE) at Big Sandy, MT, 2014.

	2014 Safflower						t-value	t-test df	P
	Grazed			Tilled					
Crop Shoot Biomass (Mg ha <sup>-1</sup> )	8.15	$\pm$	1.11	7.92	$\pm$	2.80	-0.062	4	0.95
Weed Shoot Biomass (Mg ha <sup>-1</sup> )	3.92		0.79	3.55		0.82	-0.75	4	0.50
Residue N returned from weeds (kg ha <sup>-1</sup> )	70.2	$\pm$	5.1	69.9	$\pm$	11.2	-0.30	4	0.78
Residue C returned from weeds (Mg ha <sup>-1</sup> )	1.69	$\pm$	0.35	1.53	$\pm$	0.35	-0.76	4	0.49
Residue N returned from crops (kg ha <sup>-1</sup> )	4.10	$\pm$	0.20	9.01	$\pm$	2.08	2.61	1	0.23
Residue C returned from crops (kg ha <sup>-1</sup> )	199	$\pm$	2	401	$\pm$	90	2.30	1	0.26
Grain Yield (kg ha <sup>-1</sup> )	176		17	335		184	-0.39	2	0.73
Seed N harvested (kg ha <sup>-1</sup> )	5.2	$\pm$	0.2	13.0	$\pm$	3.7	1.98	1	0.30
Harvest Index	0.25	$\pm$	0.033	0.26	$\pm$	0.10	-0.52	2	0.66

Table 2.6. Precipitation and temperature data for Fort Ellis Research and Extension Center in Bozeman, MT.

	Precipitation (mm)			Mean Temperature Maximum (C)			Mean Temperature Minimum (C)		
	2013	2014	LTA *	2013	2014	LTA *	2013	2014	LTA *
Oct - April **	332	279	231	6.6	5.3	7.1	-4.8	-6.2	-5.31
May	110	48	80	17.7	17.8	18.2	4.6	3.9	3.9
June	88	95	79	23.4	20.2	23.1	8.1	6.8	7.7
July	18	16	38	29.0	29.0	28.2	12.0	12.4	10.8
August	19	72 <sup>¶</sup>	35	28.3	26.1	27.9	11.2	10.2	10.1
September	76	41	38	21.5	22.5	22.1	7.7	5.7	5.6

\* Long-term average, 1981–2000 mean precipitation, temperature maximum, and temperature minimum for Bozeman, Montana located 5 km from the site (Western Regional Climate Center, Desert Research Institute, Reno, NV, USA).

\*\* Oct - April period includes data from the prior year for October through December, in relation to the year under the column heading for January through April and subsequent months.

¶ Rain mostly occurred in late August after crops were harvested, excluding the safflower crop.

Table 2.7. Crop management in Organic Tilled, Organic Grazed, and Conventional No-till at Fort Ellis, Sept. 2012 - Oct. 2013.

<b>Austrian Winter Pea</b>	<b>Tilled Organic</b>	<b>Grazed Organic</b>	<b>Conventional No-till</b>
Cultivar	-----Melrose-----		
Seeding date	-----18 Sep 2013-----		
Seeding rate (seeds/m <sup>2</sup> )	-----160-----		80
Row spacing (cm)	-----13-----		25
Inoculant brand	-----Ndure peat powder-----		
Other management	Tandem disked for termination 19 June 2013 Tilled with tandem disks 23 July 2013 Tilled with chisel plough with 40-cm shovels on 28 Aug 2013	Grazed for termination at 67 lambs/ha rate from 16 June - 18 July 2013 Grazed weed regrowth with 167 lambs/ha rate from 29-30 Aug 2013	Terminated with glyphosate (840 g ai/ha) and dicamba (140 g ae/ha) on 18 June 2013 Weeds sprayed with glyphosate (1120 g ai/ha) 16 Sep 2013
	Tilled with spring-tine cultivator with 18-cm shovels and trailing roller baskets on 8 Oct 2013		
<b>Winter Wheat</b>			
Cultivar	-----Yellowstone-----		
Seeding date	-----23 Sep 2012-----		
Seeding rate (seeds/m <sup>2</sup> )	-----500-----		250
Row spacing (cm)	-----13-----		25
Harvest Date	-----7 Aug 2013-----		
Other management	Residue incorporated with offset disk 16 Sep 2013	Grazed residue with 100 lambs/ha from 1 Oct-25 Nov 2013 for feedlot	Post-emergent dicamba (105 g ae/ha) mixed with 2,4-D (482 g ai/ha) on 14 May 2013
	Chisel plowed on 23 Sep 2013		270-370 kg/ha of 46-0-0 urea applied on 15 May 2013
			Sprayed with glyphosate (1120g ai/ha) on 16 Sep 2013



Table 2.7. (cont'd). Crop management in Organic Tilled, Organic Grazed, and Conventional No-till at Fort Ellis, Sept. 2012 - Oct. 2013.

<b>Lentil</b>			
Cultivar	-----Richlea-----		
Seeding date	-----2 May 2013-----		3 May 2013
Seeding rate (seeds/m <sup>2</sup> )	-----240-----		120
Row spacing (cm)	-----13-----		25
Inoculant brand	-----None-----		Apron Maxx
Harvest Date	-----Swathed 9 July 2013-----		
	-----Combined 7 Aug 2013-----		
Other Management	-----Cultivated 19 April 2013 with a spring tine cultivator with shovels and a trailing basket-----		
	-----Cultivated 25 April 2013 with chisel plow with 40-cm shovels and trailing spring tine harrows-----		
	Rolled plots 1 May 2013	-----Rolled plots May 3, 2013-----	
	Tilled 8 Aug 2013 with chisel plow	Grazed weeds and residue on 28 Aug	Sprayed with glyphosate (1120 g ai/ha)
	Tilled with chisel plow 28 Aug 2013	2013 at rate of 167 lambs/ha	with AMS on 16 Sep 2013
	Tilled with spring-tine cultivator with		
	18-cm shovels and trailing roller		
	baskets on 8 Oct 2013		
<b>Safflower / Sweet Clover</b>			
Cultivar	-----MonDak/vns yellow blossom-----		
Seeding date	-----20 April 2013-----		
Seeding rate (seeds/m <sup>2</sup> )	-----75 / 75-----		
Row spacing (cm)	-----13 /13-----		
Inoculant brand	-----w/ seed-----		Pre-Vail
Harvest Date	-----9 Oct 2013-----		
Other Management	-----Cultivated 19 April 2013 with a spring tine cultivator with shovels and a trailing basket-----		
	-----Rolled plots 23 April 2013-----		
			119 kg/ha of 46-0-0 urea applied on 15 May 2013

Table 2.8. Crop management in Organic Tilled, Organic Grazed, and Conventional No-till at Fort Ellis, Sept. 2013 - Oct. 2014.

<b>Sweet Clover</b>	<b>Tilled Organic</b>	<b>Grazed Organic</b>	<b>Conventional No-till</b>
Cultivar	-----vns yellow blossom-----		
Seeding date	-----20 April 2013-----		
Seeding rate (seeds/m <sup>2</sup> )	-----75-----		
Row spacing (cm)	-----25-----		
Other management	Terminated with two passes of tandem disk on 13 June 2014	Terminated by grazing at 50 sheep/ha rate from 12 June-22 July 2014	Stubble sprayed 25 April 2014 with glyphosate (700 g ai/ha)
	Tilled with chisel plow with 40-cm shovels on 3 July 2014	Grazed weeds at rate 133 ewes/ha from 24 July-7 Aug 2014	Terminated with salflufenacil (50 g ai/ha) and glyphosate (1120 g ai/ha) on 13 June 2014
		Grazed with rams at 208 lambs/ha from 9-16 Sep 2014	Sprayed herbicide mix above for weeds on 16 July 2014
			Sprayed glyphosate (1120 g ai/ha) 16 Sep 2014
<b>Winter Wheat</b>			
Cultivar	-----Yellowstone-----		
Seeding date	-----24 Sep 2013-----		23 Sep 2013
Seeding rate (seeds/m <sup>2</sup> )	-----500-----		225
Row spacing (cm)	-----15-----		30
Harvest Date	-----13 Aug 2014-----		
Other management	Rotary hoed stubble 18 Aug 2014	Rotary hoed stubble 19 Aug 2014	130 kg/ha of 46-0-0 urea applied on 23 Sep 2013 on lentil stubble plots only
	Tilled with chisel plot on 29 Aug 2014	Tilled with chisel plow 4 Sep 2014	Post-emergent pinoxaden (60 g ae/ha), fluroxypyr (105 g ae/ha), bromoxynil (263 g ai/ha), and MCPA (263 g ai/ha) on 2 May 2014
		Grazed plots at 50 sheep/ha on 5 Sep 2014	Rotary hoed stubble 19 Aug 2014
			Sprayed glyphosate (1120 g ai/ha) 16 Sep 2014

Table 2.8. (cont'd). Crop management in Organic Tilled, Organic Grazed, and Conventional No-till at Fort Ellis, Sept. 2013 - Oct. 2014.

<b>Lentil</b>			
Cultivar	-----Richlea-----		
Seeding date	-----15 May 2014-----		2 May 2014
Seeding rate (seeds/m <sup>2</sup> )	-----240-----		120
Row spacing (cm)	-----15-----		30
Harvest Date	-----Swathed 4 Aug 2014-----		
	-----Combined 12 Aug 2014-----		
Other Management	-----Tilled with chisel plough on 2 May 2014-----		Stubble sprayed 25 April 2014 with glyphosate (700 g ai/ha)
	-----Spring-tined cultivated on 14 May 2014-----		
	Tilled with chisel plough with 40-cm shovels on 18 Aug 2014	Grazed with at 100 rambouillets per ha from 15-18 Aug 2014	Rolled plots on 23 May 2014
	Spring-tined cultivated on 29 Aug 2014	Grazed at 208 lambs/ha from 16-22 Sep 2014	Sprayed weeds with glyphosate (1120 h ai/ha) 16 Sep 2014
<b>Safflower / Sweet Clover</b>			
Cultivar	-----MonDak/vns yellow blossom-----		
Seeding date	1 May 2014	30 April 2014	1 May 2014
Seeding rate	-----75 / 75-----		
Row spacing	-----15 / 15-----		
Seed Treatment	-----None-----		Thiram
Harvest Date	6 Oct 2014	Buckwheat harvested 23 Sep 2014	7 Oct 2014
Other Management	Rotary hoed 15 May 2014	Grazed weeds with 167 sheep per ha from 8-9 May 2014	Rotary hoed 15 May 2014
	Tilled with offset disk on 11 Oct 2014	Grazed with 117 sheep per ha from 29-30 May 2014	Post-emergent sprayed with clethodim (140 g ai/ha) on 5 June 2014
		Rep 1 terminated **	
		Safflower plots rotary hoed on 5 June 2014	
		Safflower plots grazed by 100 rams per ha from 9-16 July 2014 and 150 rambouillet rams per ha from 19-22 Aug 2014	

\*\*Rep 1 of the three safflower / sweet clover plots in the grazed organic system had poor stand establishment in spring 2014. This plot was tilled with a chisel plow on 2 June 2014 and seeded with buckwheat at 34 kg/ha and sweet clover at 75 seeds/m<sup>2</sup>.

