STRATEGIES FOR WEED MANAGEMENT IN ORGANIC PRODUCTION SYSTEMS IN THE NORTHERN GREAT PLAINS

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Strategies for Weed Management in Organic Production Systems in the Northern Great Plains

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ABSTRACT

Two field studies were conducted in North Dakota to explore methods to facilitate weed management in organic production systems. No-till farming is gaining popularity in conventional systems; however, organic producers often rely on tillage for weed control. We hypothesized that the addition of sheep grazing into an organic no-till annual production system with roller crimped cover crops would aid weed management. Despite the grazing treatment, the no-till system resulted in greater weed biomass and increased yield loss compared to a tilled system. Weed community composition differed between no-till and conventionally tilled treatments. A second study was conducted to explore alternatives to plastic mulch in perennial strawberry production systems by testing two novel mulch materials, paper and hemp hurd. Both materials were found to meet or exceed the ability of hay mulch, a commonly used mulching product, to suppress weed emergence.

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CHAPTER 1. REALIZED AND POTENTIAL WEED COMMUNITIES AS AFFECTED BY CONTINUOUS ORGANIC NO-TILL PLUS GRAZING

Abstract

Organic producers rely on the efficacy of tillage for weed management, yet could benefit from outcomes associated with no-till. In the Northern Great Plains (NGP) developing these systems has been difficult due to a cooler climate. It was hypothesized that incorporating sheep grazing into a continuous no-till annual cropping system with retained cover crops using a roller-crimper might better adapt no-till to the NGP. Crop yield and weed communities were sampled by conducting yield loss assessments, biomass harvests, and seed bank assays. Analysis of variance and multivariate analyses were used to detect differences between no-till with grazing and clean-till systems. In most instances, weed biomass and yield loss were greater under no-till management. Above-ground and seed bank analyses demonstrated divergent communities between management systems. After four years, no-till management resulted in a more diverse weed seed bank while clean-till was associated with greater seed bank density.

Introduction

Organic Grain Production

Growth in the organic market necessitates an increase of research to aid production in this niche sector. According to the Nutrition Business Journal, organic sales in the U.S. increased $12.4 billion from 2005 to 2011, and projections for 2014 demand totals $34.8 billion (USDA-ERS 2017). Diverse ranges of U.S. consumers are increasingly interested in organic foods and products, creating a marketplace in which these goods are in great demand (Dimitri 2002). Responding to consumer interest and sales and acreages increases the U.S. Congress passed the Agricultural Act of 2014, expanding funding in several areas of the organic production sector (USDA-ERS 2016). In the U. S., certified organic cropland has increased from 1.2 million acres in 2000 to 3.1 million acres in 2011; acreage in North

Dakota has remained stable during that same 11-year span, averaging ~136,000 acres (USDA-ERS 2011). This expanding market is an opportunity for certified organic growers to increase profits and an increase of research in this sector may aid in modernizing and improving production practices.

The U.S. Department of Agriculture, National Organic Program (USDA, NOP) sets standards for certified organic production, which encompass every process a producer undertakes, from procurement of seed to end-product labeling. Many inputs used in the management of conventional cropping systems cannot be used for certified organic crop production (Coleman 2012). Constraints placed on certified organic crop production prevent producers from using most synthetic fertilizers and pesticides; this pushes organic producers to approach land management in an ecological manner.

Weed Communities in Organic Systems

One of the greatest challenges organic farmers face is managing weeds without synthetic herbicides (Coleman 2012). By comparing conventional and organic cropland, Barberi et al. (1998) suggested that herbicide use coupled with tillage is needed to maintain, rather than increase, seed bank densities. Organically-managed annual crop fields often contain more dense and diverse weed populations than conventional fields (Koocheki et al. 2009; Vaisman et al. 2011). Compared to animal and pathogen pests, weeds account for the greatest production losses, which were reported to be 34% (Oerke 2006). In the long term, successful weed control is crucial as effects of weed populations carry over from year to year.

Even with these challenges, scientists have speculated that at similar weed densities organic production systems are able to maintain similar yields as conventional systems (Lehnhoff et al. 2017). Ryan et al. (2009) found that relationships between weeds and crops differ between organic and conventional management systems. Crop yields resulting from organic and conventional management were similar despite the organic management system producing up to six times greater weed biomass than the conventional system (Ryan et al. 2009). This result suggests that crops grown in organic systems may be better able to tolerate greater weed presence, possibly due to differences in resource acquisition dynamics in a community.

Niche differentiation is a broad term used to explain the function of ecosystems with respect to diversity and competition whereas resource partitioning is the aspect of niche differentiation concerned with plant utilization and acquisition of resources in a system. Species which are able to utilize resources in different forms or at different times or in spatial locations are able to coexist as resource acquisition as direct competition is reduced. There are two major theories regarding the effect of species on their immediate environment: selection effect (species dominate due to traits) and complementarity effect (diversity due to resource partitioning) (Loreau and Hector 2001). In an effort to divide these effects, Loreau and Hector (2001) used evolutionary biology concepts and found support for resource partitioning within European grasslands; the selection effect was not supported. The resource pool diversity hypothesis (RPDH) model developed by Smith et al. (2009) explains outcomes of weed-crop competition on the diversity of resource niches. Simplified system treatments, like growing a monocrop or applying a synthetic mineral fertilizer, provide little niche differentiation and, thus, plants undergo intense competition for resources, even if weed presence is kept low (Smith et al. 2009). Comparatively, diverse systems with varied rotations or that use composted waste as fertilizer, provide plants with varied resource niches and promote diversity which, in turn, minimizes the impact of weed infestations while maintaining crop yield (Smith et al. 2009). Experimental support for this hypothesis has been mixed. Poffenbarger et al. (2015) found limited support for N partitioning in a pot experiment, but overall concluded that soil fertility properties as influenced by organic vs. conventional management did not affect N resource partitioning. Similarly, Benaragama et al. (2016) discovered that organic yields were 44% lower than conventional system yields, regardless of crop rotation diversity, and even within a weed free environment. Differences in soil productivity related to the types of amendments used in organic systems were cited as a reason that some reported yields are similar between organic and conventional systems (Benaragama et al. 2016). Further research is required to fully explore the RPDH.

Weed Management Tactics for Organic Systems

A combination of management tactics, dubbed "many little hammers" by Liebman and Gallandt (1997) is considered the most successful overall strategy for weed control in organic systems. Specifically, practices focused on prevention and suppression of weeds using mechanical, biological, and cultural methods are widely used in certified organic systems (Coleman 2012). Previous weed management research in organic production systems has verified the efficacy of a variety of effective non-chemical weed control options (Bond and Grundy 2001). However, efficacy of weed management in organic systems often does not equate to the weed-free environment generally achieved with broad spectrum herbicide applications in conventional production systems; however, does provide yield protection. Information regarding the implementation of some of these strategies in the northern Great Plains (NGP) is lacking. However, one study evaluating weed management strategies used by organic producers revealed that most Midwest organic producers employ on average, 15 different weed management tactics, the most prevalent being crop rotation, tillage, and cover cropping (DeDecker et al. 2014). Because a lack of information regarding management strategies impedes growers from utilizing these weed management strategies, researchers are charged with furnishing information by developing studies to understand weed population dynamics as influenced by various management systems (DeDecker et al. 2014; Bastiaans et al. 2008).

Ecologically-based weed management is concerned with autecology (the relationship between a species and its environment), community ecology (the relationship between individual plants), and systems ecology (the interaction of plants and environments e.g., the flow of nutrients) (Liebman and Gallant 1997). This approach can be compared to strategies of crop production that rely on a single weed control tactic (i.e., 'one size fits all') (e.g., herbicide resistant crops), while disregarding the factors that differ between production sites. A systems approach to weed management relies on ‘ecological filters’. By imposing selection pressure which favors certain species over others, management tactics determine the size and structure of the weed community (Barroso et al. 2015; Froud-Williams 1988). For example, summer annual species seedlings will attempt to establish early in the spring, if the crop being grown is a winter annual or perennial, there are few management options for control; however, if a spring-sown crop is being produced, management options, like tillage or hand weeding, are available. Integrated pest management (IPM) is associated with alternative management systems and is concerned with insect pests, plant diseases, as well as weeds (although IWM, integrated weed management is specific to weed control), namely via prevention and monitoring (EPA 2016). Both IPM and ecologically-based weed management are long-term investments and according to Buhler et al. (2000), farmer use of IPM is hindered by the focus being on short-term gains vs. on long-term sustainability. To expand the current limited use of integrated approaches, Bastiaans et al. (2008) discussed a shift toward “tailor-made weed management strategies” in which farmer specializations or interests are incorporated and cost: benefit tradeoffs are analyzed. To provide relevant information for such custom management systems, crop-specific and region-specific research must be conducted.

<u>No-Till</u>

Tillage has long been the primary method for broad scale weed control in organic systems. Soil damage resulting from intensive tillage practices is a valid criticism of organic production systems (Gebheart et al. 1985). Conversely, no-till farming is associated with enhanced soil water infiltration and conservation, aiding in the prevention of soil erosion, and creating more stable soil aggregation (Arshad et al. 1999). Consequently, no-till farming methods have gained popularity in conventional crop production systems located in semi-arid regions where conservation of soil moisture is crucial (Lehnhoff et al. 2017). Although organic producers could benefit from these positive outcomes associated with no-till, production constraints associated with organic certification may act as barriers to managing weed populations, especially if tillage is not employed (Buhler et al. 1994).

By studying a 35-year-old tillage and crop rotation experiment, Sosnoskie et al. (2006), concluded that changes in the composition of weed seed banks are driven by disturbance, environment, and management. In a classic paper, Grime (1977) developed a triangular continuum that illustrates the way weeds react to ranges of competition, stress, and disturbance. Furthermore, Grime (1997) distinguished three weeds 'strategies' which elucidate the method by which a weed species functions: ruderal (maximize reproduction, short life span), competitive (maximize vegetative production in a minimally disturbed environment), and stress tolerant (characterized by adaptations to environmental stresses). Weed species with the same life cycle, annual, biennial, or perennial, tend to react similarly in the face of competition, stress, and disturbance (Grime 1977). Differing intensities of tillage, like moldboard plow, chisel plow, and no-till, tended to affect various weed species differently; this divergence was generally associated with species life cycle and emergence period (Mulugeta and Stoltenberg 1997).

The transition to no-till is usually marked with a shift in the weed community toward perennial and/or wind-dispersed weed species (Froud-Williams 1981). Barberi et al. (1998) found that grass weeds were more associated with a no-till system compared to tilled conventional or tilled organic systems, these being dominated by broadleaf species. In weed seed bank communities observed by Barberi and Cascio (2000), functional groups (i.e., perennial, summer annual, winter annual) did not consistently affiliate with management system after 12 years of experimental application. Domination of two summer annual grass species was cited as a barrier to discovering divergent communities (Barberi and Cascio 2000).

The conversion to no-till by organic producers has been hindered by a lack of alternative immediate weed control strategies given the duration required for IPM to be effective (Gebhardt et al. 1985). Therefore, some other means of suppressing weeds must be integrated alongside no-till when used for organic production. The development of successful no-till organic cropping systems has typically been based on integrating several management tactics that act together to suppress weeds.

Cropping Rotation and Cover Crops

If diverse crops (e.g., early vs. late season) are grown in rotation, more varied approaches and timing of field operations can be used to control a broader spectrum of weeds. However, because none of these methods completely eradicate every species, highly diverse crop rotations (e.g., spring wheat (*Triticum aestivum* L.)-winter wheat-corn (*Zea mays* L)-sunflower (*Helianthus annuus* L.)) tend to encourage a more diverse weed population compared to low diversity rotations (e.g., winter wheat-proso millet (*Panicum miliaceum* L)) (Anderson et al. 2007). For example, Anderson et al. (1998) found twice as many weed species in a diverse spring wheat-winter wheat-sunflower rotation compared with a less diverse spring wheat-fallow rotation. Consequently, Anderson et al. (2007) recommended rotating cool- and warm- season crops within a four-year cycle to successfully interrupt weed growth.

Depending on the crop species chosen, crop rotation can be an effective weed management strategy which disrupts the growth cycle of weed species (Teasdale et al. 2004). Emerging at a similar time as the crop allows the weed to escape or avoid disturbance events like tillage or planting so planting crops with differing phenology affords the producer with management options. For example, annual grasses were found to be more frequent in continuous wheat fields as compared to rotations which included corn or sugar beet (*Beta vulgaris* L.) (Koocheki et al. 2008). Year to year continuous wheat fields incurred similar events at similar times, however, addition of corn or sugar beet in to the cropping rotation necessitated divergent timing or activities. Similarly, a delay in crop termination resulted in weed populations consisting of later-emerging weeds (Mirsky et al. 2011). Anderson et al. (2007) followed best crop practices and discovered that kochia (*Bassia scoparia* (L.) A.J. Scott) and downy brome (*Bromus tectorum* L.) were more associated with a wheat-millet rotation than a wheat-fallow rotation. The water stress winter wheat was subjected to following the production of millet led to a scant winter wheat stand, demonstrating the importance of crop choice within rotations.