Table 2.9. Agronomics of 2013 Austrian winter pea and 2014 sweet clover cover crops.

	2013 Winter pea										
	Conventional No Till			Grazed Organic			Tilled Organic			Chisq (2 df)	P
Crop Shoot Biomass (Mg ha <sup>-1</sup> )	2.87	±	0.18	2.75	±	0.34	3.06	±	0.15	1.97	0.37
Residue N returned from crops (kg ha <sup>-1</sup> )	114	±	14	105	±	11	118	±	5	1.90	0.39
Residue C returned from crops (Mg ha <sup>-1</sup> )	1.19	±	0.06	1.14	±	0.14	1.28	±	0.07	1.82	0.40
	2014 Sweet Clover										
	Conventional No Till			Grazed Organic			Tilled Organic			Chisq (2df)	P
Crop Shoot Biomass (Mg ha <sup>-1</sup> )	4.09	±	0.50	2.98	±	0.17	3.08	±	0.26	6.98	0.031
Residue N returned from crops (kg ha <sup>-1</sup> )	114.6	±	27.8	81.3	±	11.9	87.0	±	15.6	3.67	0.16
Residue C returned from crops (Mg ha <sup>-1</sup> )	1.78	±	0.20	1.31	±	0.07	1.35	±	0.11	7.56	0.023

Table 2.10. Agronomics of 2014 winter wheat crop following 2013 Austrian winter pea.

	2014 Winter Wheat									Chisq (2df)	P
	Conventional No Till			Grazed Organic			Tilled Organic				
Crop Shoot Biomass (Mg ha <sup>-1</sup> )	15.5	±	1.0	17.7	±	0.8	17.2	±	1.1	3.33	0.19
Residue N returned from crops (kg ha <sup>-1</sup> )	52.2	±	7.6	79.0	±	1.5	79.5	±	12.2	6.96	0.031
Residue C returned from crops (Mg ha <sup>-1</sup> )	4.06	±	0.30	5.10	±	0.07	4.64	±	0.33	7.75	0.021
Grain Yield (Mg ha <sup>-1</sup> )	5.73	±	0.18	5.94	±	0.16	5.36	±	0.28	4.39	0.11
Seed N Harvested (kg ha <sup>-1</sup> )	168	±	9	174	±	5	188	±	4	5.68	0.059
Harvest Index	0.43	±	0.01	0.37	±	0.01	0.40	±	0.01	12.35	0.0021
Protein (g kg <sup>-1</sup> )	143	±	8	152	±	9	159	±	5	4.36	0.11
Test Weight (kg hl <sup>-1</sup> ) *	77.1	±	0.9	76.4	±	1.0	71.7	±	0.4	14.95	0.001

\* 77.2 kg hl<sup>-1</sup> = 60 lb bu<sup>-1</sup>

Table 2.11. Analysis of weed biomass, species richness, and Simpson's diversity for every 2013 to 2014 crop phase at Fort Ellis. Letters indicate differences ( $p < 0.05$ ).

	Grazed Organic		Tilled Organic		Conventional No-till	
	2013 Safflower	2014 Sweet Clover	2013 Safflower	2014 Sweet Clover	2013 Safflower	2014 Sweet Clover
Weed Biomass (kg ha)	681 ± 331 a	467 ± 89 a	742 ± 251 a	798 ± 133 a	726 ± 99 a	402 ± 43 a
Species Richness	9.3 ± 0.7 b*	14.7 ± 1.5 a*	10.3 ± 1.8 b*	14.3 ± 0.3 a*	12.3 ± 0.3 b*	12.0 ± 3.1 a*
Simpson's Diversity (1-D)	0.53 ± 0.13 a	0.67 ± 0.02 a	0.68 ± 0.01 a	0.59 ± 0.12 a	0.70 ± 0.03 a	0.66 ± 0.06 a
	2013 Pea	2014 W. Wheat	2013 Pea	2014 W. Wheat	2013 Pea	2014 W. Wheat
Weed Biomass (kg ha)	175 ± 93 a	16.2 ± 5.4 b	377 ± 27 a	19.6 ± 10.6 b	212 ± 73 a	39.6 ± 32.1 b
Species Richness	8.3 ± 0.3 a*	5.0 ± 0.6 b*	6.7 ± 0.9 a*	5.7 ± 1.7 b*	8.7 ± 1.8 a*	6.0 ± 1.0 b*
Simpson's Diversity (1-D)	0.30 ± 0.06 b	0.53 ± 0.04 a	0.27 ± 0.12 b	0.44 ± 0.11 ab	0.54 ± 0.16 a	0.28 ± 0.03 b
	2013 W. Wheat	2014 Lentil	2013 W. Wheat	2014 Lentil	2013 W. Wheat	2014 Lentil
Weed Biomass (kg ha)	76.8 ± 31.7 c	552 ± 62 b	276 ± 111 b	565 ± 314 ab	62.1 ± 18.3 c	1404 ± 284 a
Species Richness	7.7 ± 1.2 a	7.0 ± 0.6 a	9.7 ± 3.2 a	8.3 ± 1.7 a	9.7 ± 1.3 a	10.7 ± 0.9 a
Simpson's Diversity (1-D)	0.48 ± 0.09 b	0.74 ± 0.02 a	0.37 ± 0.07 b	0.64 ± 0.03 a	0.59 ± 0.13 b	0.66 ± 0.04 a
	2013 Lentil	2014 W. Wheat	2013 Lentil	2014 W. Wheat	2013 Lentil	2014 W. Wheat
Weed Biomass (kg ha)	701 ± 469 a	180.2 ± NA	701 ± 357 a	227 ± 107 b	993 ± 212 a	223 ± 81 b
Species Richness	8.3 ± 1.8 a	8.0 ± NA	9.0 ± 0.6 a	7.3 ± 1.45 a	10.3 ± 2.0 a	9.3 ± 2.6 a
Simpson's Diversity (1-D)	0.59 ± 0.19 a	0.51 ± NA	0.67 ± 0.04 a	0.57 ± 0.11 b	0.66 ± 0.05 a	0.23 ± 0.17 b
	2013 W. Wheat	2014 Buckwheat	2013 W. Wheat	2014 Safflower	2013 W. Wheat	2014 Safflower
Weed Biomass (kg ha)	348 ± 223 b	139 ± NA	80.8 ± 49.3 b	212 ± 49 a	54.7 ± 24.0 b	346 ± 40 a
Species Richness	6.3 ± 0.9 b*	7.0 ± NA	10.7 ± 2.9 a*	9.0 ± 2.0 a*	11.0 ± 1.5 a*	12.0 ± 2.1 a*
Simpson's Diversity (1-D)	0.12 ± 0.08 c	0.74 ± NA	0.35 ± 0.13 b	0.69 ± 0.09 a	0.58 ± 0.03 a	0.60 ± 0.02 a

\*Indicates a difference at the  $0.05 < p < 0.10$  level.

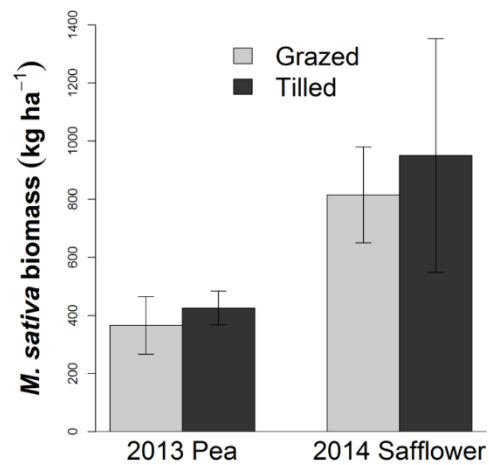


Figure 2.1. Biomass of *Medicago sativa* (alfalfa) (mean  $\pm$  SE) in 2013 Austrian winter pea and subsequent 2014 safflower crop at Big Sandy, MT, in Field A.

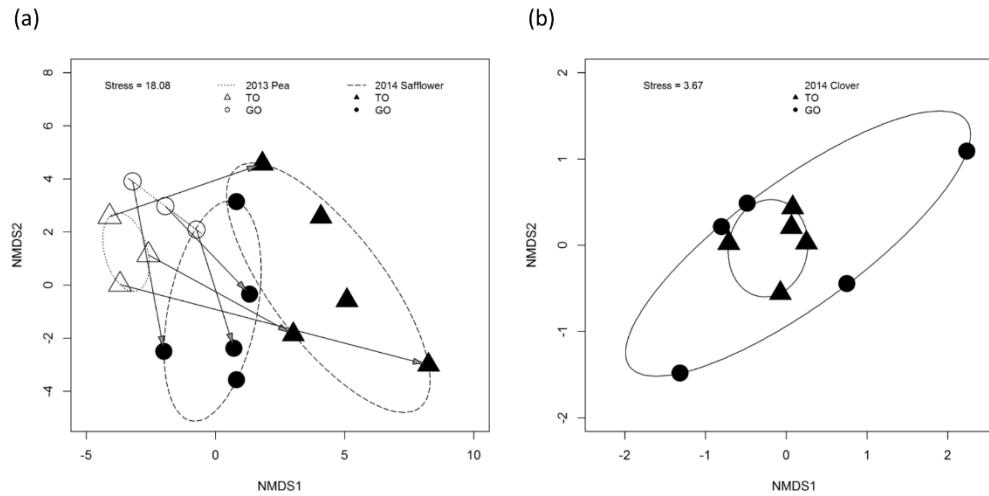


Figure 2.2. Non-metric multidimensional scaling (NMDS) ordination of weed community structure in tilled organic (TO) and grazed organic (GO) plots in Big Sandy, MT. (a) Field A: 2013 Austrian winter pea to 2014 safflower. Dotted ellipses indicate the 2013 crop by system and dashed ellipses indicate the subsequent 2014 crop by system and arrows denote the shift in community structure within the same plot from 2013 to 2014, and (b) Field B: 2014 sweet clover