Growing cover crops is another ecological filter or method of weed suppression that can be combined with diverse rotations to help manage weeds in organic systems. Cover crops that are grown out of phase (i.e., not during primary growing season) with the main or cash crop risk using resources needed during the main crop phase (Kramberger et al. 2009). This risk must be compared to the impact of permitting weed growth on the same parcel with respect to resource use and seed bank contributions. Alternatively, some cover crop species may positively contribute to the environment, such as legume crops fixing soil N. Before and/or after main crop production, cover crops provide ground cover and, thus, can act as competitors with weed species (Wayman et al. 2015).

Cover crop termination is an influential factor in the success of systems employing this strategy, especially if tillage is avoided and a residue layer is required. Failure to successfully terminate a cover crop leads to regrowth and lack of weed suppression, so careful consideration is needed when choosing cover crop species and termination method (Shirtliffe and Johnson 2012; Teasdale and Mohler 2000; Feeser et al. 2014). Carr et al. (2011) demonstrated that the cover crop with the least biomass accumulation, hairy vetch (*Vicia villosa* Roth), was associated with the greatest weed growth. Furthermore, Mirsky et al. (2011) demonstrated that biomass accumulation was affected by planting and termination dates as well as cover crop type; the earliest planting date coupled with the latest termination date was associated with the greatest biomass accumulation. Although cover crops are among the most commonly used weed management techniques for organic producers in the Midwest (DeDecker et al. 2014), the lack of consistent results in using cover crops to control weeds indicates a need for research quantifying the weed suppression provided by this method (Carr et al. 2011).

Cover crops, beyond being advantageous as a ground cover while growing, can be retained on the surface to act as weed-suppressive mulches. The Rodale Institute popularized a tool, the roller-crimper, which was specially fashioned for cover crop systems that rely on a mulch layer created by cover crop termination (Feeser et al. 2014). This implement is cylindrical with a chevron pattern of metal ridges that crush stems as the implement rolls over the cover crop. The design proved to be successful in cover crop termination as the action rolls over the crop stand not only crushing but also crimping the stems, leaving the resultant residue anchored in place (Vaisman et al. 2011). The roller crimper can be used on any scale of farm as it can be mounted on a tractor or horse or pulled by hand (Feeser et al. 2014). Feeser et al. (2014) touted the roller-crimper as advantageous over flail mowers and undercutters as the roller crimper creates a more homogenous and stable residue mat. Furthermore, the use of a roller crimper demonstrated more effective weed suppression than mowing (Feeser et al. 2014). Organic no-till methods that rely on roller-crimped cover crop residue to suppress weeds have been successfully developed in states such as Iowa, Ohio, Pennsylvania, and New York (Mischler et al. 2010; Mirsky et al. 2013).

However, in the NGP, developing successful roller-crimped cover cropping systems has been difficult due to shorter growing seasons that limit production of weed-suppressive cover crop residue (Teasdale and Mohler 2000). The NGP growing season is too short to accommodate sowing a main crop after cover crop termination, as termination is more successful if conducted after cover crop anthesis (Shirtliffe and Johnson 2012; Feeser et al. 2014). Consequently, researchers in this region have speculated about whether incorporating grazing into organic no-till systems might provide additional weed suppression to tailor this system to the NGP.

Grazing

Several researchers have speculated that integrating grazing with an annual cropping system might provide an additional weed suppression tactic to increase weed management efficacy. A grassland study analyzing grazing impacts on weed spatial patterns concluded that grazing aided in controlling dominant species, which in turn increased both density and diversity of the weed population (Gibson 1988). In contrast, during a study located in the NGP, Barroso et al. (2015) found that replacing tillage or herbicide use with grazing resulted in a modification of the weed community structure but did not impact the abundance or diversity of the community. A five-year organic no-till study, conducted in the Great Plains of Canada by Halde et al. (2015), attempted to use sheep (*Ovis aries*) grazing to prolong the productivity of plots. However, weeds overcame a rye (*Secale cereale* L.) crop, leading to study termination. A recent study comparing a grazed/reduced till organic production system with tilled organic and conventional management systems found that, over time, weed biomass increased in the grazed/reduced till organic versus remaining unchanged or declining in tilled systems (Lehnhoff et al. 2017).

In conclusion, the growth of the organic market has elevated the need for applicable organic research. Crop specific and region-specific studies will allow producers to better understand and, thus, adopt alternative, ecological approaches to weed management for their crop production systems. Weed control is among greatest problem producers to overcome and furthermore, certified organic production systems must rely on non-chemical management. An array of options is available to growers to control weeds using cultural, mechanical, and biological methods that include cropping rotation, cover crops, tillage, mulches, and grazing.

Objectives and Hypotheses

We hypothesized that incorporating livestock grazing into a no-till annual cropping system with cover crops might improve weed management and demonstrate the applicability of this management system in the NGP.

Objective 1: Quantify yield loss due to weed presence in field pea, wheat, and proso millet as influenced by management system (no-till plus grazing vs. clean tillage).

Objective 2: Quantify the soil seed bank and assess the effect of management system on the density and diversity of readily germinating seeds from the soil.

Objective 3: Quantify above-ground weed biomass as influenced by the effects of management system and crop phase.

Objective 4: Demonstrate weed species community divergence in response to management.

Objective 5: Demonstrate a successful organic no-till annual cropping system in the semi-arid region of ND.

Hypotheses 1: Grazing sheep and crop residue associated with the no-till plus grazing system will suppress weeds so that total weed biomass and density are similar to a clean tillage system.

Hypotheses 2: Percent crop loss due to weed presence will be similar in tilled and no-till plus grazing systems.

Hypotheses 3: Seed bank density and diversity will increase in the no-till plus grazing system.

Hypotheses 4: In general, by the end of the study, annual weeds will be more closely associated with the clean till system than with the no-till plus grazing system.

Hypothesis 5: In general, by the end of the study, perennial weeds will be more closely associated with the no-till plus grazing system than with the clean till system.

Materials and Methods

Site Information

A long-term study was conducted during 2013 to 2016 at the Dickinson Research Extension Center in Dickinson, ND on certified organic North Dakota State University research plot land. Present soil series are Arnegard loam (44% of plot area) and Reeder-Farnuf loam (56% of plot area) (Soil Survey Staff USDA-NRCS). The site was managed organically, with certification obtained through the Organic Crop Improvement Association and International Certification Services, for 2 years prior to the implementation of this study.

The site is located at 46.893566, -102.819951 with an elevation of 779 m. Ten-year average rainfall is 34.8 cm. During the time period over which the experiment was conducted, (1) maximum summer temperature was 38.4 C, (2) average summer temperature was 19.4 C, (3) minimum winter temperature was -33.9 C, (4) average winter temperature was -8 C, (5) wind speeds averaged 3.58 m/s with a maximum wind speed of 28.13 m/s, (6) average dew point was -11.6 C, and (7) average wind chill was -14.01 C with a minimum wind chill of -45.23 C (Anonymous 2017b).

Experimental Design

The five-crop rotation followed for this experiment was (1) field pea (*Pisum sativum* L.) followed by hairy vetch cover crop (CC hereafter), (2) hairy vetch CC grown in phase followed by winter wheat (*Triticum aestivum* L. emend. Thell.), (3) winter wheat followed by an out of phase CC mixture of wheat, oat *(Avena sativa* L.), mustard (*Brassica rapa* L.), and field pea, (4) proso millet followed by a winter rye CC out of phase, (5) winter rye followed by an in-phase navy bean (*Phaseolus vulgaris* L.) crop. In the interest of including all crop phases in the cropping rotation present each year, plots entered into the rotation at different points. Although the same overall cropping rotation is being followed in order, plots were assigned a certain sequence of that rotation and given labels A, B, C, D, and E (Table 1.1). Field pea was planted during early April and proso millet was planted during early June. During the winters of 2012-13 and 2013-14, winterkill terminated the winter wheat crop established the prior fall. This necessitated a replanting of spring wheat. Plots measured 9.14 by 30.48 m. Composted beef cattle manure was applied at a rate of 5 tons ac^{-1} when the study began, no other fertilizer applications were conducted. Cover crops were terminated using a roller-crimper and the residue was retained on the surface for weed suppression. Tillage was accomplished during the spring and fall in the clean tilled plots via the use of a tandem disk, penetrating to a depth of ~13 cm. Sheep were set out to graze the no-till plots to aid weed suppression. Grazing was conducted post-harvest of all crops, prior to seeding of CC, and before seeding of the proso millet crop phase. Sheep were fenced in to graze each paddock and remained for a period of 9 hours per day for 4 consecutive days. The number of sheep per paddock was increased from 15 during 2013 and 2014 to 17 in 2015 and 2016. Acetic acid (Weed Pharm 20%; Pharm Solutions Inc; Port Townsend, WA) was applied in no-till plots prior to planting and after grazing in pea, wheat and millet; application rates ranged from 110 to 454 L ha^{-1}. The field experiment was designed as a 2 [no-till with grazing (NT hereafter) vs. clean till (CT hereafter)] by 5 [cropping sequence (A, B, C, D, E) (Table 1.1)] factorial arranged in a randomized complete block with 5 replications. However, some data collection only took place during certain crop phases and, thus, the arrangement is considered to be a 2 (NT vs. CT) by 3 (field pea, wheat, proso millet) factorial designed in the same fashion.

Table 1.1. Crop sequences A, B, C, D, and E. Cover crops (CC) and main crops (MC) are listed under the year in which they were terminated or harvested, respectively.

	2013		2014		2015		2016	
	CC	MC	CC	MC	CC	MC	CC	MC
A	Mixture	Proso Millet	Winter Rye	Navy Bean	———	Field Pea	———	Hairy Vetch[a]
B	Winter Rye	Navy Bean	———	Field Pea	———	Hairy Vetch	———	Winter Wheat
C	———	Field Pea	———	Hairy Vetch	———	Winter Wheat	Mixture	Proso Millet
D	———	Hairy Vetch	———	Spring Wheat	Mixture	Proso Millet	Winter Rye	Navy Bean
E	———	Spring Wheat	Mixture	Proso Millet	Winter Rye	Navy Bean	———	Field Pea

[a] Hairy vetch was grown as a CC during the growing season, no MC was produced in these phases. This is unlike the other CC species, which were grown out of phase with a main cash crop.

Data Collection

Destructive harvest collections associated with yield loss and peak weed biomass occurred yearly only during field pea, wheat, and proso millet crop phases of the cropping sequence (i.e., 2 by 3 factorial). Perennial weed data and the seed bank data were collected only during the first (2013) and last (2016) years of the experiment (i.e., 2 by 5 factorial), to assess changes in these components of the weed community during the course of the experiment.

Yield Loss

To assess yield loss due to weed competition, paired micro-plots (1 m^2 each) were established at two fixed interior locations within each plot shortly after crop stand establishment in spring. One of the paired micro-plots was hand-weeded throughout the growing season to maintain a weed-free environment while the other was left weedy. The crop plants present within these micro-plots were harvested at crop maturity to obtain measures of crop yield. Crop samples were processed to separate grain from other plant biomass. The moisture content of grain samples was measured (Moisture Check Plus Grain Moisture Tester SW08120; Deere & Company; Moline, IL). Subsequently, grain samples were weighed and the measures of moisture content were used to adjust the values to a standard moisture content.

Peak Weed Biomass

Weed density and biomass data were gathered via destructive biomass harvest during early July (wheat and field pea crop phases) and early August (proso millet crop phase) using two-0.5 m^2 quadrats placed systematically within the northwestern and southeastern corners of each plot. Border effects were taken into consideration when placing quadrats by placing quadrats at least 1 m from plot edges. All above ground plant biomass was clipped at the soil surface of the quadrat area, sorted and counted by species. These weed samples were then placed in brown paper bags and dried at 70 C to a constant mass before being weighed. The weed community sampled was diverse, researchers found

42 species at the site, and as such, only the most prevalent and dominant species represented at the site will be discussed (Table 1.2, 1.3).

Table 1.2. A portion of the weed species represented in this study. Listed in ascending alphabetical order by common name.

Bayer Code	Common Name	Scientific Name
MEDSA	Alfalfa	*Medicago sativa* L.
ECHCG	Barnyardgrass	*Echinochloa crus-galli* (L.) Beauv.
CIRAR	Canada Thistle	*Cirsium arvense* (L.) Scop.
CHEAL	Common Lambsquarters	*Chenopodium album* L.
MALNE	Common Mallow	*Malva neglecta* Wallr.
POROL	Common Purslane	*Portulaca oleracea* L.
AGRCR	Crested Wheatgrass	*Agropyron cristatum* (L.) Gaertn.
TAROF	Dandelion	*Taraxacum officinale* G.H. Weber ex Wiggers
BROTE	Downy Brome	*Bromus tectorum* L.
CONAR	Field Bindweed	*Convolvulus arvensis* L.
THLAR	Field Pennycress	*Thlaspi arvense* L.
DESSO	Flixweed	*Descurainia sophia* (L.) Webb. ex Prantl
HORJU	Foxtail Barley	*Hordeum jubatum* L.
SETVI	Green Foxtail	*Setaria viridis* (L.) Beauv.
LEPDE	Greenflower Pepperweed	*Lepidium densiflorum* Schrad.
VICVI	Hairy Vetch	*Vicia villosa* Roth
ERICA	Horseweed	*Conyza canadensis* (L.) Cronq.
KCHSC	Kochia	*Kochia scoparia* (L.) Schrad.
LACSE	Prickly Lettuce	*Lactuca serriola* L.
AMABL	Prostrate Pigweed	*Amaranthus blitoides* S. Wats.
VEBBR	Prostrate Vervain	*Verbena bracteata* Lag. & Rodr.
AMARE	Redroot Pigweed	*Amaranthus retroflexus* L.
SASKR	Russian Thistle	*Salsola tragus* L.
CAPBP	Shepherspurse	*Capsella bursa-pastoris* (L.) Medik.
BROIN	Smooth Brome	*Bromus inermis* Leyss.
TANMU[a]	Tumble Mustard	*Sisymbrium altissimum* L.
TRODM	Western Salsify	*Tragopogon dubius* Scop.
POLCO	Wild Buckwheat	*Polygonum convolvulus* L.
AVEFA	Wild Oat	*Avena fatua* L.
PANCA	Witchgrass	*Panicum capillare* L.
SETLU	Yellow Foxtail	*Setaria pumila* (Poir.) Roemer & J.A. Schultes

[a] Species was undecided at time of analysis and as such, a simple code was created as a placeholder. Actual Bayer Code for this species is SSYAL.