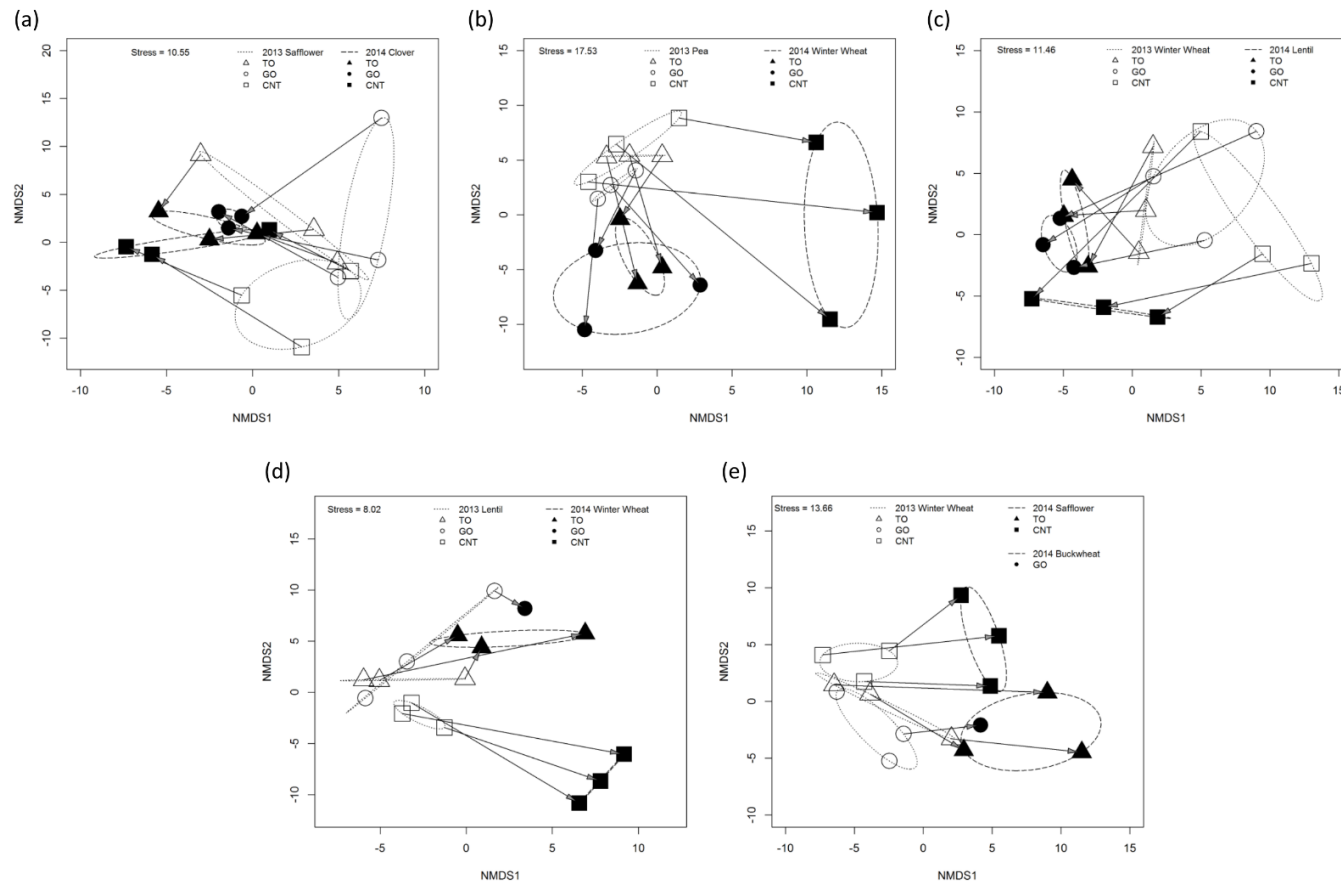


Figure 2.3. Non-metric multidimensional scaling (NMDS) ordination of weed community shifts in tilled organic (TO), grazed organic (GO), and conventional no-till systems (CNT) at the Fort Ellis Research and Extension Center, Montana. (a) 2013 safflower to 2014 sweet clover, (b) 2013 Austrian winter pea to 2014 winter wheat, (c) 2013 winter wheat to (b) 2014 lentil, (d) 2013 lentil to 2014 winter wheat, and (e) 2013 winter wheat to 2014 safflower / buckwheat. Dotted (c) ellipses indicate the 2013 crop by system and dashed ellipses indicate the subsequent 2014 crop by system. Arrows (d) denote the shift in community structure within the same plot from 2013 to 2014.

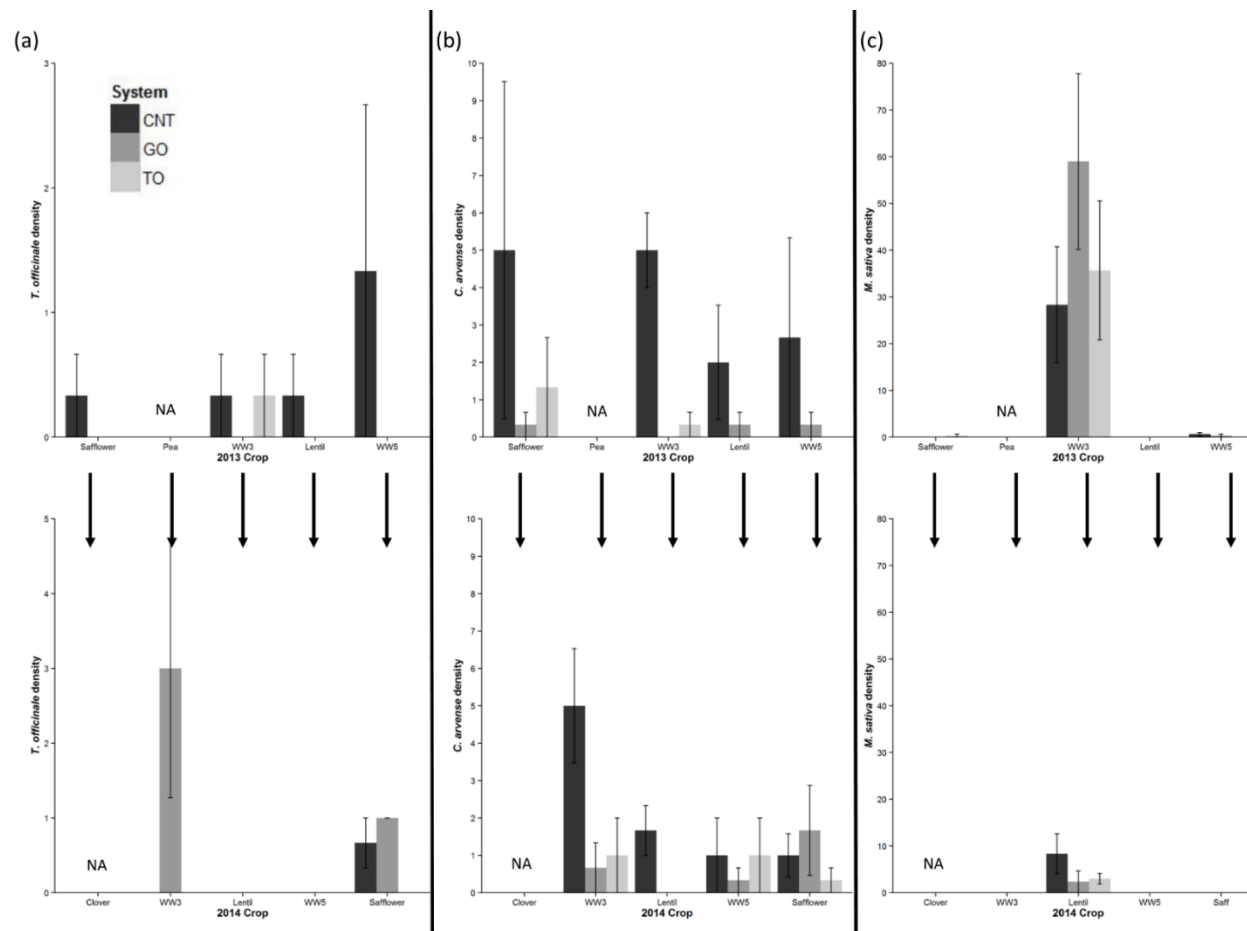


Figure 2.4. Density estimates (mean  $\pm$  SE) of perennial weeds at Fort Ellis in 10 m<sup>2</sup>. Note that within columns, the 2013 crop in the 1<sup>st</sup> row is directly above the subsequent 2014 crop in the 2<sup>nd</sup> row. The three systems compared were: CNT = conventional no-till, GO = grazed organic, and TO = tilled organic. (a) *Taraxacum officinale* (dandelion), (b) *Cirsium arvense* (Canada thistle / creeping thistle), (c) *Medicago sativa* (alfalfa). ‘NA’ refers to those plots that were not sampled for density. Clover = Sweet Clover, Pea = Austrian winter pea, WW3 = winter wheat following Austrian winter pea, WW5 = winter wheat following lentil.

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CHAPTER THREE

CROPPING SYSTEMS MODIFY THE IMPACTS OF BIOTIC  
PLANT-SOIL FEEDBACKS ON WHEAT  
(*TRITICUM AESTIVUM* L.) GROWTH  
AND COMPETITIVE ABILITY

Contribution of Authors and Co-Authors

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Summary

1. Biologically-mediated plant-soil feedbacks (PSFs) are known to alter plant growth, plant-plant interactions, and plant community dynamics in natural systems. Yet, little is known about the magnitude and importance of PSFs in agro-ecosystems. Here, we investigated if agricultural management systems affect the impact of PSFs on crop growth and crop-weed competition.
2. Utilizing soil collected from eight farms, we evaluated the extent to which PSFs differ between conventional and organic farming systems. Soils were conditioned by growing two common annual weeds, either *Amaranthus retroflexus* L. (redroot pigweed) or *Avena fatua* L. (wild oat). Feedbacks were measured in wheat (*Triticum aestivum* L.) growth and crop-weed competitive interactions.
3. Results indicated that in general, PSFs were more positive when soil inocula was collected from organic farms compared to conventional farms, suggesting that cropping systems modify the relative abundance of mutualistic and pathogenic organisms responsible for the observed PSFs. Also, as feedbacks became more positive, crop-weed competition decreased and facilitation increased.
4. *Synthesis and applications.* In annual cropping systems, PSFs can alter plant growth and crop-weed competition. By identifying the management practices that promote positive PSFs for crops and minimize the impacts of crop-weed competition, producers can decrease their reliance on off-farm chemical and mechanical inputs to control weeds, enhancing agroecosystem sustainability.

## Introduction

Recent research has increased our understanding of the mechanisms by which plants alter nutrient availability (Ehrenfeld et al. 2005), soil moisture (Nielsen et al. 2005), and soil biota (Wolfe and Klironomos 2005) and how they, in turn, modify interactions with organisms at the same or different trophic levels (Hol *et al.* 2013). Despite this knowledge, weed science has been primarily focused on developing chemical and mechanical methods to minimize weed abundances rather than assessing the mechanisms driving crop-weed competitive interactions (Ward *et al.* 2014). While this approach to weed management has helped to improve yields and farm labor efficiencies, it has known drawbacks including soil erosion from tillage (Greer et al. 2006), soil and ground water contamination from pesticides (Hallberg 1989, Van Oost et al. 2005), and the evolution of herbicide resistant weeds (Powles and Yu 2010).

New societal concerns as well as climate, policy, and market challenges require weed science to address the ecological principles underlying complex issues in weed management (Fernandez-Quintanilla et al. 2008, Davis et al. 2009, Navas 2012). In this context, Smith, Mortensen, and Ryan (2010) proposed the Resource Pool Diversity Hypothesis (RPDH) to explain how cropping systems and the soil resource pool, a function of soil microbial communities (Reynolds *et al.* 2003), may mediate crop-weed competitive interactions. The RPDH proposes that cropping system diversification results in increased niche differentiation and resource partitioning which, in turn, translates to reduced yield loss from crop-weed competition. In accordance, Ryan *et al.*

(2009, 2010) provide evidence that under increased cropping system diversification, crop-weed competition is less intense.

Crop-weed interactions may be at least partially explained through biotic plant soil feedbacks (PSFs hereafter), where management practices such as tillage, cropping system diversification, and cover cropping alter soil microbial communities (Wortman *et al.* 2013), and these alterations in turn impact the growth of plants that subsequently occupy that site (Wolfe and Klironomos 2005). Recently, interest has risen regarding the potential role of PSFs in determining crop and weed growth (Smith *et al.* 2011, Miller and Menalled 2015) as well as crop-weed competitive interactions (Hol *et al.* 2013). While organically managed systems typically have a greater abundance and diversity of weeds than conventionally managed ones (Menalled, Gross & Hammond 2001; Pollnac, Maxwell & Menalled 2009), yield loss in organic fields is often not commensurate with weed abundance (Smith *et al.* 2010), suggesting that crops in organic systems exhibit greater tolerance to weeds. Is it possible that through their impacts on PSFs, cropping systems are responsible for the increased tolerance to weed-crop competition observed in organic systems when compared to conventional ones? In this study, we evaluated the extent to which PSFs that occur in organic and conventional cropping systems could modify (1) wheat growth and (2) competitive interactions with weeds.

## Materials and Methods

### Soil Collection

Eight paired USDA certified organic and conventional farms located in north-central Montana were sampled in July, 2013 to obtain the soil inocula used in our greenhouse experiment (see Fig. 3.S1 in Supporting Information). Paired farms were located on average 3.3 km (SD = 4.5) apart from each other, with pairs distributed across a broad region (mean distance between pairs 137 km, SD = 40). Conventional farms all practiced a no-tillage wheat-fallow rotation, and organic farms had been managed with tillage-intensive, diverse crop rotations that included legumes and multiple grain species (see Table 3.S1). Sampled fields could not be randomly selected because of logistical constraints, including the need for farms to be paired, sampled fields being planted to a wheat crop [except the organic Dutton location planted to *Triticum turanicum* Jakubz. (var. Kamut), a close relative of wheat], and obtaining landowner permission for soil collection. Despite these limitations, sampled fields represented a wide range of soil characteristics (loams, clay loams, and silty clay loams), temperatures (mean max of 12.9 – 14.8 C; mean min (-2.7 – -0.9 C), and annual precipitation (265 – 388 mm) (see Table 3.S1).

Within each field, soil was collected to a depth of 13 cm via 6 cm diameter cores every 10 m along a 200-m W-shaped transect, for a total of 21 subsamples per transect. Transects were located at least 100 m from any field edge and positioned on relatively uniform slopes in order to reflect spatial heterogeneity in the fields. Subsamples were pooled into one sample per field and all soil was refrigerated at 4° C until the experiments

began. Prior to commencing the experiment, the soils were air-dried for 2 weeks and sifted through a 1 cm<sup>2</sup> sieve. To isolate the effects of soil biotic communities, each soil sample was split. Half the soil was heated to 120° C for two 1 h periods with 24 h between sterilizations (sterilized, hereafter). Half was left unsterilized (biologically-active, hereafter).

### Experimental Design

This study was conducted at Montana State University, Bozeman, MT. The potting media used was a steam pasteurized (70 °C for 4 h) greenhouse soil mix with equal parts by volume of loam soil, washed concrete sand, and Canadian sphagnum peat moss, with AquaGro 2000 G wetting agent blended at 0.59 kg m<sup>-3</sup>. A total of 576 pots (2.5 L volume, 18 cm diameter x 14 cm height) were filled with the potting media. Pots were individually inoculated with a small amount (80 mL, approximately 3.5% by volume) of either a biologically-active or sterilized soil inoculum collected from one farm, and mixed into top one-third of potting media

Two trials were conducted in separate greenhouses due to space limitations. Plants were grown under a 16-h photoperiod of natural sunlight supplemented with mercury vapor lamps (165μE m<sup>-2</sup> s<sup>-1</sup>) at 22 C/18 C day/night. Within each greenhouse, pots were arranged following a randomized block design with three replicated blocks per greenhouse. This experiment followed a two phase design: a conditioning phase and a response phase. The conditioning phase allowed either *Amaranthus retroflexus* L. (redroot pigweed) or *Avena fatua* L. (wild oat) growth to alter the soil biotic community in species-specific ways. These weed species are problematic in grain growing regions of



North America, Asia, Europe and Australia, and were chosen due to their abundance in organic and conventional fields in Montana (Pollnac et al. 2008, 2009). We used weed seeds collected locally. The response phase assessed the relative impact of farming system (conventional or organic), type of inocula (biologically-active or sterile), and conditioning species identity (*A. retroflexus* or *A. fatua*) on the growth and competitiveness of wheat.

The conditioning phase consisted of two 8-week growing periods where individual pots were seeded with either an average of 60 *A. retroflexus* seeds or 12 *A. fatua* seeds and thinned 10 days after emergence to either ten or six evenly spaced individuals, respectively. Prior experimentation was conducted to find planting densities for each species that resulted in similar biomass growth in the allotted time period. The two growing period were separated by a 2-week dry fallow period. Pots were watered as necessary and were not fertilized during the conditioning phase as fertilization often changes soil biota dynamics (Marschner 2003), including varying effects on mycorrhizal, pathogenic and saprophytic micro-organisms (Brinkman et al. 2010). Aboveground plant biomass was calculated from the combined total of both conditioning periods, dried to a constant weight in an oven at 40 °C, and weighed to the nearest 0.01 g. Soil samples (10 cm depth x 1 cm diameter) were collected at the end of the conditioning phase from 192 pots, representing 6 replicates per conditioning phase treatment for each inocula source (locality, and conventional or organic), and analyzed for concentrations of  $\text{NO}_3^-$ , Olsen/Bray P, and K.

After above-ground plant biomass from the second conditioning phase was removed with roots left intact in the potting soil, pots with soil from the conditioning phase remaining in them, were randomly assigned to one of three response phase treatments (competitive status): 1) spring wheat (var. Vida) grown in monoculture, or wheat in competition with either 2) *A. fatua*, or 3) *A. retroflexus*. Six wheat seeds were planted in each pot with two seeds at three locations. The competition treatment consisted of either twelve *A. fatua* seeds evenly spaced in six locations in between the wheat, or approximately 60 seeds of *A. retroflexus* seeds evenly spaced in nine locations between the wheat. Seedlings were thinned 10 days after emergence to three, six, or nine individuals for wheat, *A. fatua*, and *A. retroflexus*, respectively. As before, pots were watered as necessary and were not fertilized. Eight weeks after seeding, approximately at crop flowering, plants were harvested, separated by species, dried, and weighed as above.

### Statistical Analyses

Following Brinkman *et al.* (2010), PSFs in the response phase were calculated as:

$$PSF_{ij} = \ln\left(\frac{\text{plant biomass}_{ijlm} \text{ in pots inoculated with living soil}}{\text{plant biomass}_{ijlm} \text{ in pots inoculated with sterilized soil}}\right) \quad (\text{Eq. 1})$$

where  $\text{biomass}_{ij}$  represents the summed biomass of species  $i$  grown in the response phase and conditioned by species  $j$ , within block  $l$  in each greenhouse trial  $m$ . This metric is centered on zero when the plant biomass in pots receiving a biologically-active inoculum is equal to the biomass in pots receiving a sterilized inoculum. PSF values are positive when plant biomass is greater in pots that received the biologically-active inoculum, and negative when plant biomass is greater in pots that received a sterilized inoculum.

Results are presented in terms of both PSF and biomass, as recommended by Pernilla Brinkman *et al.* (2010).

We fit linear mixed effects regression models to evaluate differences in biomass and PSF responses considering locality a random effect and accounted for locality differences by nesting farming system (conventional or organic) within localities, and inoculum type (sterile or biologically-active) within farming system. Blocks nested within greenhouses were also included as random effects. Farming system, conditioning species identity, competitive status, and inoculum type were included as fixed effects. We also included  $\text{NO}_3^-$ , Olsen/Bray P, K, and combined biomass sampled at the end of the conditioning phase as covariates. Model selection was accomplished using likelihood ratio tests to calculate chi-square statistics comparing the full model with the explanatory variable in question against a model without that variable. We started with a saturated model that included all explanatory variables and interactions, and used a stepwise procedure to find the optimal random slope structure for each random intercept under restricted maximum likelihood (Barr et al. 2013). We then used maximum likelihood estimation and a backwards stepwise procedure to test the fixed effects and repeated this process until no additional explanatory variables could be removed. To assess differences in the strength of PSFs among competitive status treatments, we included an interaction term between farming system and competitive status. Confidence intervals and planned comparisons under each competition scenario were made using least squares means and Satterthwaite's approximation of degrees of freedom. Normality and equality of variances were visually evaluated using residual plots. Weed biomass values in the

response phase were natural log-transformed to improve normality and homogeneity of variances. Wheat biomass values did not require transformations.