Table 1.3. Top 10 weed species by biomass in no-till plus grazing (NT) and clean till (CT) management systems during the first (2013) and last (2016) years of the study, combined across crop phases. Scientific name and common name of species can be found in Table 1.2.

	NT		CT	
	2013	2016	2013	2016
1	LACSE	AGRCR	ECHCG	SETVI
2	VICVI	BROIN	SETVI	CIRAR
3	POLCO	TRODM	LACSE	CHEAL
4	ECHCG	CIRAR	POLCO	CONAR
5	SASKR	HORJU	ERICA	ECHCG
6	SETVI	TAROF	AMARE	AMARE
7	MEDSA	VICVI	CHEAL	SASKR
8	CHEAL	SETVI	CAPBP	SETLU
9	DESSO	MEDSA	CONAR	LACSE
10	TAROF	LACSE	MALNE	CAPBP

Perennial Weed Presence

Because some perennial weed populations were patchy, and thus may not have been accurately captured during the peak biomass harvest, additional assessments were conducted to quantify the presence of Canada thistle (*Cirsium arvense* L.), field bindweed (*Convolvulus arvensis* L.), and dandelion (*Taraxacum officinale* F.H. Wigg) in each plot at the beginning and end of the study. Plots associated with crop sequence B, C, and E were first assessed during 2013, whereas plots associated with sequences A and D were first assessed during 2014. All plots were assessed during 2016, the end of the study. These assessments were conducted approximately three weeks after the last field operation to allow time for weed regrowth following the mechanical or grazing disturbance. To quantify weed presence and absence, 12- 1 m^2 quadrats were placed in a systematic ‘W’ formation across each plot.

Seed Bank Assay

To assess changes in the weed seed bank over time and in response to management system and entry point, the seed bank was quantified during 2013 and 2016. Samples were collected in the spring (9 May 2013 and 13 April 2016) before weed emergence occurred. From each plot, 20- 10 cm (length) by 6 cm (diameter) soils were extracted with a bulb planter in stratified random locations within each plot. The cores were mixed in a bucket to homogenize and placed in a 3.8 L plastic zip top bag. A layer of potting medium (Sunshine Mix #1; Sun Gro Horticulture Canada Ltd; Seba Beach, AB) was spread in 54.6 by 28.2 by 5.1 cm plastic planting trays, covered with mesh cloth, and 2,850 cm^3 of the sampled soil was placed on top. The trays were placed in a greenhouse with supplemental light used to achieve 14/8-hour light and dark periods and 24/18 C day and night temperatures. Trays were watered as needed to keep the soil surface evenly moist. Once a week, seedlings were counted, identified to species, and removed. Seedlings were counted until new emergence ceased.

Statistical Analysis

ANOVA

Analysis of variance (ANOVA) was used to understand the effects of management system, crop phase (or entry point in some cases), year, and their interactions on numerous response variables. Replication was included in all models as a random effect. Prior to conducting ANOVAs, data were assessed for homogeneity of variance (Levene's test) and normality (Shapiro-Wilk test) to determine whether data met the assumptions of ANOVA for each univariate response variable. When required, data were natural log-transformed to improve data conformation to assumptions. When higher order interactions were significant, the SLICE option in the LSMEANS statement was used to assess simple main effects of management system and sampling time period. Resulting *p*-values were adjusted using a post-hoc Bonferroni procedure. Response variables tested included total weed seed bank density, total peak growth weed shoot density, total peak growth weed biomass, peak growth dandelion biomass, change in dandelion presence, weed community diversity (Shannon index) (Gotelli and Chao 2013), and percentage crop yield loss due to weeds. The effect of treatments on the proportion of quadrats occupied by Canada thistle and field bindweed could not be tested due to lack of data (i.e., most plots did not contain these species). Therefore, only observational results are presented for the perennial weed assessments of these two species. For crop yield loss, data were analyzed separately by crop phase. The response variable was [ln (percentage yield loss + 100)]. Percentage yield loss was calculated as [1 - (Weedy Yield) / Weed Free Yield] * 100. For the few instances of negative yield loss, the value was set to zero.

NMDS

To determine weed species community dissimilarity among management systems and crop phases, weed species data (species abundance at peak biomass, shoot biomass at peak biomass, seed bank count data) were subjected to ordination via nonmetric multidimensional scaling (NMDS) procedures using the metaMDS function in the R software 'VEGAN' package (R Development Core Team, R: A Language and Environment for Statistical Computing; R Foundation for Statistical Computing: Vienna, Austria, 2011). Curtiss-Bray distances were used to generate a four-dimensional projection (k=4). A minimum of 20 random starts was used to iteratively search for a stable solution with stress < 0.13. The function 'envfit' in the 'VEGAN' package was used to test differences between or among groups (management system and crop phase) via goodness of fit statistics. This function generates an r-squared value that represents the correlation between latent variables and groups.

Results and Discussion

Crop Loss, Weed Biomass, and Weed Density

ANOVA results for treatment effects on total weed biomass ($p < 0.0001$) and total weed density ($p = 0.0272$) revealed three-way interactions between year, crop phase, and management system. The focus of the discussion will be on the management system effects, comparing no-till plus grazing and clean till, as this response is central to the study hypotheses.

Wheat

Percent wheat yield lost to weed pressure was consistently affected by management ($p < 0.0001$) and unaffected by year differences ($p = 0.4719$). NT plots planted to wheat were associated with greater yield loss than CT plots (30.8 vs. 3.3%, respectively) (Figure 1.1).