To assess the impact of PSFs on competitive interactions, we evaluated differences in the intensity of competition using the log response ratio (LnRR) (Weigelt & Jolliffe 2003):

$$\ln RR_{ijklm} = \ln\left(\frac{\text{wheat biomass in monoculture}_{ijklm}}{\text{wheat biomass in competition}_{ijklm}}\right) \quad (\text{Eq. 2})$$

where  $\ln RR_{ijklm}$  represents the log response ratio for competitive status treatment  $i$  at the combination of conditioning species identity  $j$ , soil inoculum source  $k$ , and block  $l$  within each greenhouse trial  $m$ . The log response ratio is centered on zero, allowing us to test for linear relationships in the intensity of competition ( $\ln RR > 0$ ) or facilitation ( $\ln RR < 0$ ) (Oksanen et al. 2006). We used this index to evaluate if the intensity of competition for *T. aestivum* in biologically-active inoculated pots varied with increasing weed biomass under competition, and if it depended on the strength of the PSF. Weed biomass values were log-transformed to better satisfy model assumptions.

We used ‘R’ statistical software (R Core Team 2013) for analysis, package ‘lme4’ (Bates et al. 2014) to fit linear mixed effect models, package ‘sciplot’ to build bargraphs, package ‘ggplot2’ (Wickham 2009) to build regression plots, and package ‘lmerTest’ (Kuznetsova et al. 2014) for least squares means comparisons, confidence interval estimates, and inferences about regression coefficients.

## Results

### Impact of Conditioning Phase Biomass and Nutrient Status on Response Phase Plant Growth

There was no evidence of a relationship between the biomass produced during the conditioning phase and the biomass harvested at the end of the response phase for either wheat ( $p = 0.44$ ), *A. retroflexus* ( $p = 0.064$ ), or *A. fatua* ( $p = 0.45$ ); regardless of inoculum source or type, conditioning species identity, or competitive status. Therefore, conditioning phase biomass was excluded as a covariate from all further analyses. The inclusion of Olsen/Bray P or K as covariates of the wheat biomass harvested at the end of the response phase increased the model deviance, indicating that these variables did not help explain the observed results. As expected, there was a positive relationship between  $\text{NO}_3^-$  concentration at the end of the conditioning phases and wheat biomass harvested during the response phase ( $p = 0.0007$ ). Pots that received the biologically-active inoculum had 1.71 times more  $\text{NO}_3^-$  available in them than those receiving the sterilized inoculum (95% CI = 1.47 – 1.99), and  $\text{NO}_3^-$  levels were similar between farming systems [ $\chi^2(1) = 1.5575$ ,  $p = 0.21$ ]. While pots that had received a biologically-active inoculum and were conditioned by *A. retroflexus* had 1.56 times more  $\text{NO}_3^-$  (95% CI = 1.32 – 1.84) than those conditioned by *A. fatua*, there were no differences in  $\text{NO}_3^-$  levels between conditioning species in pots that received sterile inoculum ( $p = 0.52$ ), resulting in an interaction between inoculum type and conditioning species identity [ $\chi^2(1) = 10.156$ ,  $p = 0.0014$ ].

Weed Growth and Weed  
Responses to Plant Soil Feedbacks

During the response phase, the identity of the conditioning phase species impacted *A. fatua* and *A. retroflexus* growth differently depending on the inocula type (Table 3.1a, b). Also, the effect of farming system on *A. retroflexus* growth depended on the inocula type (Table 3.2b). Generally, pots with biologically-active inoculum produced more plant biomass than did those with a sterilized inoculum, regardless of the inoculum source (Fig. 3.1a-e). In biologically active soils, *A. fatua* grew 1.23 times more biomass (95 % C.I. = 1.09 – 1.39) when conditioned by *A. retroflexus* compared to *A. fatua* conditioned soils, but no differences were observed between conditioning species treatments in sterilized treatments (Fig. 3.1a). There was no effect of farming system on *A. fatua* growth, regardless of inocula type, with differences found only between inocula type (Fig. 3.1b). In biologically active soils, *A. retroflexus* grew 2.40 times more biomass (95% C.I. = 1.88 – 3.06) when conditioned by conspecifics, yet no differences were found in sterile inoculated treatments (Fig. 3.1c). Further, *A. retroflexus* grown in biologically active soils from organic farms grew 1.86 times more biomass (95% C.I. = 1.33 – 2.59) than conventional soils, but the inocula source had no impact on weed growth in sterilized treatments (Fig. 3.1d).

In accordance with the biomass results, PSFs observed in *A. fatua* were 1.23 times more positive (95 % C.I. = 1.04 – 1.46) following heterospecific than conspecific growth (Fig. 3.1e), but there was no evidence that PSFs differed between farming systems (Table 3.2a; Fig. 3.1f). For *A. retroflexus*, species identity during the conditioning phase and farming systems altered PSFs, with no interactions between these variables (Table 3.2b).

Specifically, *A. retroflexus* PSFs were 2.1 times more positive (95% CI = 1.48 – 2.86) in conspecific conditioned soils versus *A. fatua* conditioned soils (Fig. 3.1g). In addition, *A. retroflexus* PSFs observed in pots that had received the inoculum collected from organic farms were 1.9 times more positive (95% C.I. = 1.06 – 3.56) than those from conventional farms (Fig. 3.1h).

#### Wheat Growth and Responses to Plant Soil Feedbacks

During the response phase, the conditioning phase species identity, competitive status treatments, and effect of farming system all interacted with the inocula type in determining wheat biomass (Table 3.1c). *Avena fatua* reduced wheat biomass by 27% (95% C.I. = 18% - 35%) in pots that had received a biologically-active inoculum, yet sterilized inoculated treatments showed no difference (Fig. 3.2a). *Amaranthus retroflexus* did not affect wheat biomass (95% C.I. = -7% - 10%), when compared to the wheat monoculture (Fig. 3.2a). Regardless of conditioning species identity or response phase competitive status, wheat always grew more biomass in soils that received a biologically-active inoculum collected from organic farms, with biomass 31% (95% C.I. = 14% - 48%) greater than those plants that received inoculum collected from a conventional farm (Fig. 3.2b).

Similar to the biomass results, farming systems and competitive status during the response phase altered PSFs observed in wheat, but no significant effects of conditioning species identity were found (Table 3.2c). When growing in competition with *A. fatua*, PSFs observed in wheat were more inhibitory (95% C.I. = 0.68 - 0.89) than when grown

in monocultures (Fig. 3.2c). In contrast, wheat competing with *A. retroflexus* had similar PSFs as those observed in wheat monocultures (Fig. 3.2c). Finally, wheat PSFs were 1.3 times more positive when pots received the inoculum from organic farms when compared to conventional farms (95% C.I. = 1.17 - 1.46) (Fig. 3.2d).

We further evaluated the extent to which competitive status (wheat monoculture, wheat – *A. fatua* mixture, or wheat – *A. retroflexus* mixture) interacted with farming system (organic vs. conventional) in determining PSFs (Fig. 3.2e). Competitive interactions resulted in lower wheat biomass, but the strength of these competitive interactions varied between organic and conventional systems. In pots where *A. fatua* and wheat competed for resources and had received inocula from organic farms, wheat PSFs were 1.3 times (95% C.I. = 1.06 – 1.56) more positive than those receiving inocula from conventional farms. Similarly, PSFs for wheat growing in competition with *A. retroflexus* were 1.5 times more positive when the inoculum originated from organic farms compared to the PSFs observed with inoculums collected from conventional farms (95% C.I. = 1.21 – 1.77).

#### Impact of Weeds and PSFs on Competitive Intensity Across Cropping Systems

There was no relationship between competitive intensity (i.e., lnRR) and *A. fatua* biomass ( $p = 0.93$ ,  $df = 91$ ), including no two- or three-way interactions with conditioning species identity or farming system (Fig. 3.3a). For wheat under competition with *A. retroflexus*, the relationship between competitive intensity and weed biomass depended on the interaction between farming system and conditioning species identity ( $p$



= 0.028) (Fig. 3.3b). In *A. retroflexus* conditioned soils that had received a conventional farm inoculum, competition intensity increased with higher weed biomass ( $p = 0.0004$ ,  $df = 85$ ), but there was no evidence of this relationship in organic inoculated soils ( $p = 0.28$ ,  $df = 82$ ). In *A. fatua* conditioned soils, there was no evidence of a relationship between competition intensity and *A. retroflexus* biomass, regardless of farming system.

The relationship between competitive intensity and PSFs did not differ between farming systems or conditioning species identities, regardless of the competitive status treatment (Figs. 3.3c and 3.3d). For the *A. fatua* competition treatments, the relationship between competitive intensity and PSFs was negative ( $p = 0.02$ ,  $df = 89$ ), where a doubling of PSFs was associated with 1.2 times less competitive intensity (95% CI = 1.03 - 1.35). Similarly, there was a strong negative relationship between competitive intensity and PSFs for *A. retroflexus* competition treatments ( $p < 0.0001$ ,  $df = 86$ ), where a doubling in PSFs was associated with 1.3 times less competitive intensity (95% CI = 1.15 to 1.48). There were no overall differences for the effects of farming system or conditioning species identity for either competition treatment, and we generally observed shifts from competition ( $\ln RR > 0$ ) to facilitation ( $\ln RR < 0$ ) as PSFs became more positive.

## Discussion

There is growing interest in manipulating farm management practices to enhance soil biological characteristics in ways that positively impact agroecosystems (Brussaard, de Ruiter & Brown 2007, Tiemann et al. 2015). However, while progress has been made

in determining the role of soil biota in weed invasiveness (Wolfe and Klironomos 2005), little is known about the impacts of increased cropping system diversification on PSFs and crop-weed interactions. In our study, wheat biomass production was enhanced in pots that were inoculated with biologically-active soils, highlighting the importance of soil biota in determining plant growth. Additionally, PSFs were more positive when the biologically-active inoculum was collected from organic farms than from conventional farms, suggesting that cropping systems modify the relative abundance of mutualistic and pathogenic organisms (Matson 1997).

Our results provided evidence that PSFs translated into an increased ability of wheat to tolerate weed competition when growing in soils that had been inoculated with soil biota from organic farms compared to conventional. Wheat competing with *A. fatua* in organic inoculated soils performed equally well as wheat monocultures growing in pots that had received the conventional farm inoculum. For competition with *A. retroflexus*, wheat in pots that received inoculum from organic farms produced more biomass than in wheat monoculture pots that received inocula from conventional farms. Furthermore, for both *A. fatua* and *A. retroflexus*, as PSFs became more positive, competition decreased and facilitation increased. These results demonstrate that PSFs can act as drivers of crop and weed growth as well as competitive interactions in agricultural systems as proposed in the RPDH (Smith et al. 2010).

A caveat from this study is that it does not allow us to draw conclusions on the specific changes in soil biota responsible for the observed results. Yet, it is possible to speculate on the relative impact of management practices associated with organic and

conventional farming on the magnitude and impacts of PSFs. Mechanical practices like tillage, commonly used in organic farming systems, have been associated with a decrease in microbial biomass and earthworm populations (Karlen et al. 1994), as well as a decrease in microbial diversity (Lupwayi et al. 1998). Yet organic farms often have increased weed diversity (Menalled, Gross & Hammond 2001; Pollnac, Maxwell & Menalled 2009) and higher plant diversity has been linked with increased microbial biomass (Thakur et al. 2015), respiration, and fungal abundance (Zak et al. 2003). On the other hand, agriculture intensification with fertilizers and herbicides, a staple practice in no-tillage conventional farming, has a negative impact on meso- and macro-biota in the short term, and microbiota over time (Postma-Blaauw et al. 2010). This is in spite of N addition possibly increasing PSFs (Manning et al. 2008), and is likely mediated through simplified plant communities and long-term loss of organic matter. Crop rotations also differed between farming systems, with the organic farms having diverse rotations and the conventional farms all followed wheat-fallow rotations. In accordance, previous studies have demonstrated that diverse crop rotations increase the diversity of soil biota (Lupwayi et al. 1998), and new research is pointing to other possible mechanisms for negative feedbacks such as self-DNA autotoxicity from plant litter (Mazzoleni et al. 2015). Nonetheless, organic versus conventional changes in soil biota differ with landscape complexity (Flohre et al. 2011), and future studies should distinguish determining factors.

Worldwide, the landscape homogeneity of extensive monocultures that characterizes conventional industrially-managed small grain cropping systems has resulted

in the development of specialized pest complexes and an associated heavy reliance on off-farm synthetic inputs to control them. Alternatively, encouraging positive biotic interactions, while maintaining acceptable levels of production are key components of ecologically-based cropping systems. Overall, our results show that PSFs can play an important role in mediating plant growth and crop-weed competition in agroecosystems and indicate that diversified organic cropping systems are associated with more positive PSFs. As such, this study suggests that by identifying the management practices that promote positive PSFs for crops and minimize the impacts of crop-weed competition, producers can decrease their reliance on off-farm chemical and mechanical inputs to control weeds and enhance the economic and environmental sustainability of their enterprise. Biotic interactions in agroecosystems are complex and future research should explicitly address the specific mechanisms driving the observed results, including the effects of rotational diversity, weed management technique, and weed diversity on PSFs and crop-weed competition.

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Table 3.1. Impact of conditioning species identity, farming systems, inocula type, competitive status, and their interactions on (a) *Avena fatua*, (b) *Amaranthus retroflexus*, or (c) wheat (*Triticum aestivum*) biomass of plants growing in pots that received a sterilized inoculum and biologically-active inoculum. Data were analyzed with a likelihood ratio tests using backwards elimination. The saturated model includes all possible main effects and interactions.

(a)						
Source	Df	logLik	Deviance	Chisq	Chi Df	Pr(>Chisq)
Farming system (S)	10	-62.02	124.04	1.91	1	0.17
Conditioning phase spp. (C)*I	10	-63.45	126.90	4.77	1	0.029
S*Inocula type (I)	11	-61.07	122.13	0.20	1	0.66
S*C	12	-60.97	121.93	1.86	1	0.17
S*C*I	13	-60.04	120.07	3.11	1	0.078
Saturated model	14	-58.48	116.96			
(b)						
Source	Df	logLik	Deviance	Chisq	Chi Df	Pr(>Chisq)
C*I	11	-184.70	369.39	18.15	1	<0.0001
S*I	11	-178.96	357.93	6.69	1	0.0097
S*C	12	-175.62	351.24	0.02	1	0.89
S*C*I	13	-175.61	351.22	0.17	1	0.68
Saturated model	14	-175.52	351.05			
(c)						
Source	Df	logLik	Deviance	Chisq	Chi Df	Pr(>Chisq)
C*I	15	326.95	-653.89	6.59	1	0.010
Competitive status (R)*I	14	317.47	-634.95	25.54	2	<0.0001
S*I	15	327.21	-654.42	6.06	1	0.014
S*C	16	330.24	-660.48	2.87	1	0.090
R*C	17	331.68	-663.35	0.41	2	0.81
S*R	19	331.88	-663.76	2.27	2	0.32
R*C*I	21	333.01	-666.03	1.44	2	0.49
S*C*I	23	333.74	-667.47	1.08	1	0.30
S*R*I	24	334.27	-668.55	2.98	2	0.23
S*R*C	26	335.76	-671.52	2.00	2	0.37
S*C*R*I	28	336.76	-673.52	0.15	2	0.93
Saturated model	30	336.84	-673.68			

Table 3.2. Impact of conditioning species identity, farming systems, competitive status, and their interactions on plant soil feedbacks (PSFs) observed on (a) *Avena fatua*, (b) *Amaranthus retroflexus*, or (c) *Triticum aestivum*. Data was analyzed with a likelihood ratio tests using backwards elimination. The saturated model includes all possible main effects and interactions.

(a)						
Source	Df	logLik	deviance	Chisq	Chi Df	Pr(>Chisq)
Conditioning phase spp. (C)	7	-59.65	119.31	5.68	1	0.017
Farming system (S)	7	-56.94	113.89	0.26	1	0.61
S * C	8	-56.82	113.63	2.88	1	0.090
Saturated model	9	-55.38	110.75			
(b)						
Source	Df	logLik	deviance	Chisq	Chi Df	Pr(>Chisq)
Conditioning phase spp. (C)	7	-124.76	249.53	17.40	1	<0.0001
Farming system (S)	7	-118.85	237.70	5.57	1	0.018
S * C	8	-116.06	232.13	0.08	1	0.78
Saturated model	9	-116.02	232.05			
(c)						
Source	Df	logLik	deviance	Chisq	Chi Df	Pr(>Chisq)
Conditioning phase spp. (C)	9	-197.27	394.54	0.30	1	0.59
Competitive status (R)	8	-205.67	411.35	17.10	2	0.0002
Farming system (S)	9	-202.27	404.53	10.29	1	0.0013
R * C	10	-197.12	393.25	0.98	2	0.61
S * C	12	-196.63	393.27	0.23	1	0.63
S * R	13	-196.52	393.03	2.23	2	0.33
S * C * R	15	-195.40	390.81	0.41	2	0.81
Saturated model	17	-195.20	390.39			

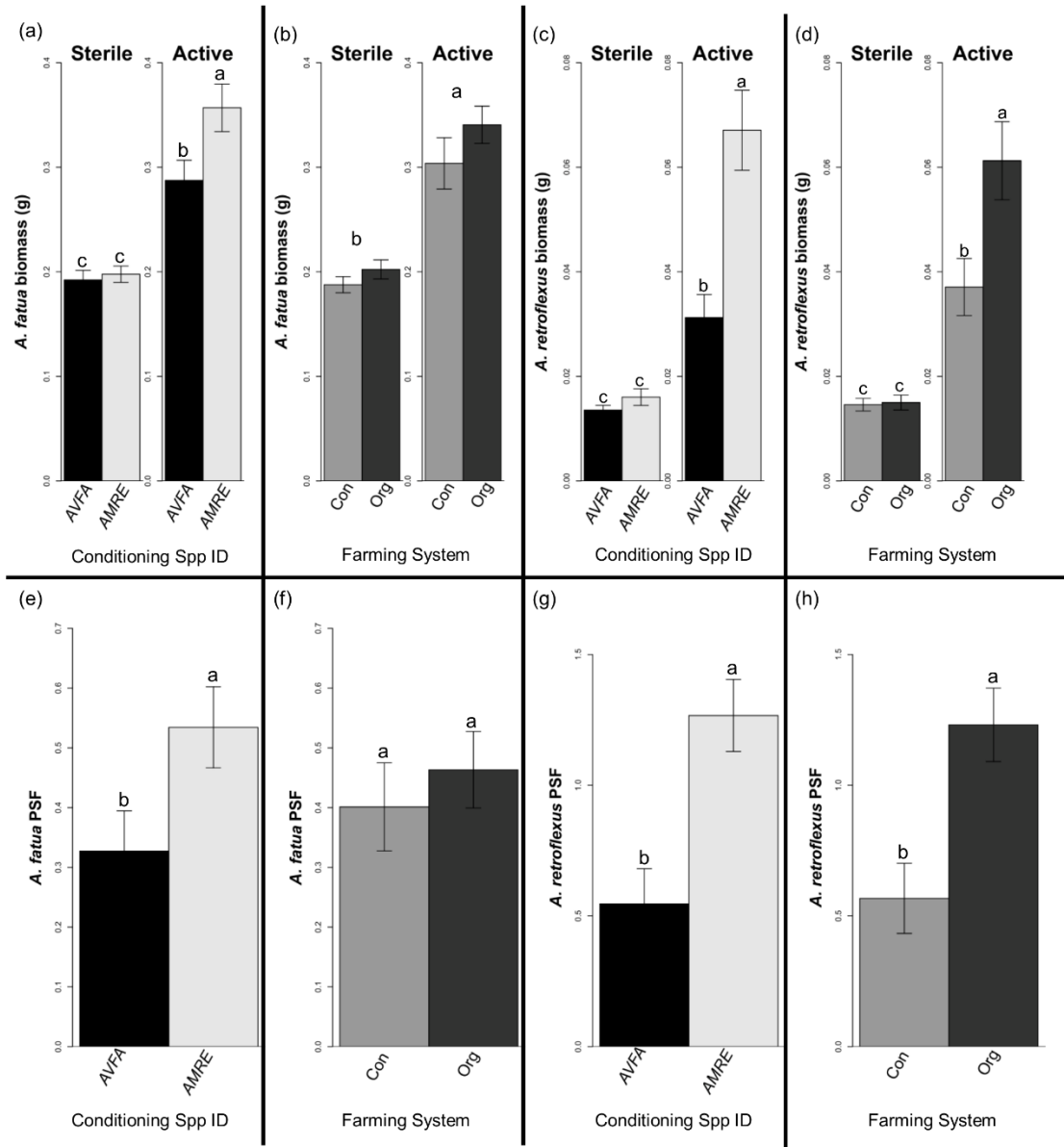


Fig. 3.1. Biomass (mean  $\pm$  SE) of sterile and living inoculated pots, and plant soil feedback (PSF) (mean  $\pm$  SE) produced during the response phase. *Avena fatua* biomass as a function of conditioning species identity (a) and farming system (b); *Amaranthus retroflexus* biomass as a function of conditioning species identity (c) and farming system (d); *A. fatua* PSF as a function of conditioning species identity (e) and farming system (f); *A. retroflexus* PSF as a function of conditioning species identity (g) and farming system (h). Letters indicate differences ( $p < 0.05$ ). Comparisons were made on natural-log transformed data for *A. fatua* and *A. retroflexus*, but raw data are presented. Con = conventional and Org = organic. AVFA = *A. fatua* and AMRE = *A. retroflexus*.