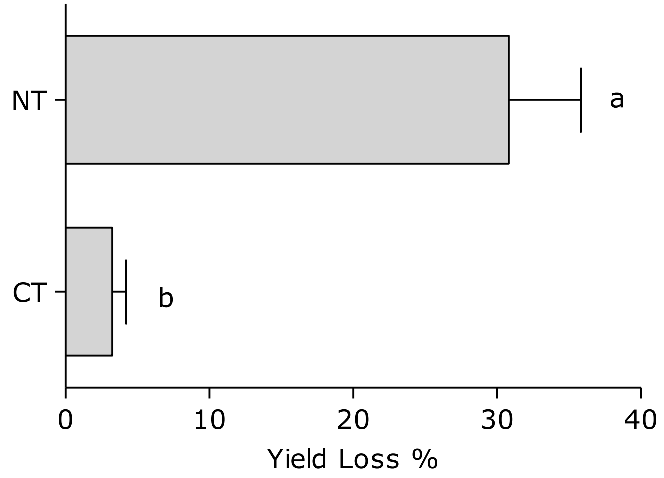

Figure 1.1. Mean (±S.E.) percent yield loss in wheat as affected by tillage system. Data were pooled across four years. Bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD.

For plots planted to wheat in 2014 (spring wheat) and 2016 (winter wheat), weed biomass was greater for NT plots than CT plots (110.8 vs. 6.5 and 18.6 vs. 1.8 g m^{-2}, respectively) (Figure 1.2). Weed biomass in NT and CT plots planted to wheat did not differ during 2013 or 2015 ($p = 0.2965$ or $p = 0.3012$, respectively) (Figure 1.2). Weed biomass did not differ between years with respect to NT or CT plots planted to wheat ($p = 0.2174$ or $p = 0.2309$, respectively).

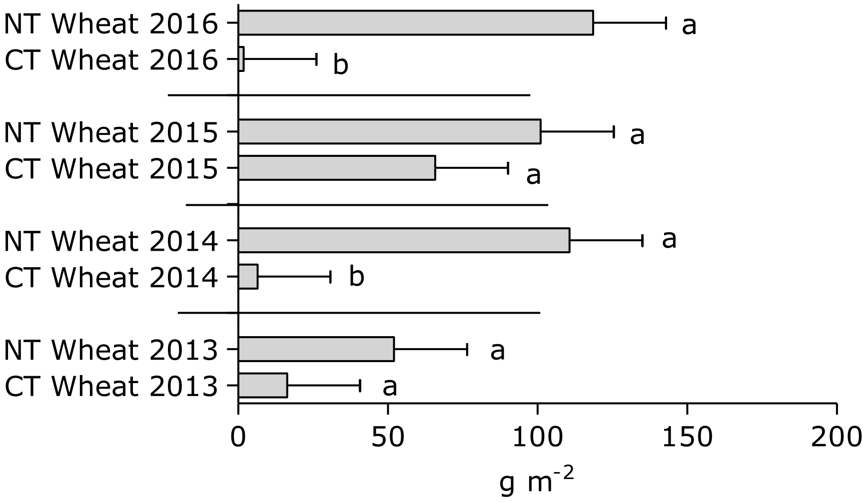

Figure 1.2. Mean (±S.E.) total weed biomass in wheat as affected by management system. Bars labeled with different lowercase letters between systems in the same year differ ($P \leq 0.05$) according to Tukey's HSD.

For plots planted to wheat in 2016, weed density was greater for NT plots than CT plots (325.9 vs. 52.2 stems m^{-2}, respectively) (Figure 1.3). During years 2013, 2014, and 2015 weed density in wheat plots did not differ with respect to management system (p = 0.0842; p = 0.2198; p = 0.5455, respectively) (Figure 1.3). Weed density did not differ with respect to year in wheat plantings in CT or NT plots (p = 0.1546 or p = 0.244, respectively).

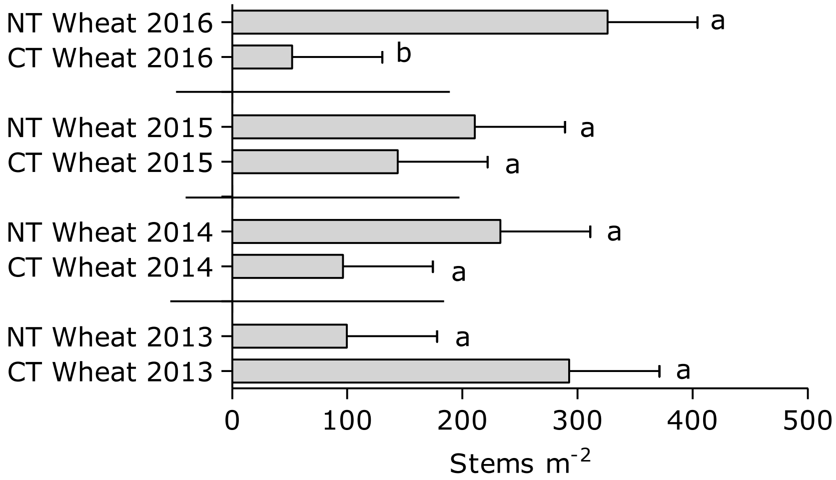

Figure 1.3. Mean (±S.E.) total weed density in wheat as affected by management system no-till plus grazing (NT) and clean till (CT). Bars labeled with different lowercase letters between systems in the same year differ (*P* ≤ 0.05) according to Tukey's HSD.

Wheat Results Synthesis

Wheat crop loss due to weeds was consistently greater in NT compared to CT; however, weed biomass was not consistently greater in NT than CT. During 2013 and 2015 weed biomass and density were similar between NT and CT. Vaisman et al. (2011) found when tillage was replaced with a roller crimper a reduction in wheat yield followed. Yield reductions were attributed to delayed N availability and potentially lower soil temperatures in the undisturbed system (Vaisman et al. 2011). Similar to our study, during 2015 and 2016, winter wheat yield depression was associated with a grazed organic system compared to a conventional or a tilled organic system, as reported by Lehnhoff et al. (2017). Regardless of wheat type, differences were observed during the years with the most extreme weather over the duration of the experiment, 2014 being the coldest and wettest and 2016 being the warmest. Conversely, 2013 and 2015 were the closest to normal, potentially mitigating the differences observed when the plant community was under abiotic stress. No divergence was associated with the growth of winter wheat vs. spring wheat.

Field Pea

A management system by year interaction was detected for field pea yield loss (*p* = 0.0007). During years 2013, 2015, and 2016, NT plots had a greater percentage of field pea yield loss than CT plots (61.4 vs. 27.2, 81.9 vs. 16.9, and 31.5 vs. 12.8 %, respectively) (Figure 1.4). Pea yield did not differ between systems during 2014 (*p* = 0.6161).