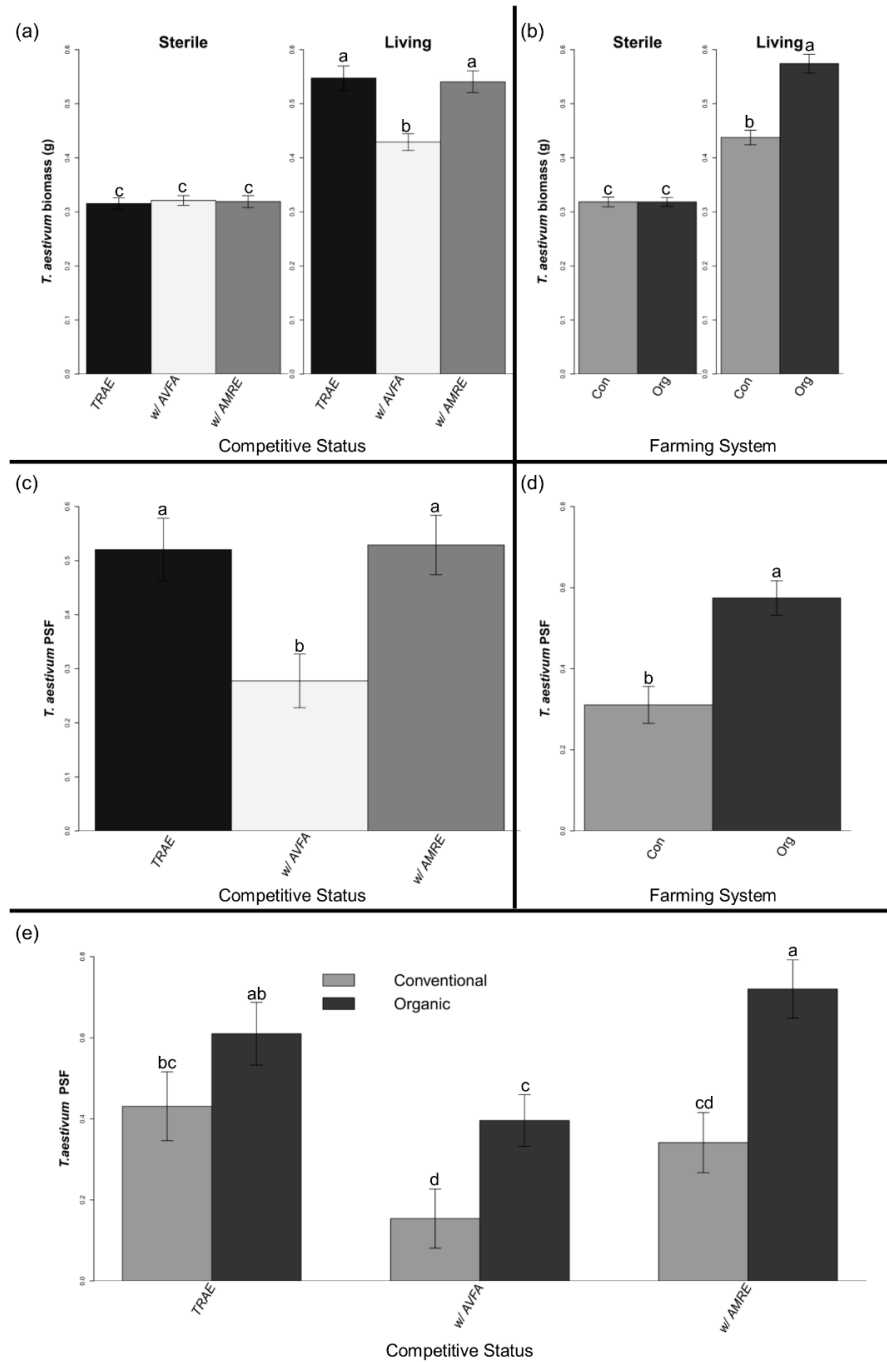


Fig. 3.2. Wheat (*Triticum aestivum*, TRA/E) biomass (mean  $\pm$  SE) and plant soil feedback (PSF) (mean  $\pm$  SE) observed during the response phase as functions of competitive status treatments (a) and (c), farming systems (b) and (d), and the interactions (e). Letters indicate differences ( $p < 0.05$ ). Con = conventional and Org = organic. AVFA = *Avena fatua* and AMRE = *Amaranthus retroflexus*.

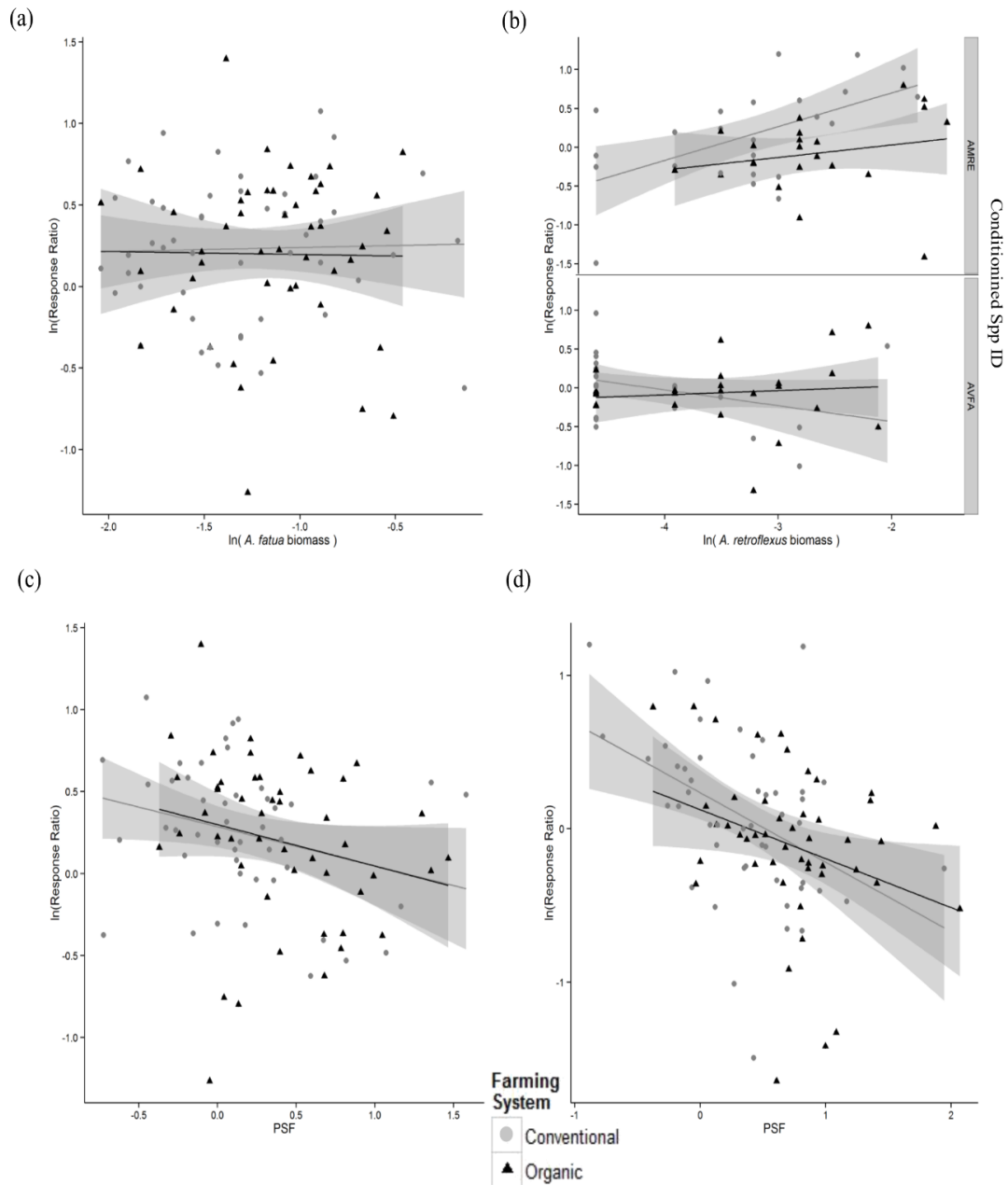


Fig. 3.3. Regression of wheat (*Triticum aestivum*) competition intensity with *Avena fatua* (a) and *Amaranthus retroflexus* biomass separated by conditioning species treatments (b). Competition intensity and plant soil feedbacks (PSF) for wheat in competition with *A. fatua* (c) and *A. retroflexus* (d). Competition strength is denoted by the natural logarithm of the response ratio of wheat grown in monoculture compared to wheat grown in competition. Gray shading around the mean lines represents one standard error. AMRE = *A. retroflexus* and AVFA = *A. fatua*.

Supporting Information

Additional Supporting Information may be found in the online version of this article:

Table S1. Site descriptions for farms sampled.

Fig. S1. Site locations for farms sampled.

Table 3.S1. Site descriptions, agronomic practices, crop rotation, weed community characteristics, and nutrient results from bulk soil used to assess the importance of biologically mediated plant soil feedbacks on wheat growth and competitive interactions.

Location (Montana, USA)	Mean Max / Min Temp. (C)*	Mean Annual Precipitatio n*	System	Rotation	Herbicide	Tillage	Weed Species Richness §	Simpson Diversity (1-D) §	Soil Class	pH	OM (%) ¶	Soil Characteristics ‡					CEC (Meq/ 100g)
												NO <sub>3</sub> <sup>-</sup> (ppm)	Olsen-Bray P (ppm)	K (ppm) ¶	Ca (ppm)	Mg (ppm) ¶	
Big Sandy	14.8 C / -1/2 C	325 mm	Organic	<i>Pisum sativum</i> , <i>Triticum turanicum</i> , <i>Melilotus officinalis</i> , <i>T. turanicum</i> , <i>P sativum</i> , winter wheat	None.  Organic for 20+ years	Yes	10	0.76	Telstad- Joplin loams	6.3	2.3	2.5	6	328	1444	420	11.6
			Conven- tional	Winter wheat, fallow	Yes	No	15	0.66	Telstad Joplin loams	6.3	1.8	1.5	12	274	1513	351	11.2
Dutton	14.1 C / -0.9 C	295 mm	Organic	Spring wheat, <i>M. officinalis</i> , <i>Linum usitatissimu</i> m , <i>Triticum spelta</i> , <i>T. turanicum</i>	None. Organic since 2009	Yes	13	0.49	Tanna clay loam/Megon osilty clay loam	7.8	3.9	7.5	11	440	4322	546	27.3
			Conven- tional	Winter wheat, fallow	Yes	No	5	0	Megonot silty clay loam	7.8	2.8	5	17	401	3720	452	23.4
Lewistown	12.9 C / -0.9 C	388 mm	Organic	<i>Onobrychis viciaefolia</i> . Spring wheat	None. Organic for 20+ years.	Yes	16	0.68	Tamaneen- Judith clay loams	7.2	4.5	6	23	455	3054	433	20.1
			Conven- tional	Winter wheat, fallow	Yes	No	2	0.03	Tamaneen clay loam	7.5	4	3.5	17	336	4453	197	24.8
Havre	12.9 C / -2.7 C	265 mm	Organic	<i>Hordeum vulgare</i> , <i>M. officinalis</i> , <i>Lathyrus sativa</i> , spring wheat, winter wheat	None. Organic since 2009	Yes	13	0.46	Telstad- Joplin loams	7.2	2.4	1	9	385	2516	662	19.1
			Conven- tional	Winter wheat, fallow	Yes	No	4	0.02	Telstad- Joplin loams	7.1	1.5	3.5	13	232	2340	336	15.1

§ Weed species richness = total number of species. Simpson's diversity index  $D = \frac{1}{\sum p_i^2}$ , where  $p_i$  is the proportion of species  $i$ , and  $s$  is the number of species

‡ OM = organic matter, P = phosphorous, K = potassium, Ca = calcium, Mg = magnesium, CEC = cation exchange capacity

¶ Differences found between organic and conventional soil nutrient samples (t-test on 3 df): OM (p = 0.029), K (p = 0.057), Mg (p = 0.058)

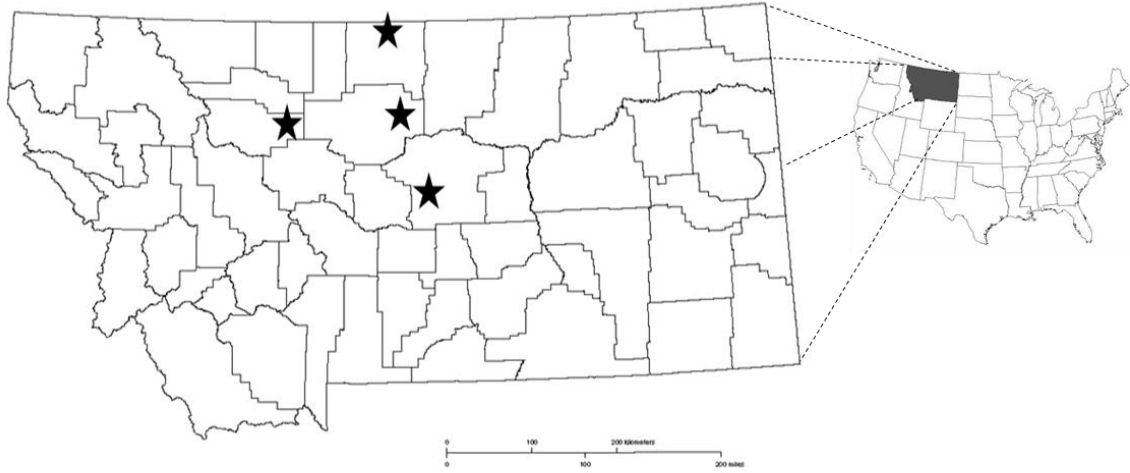


Fig. S1. Site locations for pairs of organic and conventional farms sampled in Montana, USA, for soil inocula used to assess the impacts of biotic plant-soil feedbacks on crop growth and crop-weed competition.

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## CHAPTER FOUR

SUMMARY OF FINDINGS  
AND FURTHER RESEARCH

With an increased global population and demand for food, fiber, and energy; agriculture must balance increased productivity with ecosystem services and sustainability (Tilman et al. 2002, Robertson and Swinton 2005). Agroecologists have done this by using a systems-oriented perspective that looks at the farm as a complex ecosystem (Cassman 1999, Robertson and Swinton 2005, Robertson et al. 2014). My research has added to the growing body of literature on the application of animal-integrated farming systems for cover crop and residue management (Russelle et al. 2007, Plachter et al. 2010, Franzluebbbers et al. 2012), although more research for farmers in Montana and the Northern Great Plains (NGP) is warranted (Thiessen Martens and Entz 2011). Further, we investigated the ecological consequences of animal-integration on weed communities and the impact of cropping systems on crop-weed competitive interactions.

Results indicated that organic farmers interested in using sheep to terminate cover crops, manage weeds, and reduce the number of tillage passes can expect similar yields in subsequent crops during the transition phase, although investments in proper seeding equipment may be necessary, and better understanding of timing and grazing intensity on near-surface soil compaction. Our on-farm trials were complicated by high weed pressure and improper seeding, however we did not find differences in weed

communities or pressure between grazed and tilled treatments. Weed community differences may become more apparent over time between these two systems, which warrants long-term studies. In addition, at current market prices and the forage quality of the tested farm, growers leasing their land under a grazing lease would have brought in approximately \$27 ha<sup>-1</sup> in 2013 and \$44 ha<sup>-1</sup> in 2014.

Our on-farm trial was complemented by a larger study on a research and extension-center. This allowed us the opportunity to implement a long-term study comparing traditional tillage-based organic to reduced-tillage organic with animal-integration, as well as to benchmark these organic systems with respect to a no-till conventional system with fertilizer and pesticide inputs. All three systems were constrained to the same crop rotation, which gave us the opportunity to simply compare systems-level responses in crop agronomics and well as weed community shifts. There were no differences in cover crop growth and subsequent winter wheat yielded the same among all three systems during the transition phase; however it is apparent that in 2015, the first year of certified organic production, winter wheat yields were much lower in the grazed organic than in the other two systems. During transition, all three systems had high protein levels, however, in 2015, protein concentrations for the organic systems were low (<11%) with respect to conventional no-till winter wheat with grain protein near 14%. Still, Organic systems did cycle more residue C and N through chaff back into these soils which may have long-term impact on organic matter and future mineralization of nutrients. These results indicate that organic producers can expect similar or better yields and grain quality in transitioning to organic, yet shortcomings of these systems

may be more apparent after this short period, especially in terms of soil quality parameters and the presence of perennial weeds such as *Taraxacum officinale* F.H. Wigg. Further, integrating grazing leases provides an opportunity to subsidize the costs associated with herbicide application or tillage. In 2013, growers could expect approximately \$43 ha<sup>-1</sup> from a grazing lease, and in 2014, \$48 ha<sup>-1</sup>.

The use of tillage, herbicide, fertilizer, or grazers all can act as different ecological filters on weed communities (Funk et al. 2008). However, we found little evidence that weed communities differed among the three management systems in the transition to organic period. Generally, shifts occurred across all system from one crop to the next, indicating yearly fluctuations with cropping sequence diverged weed communities more than divergent tillage and weed management practices. Nonetheless, there was some indication that weed communities were starting to diverge, mainly separating the conventional no-till system from the two organic systems, although preliminary 2015 data indicates that the two organic systems may differ as well with higher weed pressure in the grazed-organic systems. In transitioning to organic, growers integrating targeted grazing can expect similar weed communities and pressure as found with tillage-based management, but long-term impacts of reducing tillage on organic farms may result in different weed control problems.

Studies that have integrated sheep grazing have noted an increase in perennial weed species (Renne and Tracy 2013, Miller et al. 2015b). We did find that *Taraxacum officinale* did appear to increase in periods of no-tillage (2013 safflower to 2014 sweet clover) for all systems. The largest abundance of this weed, however, was found in 2014

winter wheat following Austrian winter pea in grazed organic systems. Otherwise, perennial abundances were more variable under each management system, and further research is needed to investigate long-term effects of each management system on perennial weed communities.

Despite advances in understanding the ecology of weeds in agricultural systems, weed science has been primarily focused on developing chemical and mechanical methods to minimize weed abundances rather than assessing the mechanisms driving crop-weed competitive interactions (Ward *et al.* 2014). Weed management needs to be analyzed from a systems-oriented perspective (Barberi 2002), and weed biology and ecology may play more important roles in agro-ecosystems than previously realized (Petit *et al.* 2011). Therefore, we implemented a greenhouse study that investigated the impact of organic and conventional management systems on crop growth and crop-weed interactions as mediated through plant-soil feedbacks (PSFs). We not only found that inoculating plants with living soils was integral to improved plant growth, but wheat and weeds grew better in inoculated with soils from organic farms. Further, even while under competition with other weeds, wheat still grew better in organic inoculated soils compared to conventional, supporting the Resource Pool Diversity Hypothesis (Smith *et al.* 2010). Our results indicate that cropping system diversification results in increased niche differentiation and resource partitioning which, in turn, translates to reduced yield loss from crop-weed competition. Future studies should investigate the mechanisms that drive difference in plant soil feedbacks, and which farming management practices enhance those mechanisms.

Overall, this research has increased our understanding of the application of reduced tillage-based organic systems that use animal integration as another tool for cover crop termination, and residue and weed management in the NGP. We used an applied approach that allowed us to ask more complex ecological questions concerning weed communities and crop-weed interactions. Cropping diversification and animal-integration have known agro-ecological benefits, but obstacles still arise when implemented in the dryland growing regions of the NGP. We hope this research has both served to begin to answer applied questions for practitioners interested in reducing tillage or integrating animals, as well as instilled an interest in below-ground biological components that may be assessed to increase the sustainability of their farm ecosystems.

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