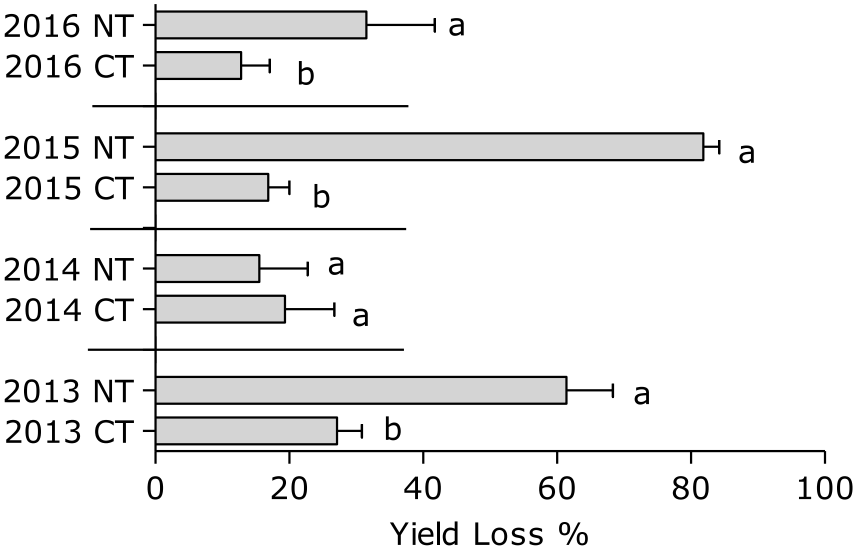

Figure 1.4. Mean (±S.E.) percent yield loss in field pea as affected by year and management system (no-till plus grazing, NT, or clean till, CT). Bars labeled with different lowercase letters between systems in the same year differ ($P \leq 0.05$) according to Tukey’s HSD.

For plots planted to field pea in 2013, 2014, and 2015, weed biomass was greater for NT plots than CT plots (460.5 vs. 131.1, 110.3 vs. 30.0, and 206.7 vs. 78.7 g m^{-2}, respectively) (Figure 1.5). Weed biomass in NT and CT plots planted to field pea did not differ during 2016 (*p* = 0.3255) (Figure 1.5). Weed biomass in CT plots planted to pea was greater during 2013 than during 2014 or 2016 (131.1 vs. 30.0, and 46.0 g m^{-2}, respectively). Weed biomass during 2015 did not differ from any other year (Figure 1.5). For NT plots planted to pea, 2013 was associated with greater weed biomass (460.5 g m^{-2})

than any other year; 2016 and 2014 resulted in the least weed biomass (79.6, and 110.3 g m^{-2}, respectively), and 2015 was intermediary (206.7 g m^{-2}) (Figure 1.5).

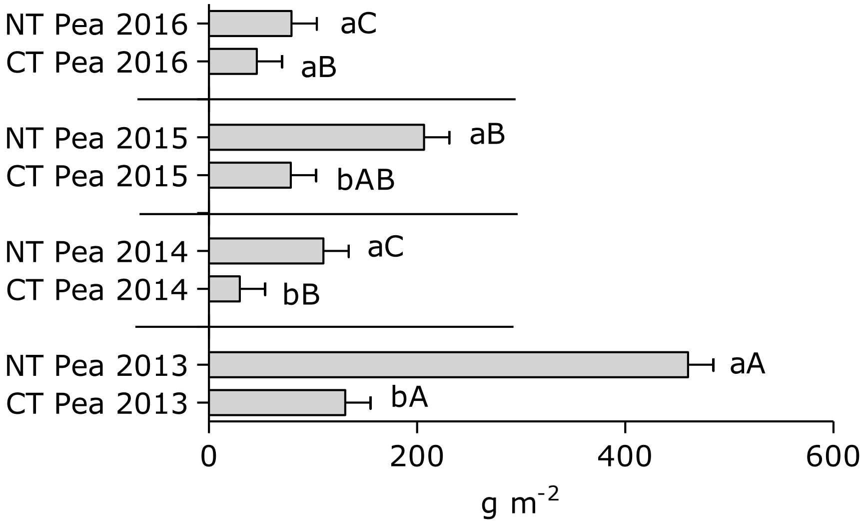

Figure 1.5. Mean (±S.E.) total weed biomass in field pea as affected by management system (no-till plus grazing, NT, or clean till, CT). Bars labeled with different lowercase letters between systems in the same year differ ($P \leq 0.05$) according to Tukey's HSD. Bars labeled with different uppercase letters between years in the same management system differ ($P \leq 0.05$) according to Tukey's HSD.

For plots planted to field pea in 2014, weed density was greater for NT plots than for CT plots (609.3 vs. 258.2 stems m^{-2}, respectively) (Figure 1.6). Alternatively, in 2015 pea plots, weed density was greater for CT plots than for NT plots (448.2 vs. 210.7 stems m^{-2}, respectively) (Figure 1.6). No differences occurred between CT and NT plots planted to field pea during 2013 and 2016 ($p = 0.9117$ and $p = 0.1445$, respectively) (Figure 1.6). Weed density in NT plots planted to pea was greatest during 2014 compared to 2013, 2015, or 2016 (609.3 vs. 227.1, 210.7, or 269.7 stems m^{-2}, respectively) (Figure 1.6). Weed density did not differ with respect to year in CT pea plots ($p = 0.1169$).

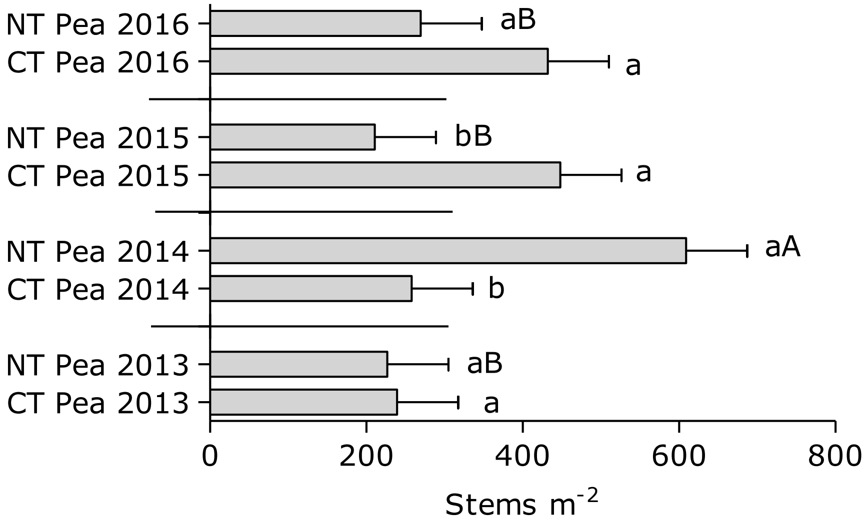

Figure 1.6. Mean (±S.E.) total weed density in pea as affected by management system (no-till plus grazing, NT, or clean till, CT). Bars labeled with different lowercase letters between management system in the same year differ ($P \leq 0.05$) according to Tukey's HSD. Bars labeled with different uppercase letters between years and in the same system differ ($P \leq 0.05$) according to Tukey's HSD.

Field Pea Results Synthesis

During 2014, field pea yield loss was similar between NT and CT plots despite weed biomass and density being greater in NT than CT. This is in contrast with findings during 2016 when weed biomass and density were similar between the two systems yet NT plots lost a greater percentage of field pea yield. In a climate summary, Akyuz (2017) noted that in ND during 2014, persistent cold temperatures had delayed spring planting and slowed crop growth. Slow early season growth related to the low temperatures may have mitigated the yield loss differences observed in the other three years of the study. Furthermore, the greater weed biomass and density in NT plots compared to CT with yield remaining equal supports the resource allocation hypothesis suggested by Smith et al. (2009). Despite fertilizer inputs being the same between systems, the difference of tillage and addition of grazing may have created more resource niches in the NT system. The increase in CT weed density compared to NT during 2015 is attributable to a carpet of small grasses, ≤ 8 cm, which formed under the crop canopy but likely didn't appreciably affect crop yield. According to Akyuz (2017), above average temperatures during the summer of 2016 led to most crops accumulating growing degree days at a faster than normal rate. This warm weather may have negatively affected the cool-season field pea crop. Guilioni et al. (2003) determined that peas grown under elevated temperatures or water deficit have diminished growth compared to optimal conditions. Differing water availability between systems may have led to varied responses to this temperature stress.

Proso Millet

During 2015 and 2016, the effect of management system was consistent (*p* = 0.0018), with greater proso millet yield loss due to weeds in the NT system (89.8%) compared to the CT system (39.9%) (Figure 1.7).

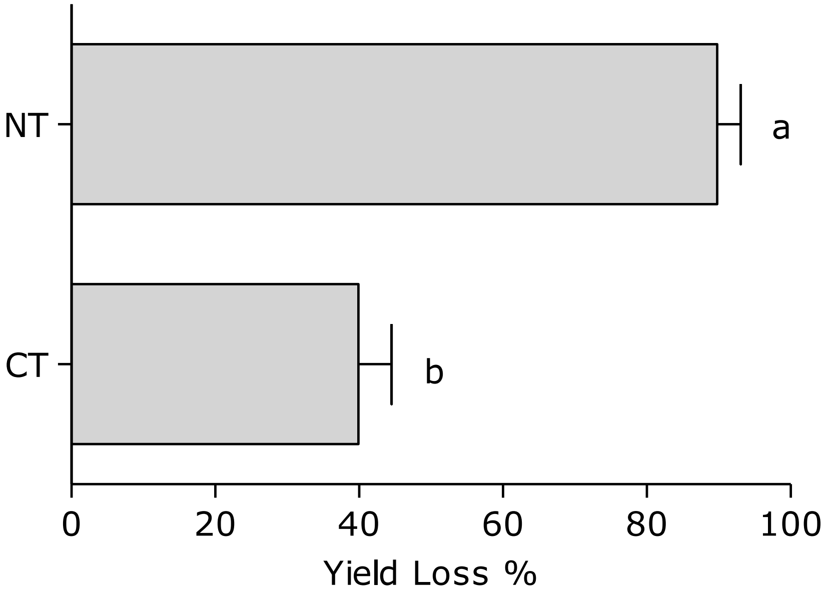

Figure 1.7. Mean (±S.E.) percent yield loss in proso millet as affected by management system, no-till plus grazing (NT) and clean till (CT). Data were pooled across four years. Bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD.

For plots planted to proso millet in 2013 and 2014, weed biomass was greater for NT plots than CT plots (149.2 vs. 75.5 and 200.3 vs. 18.9 g m^{-2}, respectively) (Figure 1.8). Weed biomass in NT and CT plots planted to proso millet did not differ during 2015 or 2016 ($p = 0.4505$ or $p = 0.2748$, respectively) (Figure 1.8). Weed biomass did not differ among years in CT plots planted to proso millet ($p = 0.1221$) (Figure 1.8). However, for NT plots planted to proso millet, 2014 differed from 2016 (200.3 vs. 23.6 g m^{-2}, respectively); other years, 2013 and 2015, were intermediary (Figure 1.8).

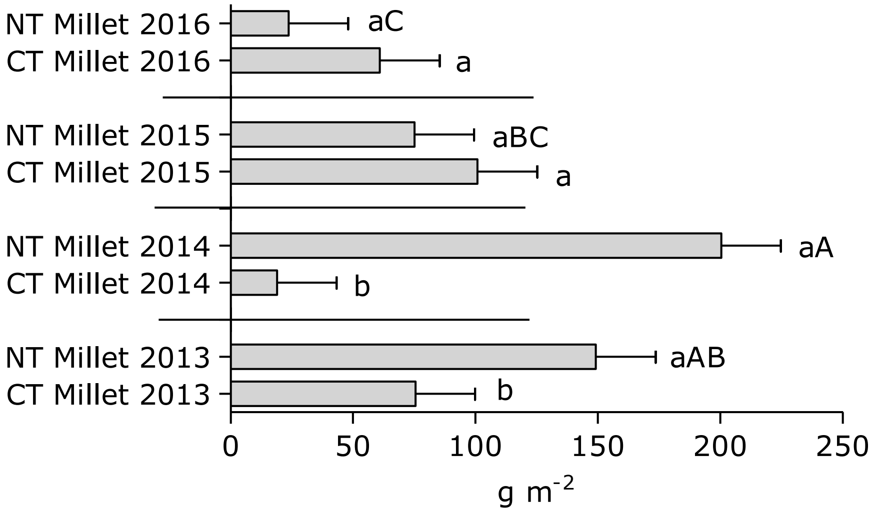

Figure 1.8. Mean (±S.E.) total weed biomass in proso millet as affected by management system, no-till plus grazing (NT) and clean till (CT). Bars labeled with different lowercase letters between system and in the same year differ ($P \leq 0.05$) according to Tukey's HSD. Bars labeled with different uppercase letters between years in the same system differ ($P \leq 0.05$) according to Tukey's HSD.

For plots planted to proso millet in 2014, weed density was greater for NT plots than CT plots (410.7 vs. 88.9 stems m^{-2}, respectively) (Figure 1.9). During years 2013, 2015, and 2016 weed density in proso millet plots did not differ with respect to management type ($p = 0.8118$; $p = 0.8441$; $p = 0.8427$, respectively) (Figure 1.9). Weed density did not differ with respect to year in proso millet plantings in CT or NT plots ($p = 0.2422$ or $p = 0.03$, respectively) (Figure 1.9). Although the overall F-test was significant for year differences within NT proso millet, the Bonferroni adjustment caused a lack of differences for all pairwise comparisons.

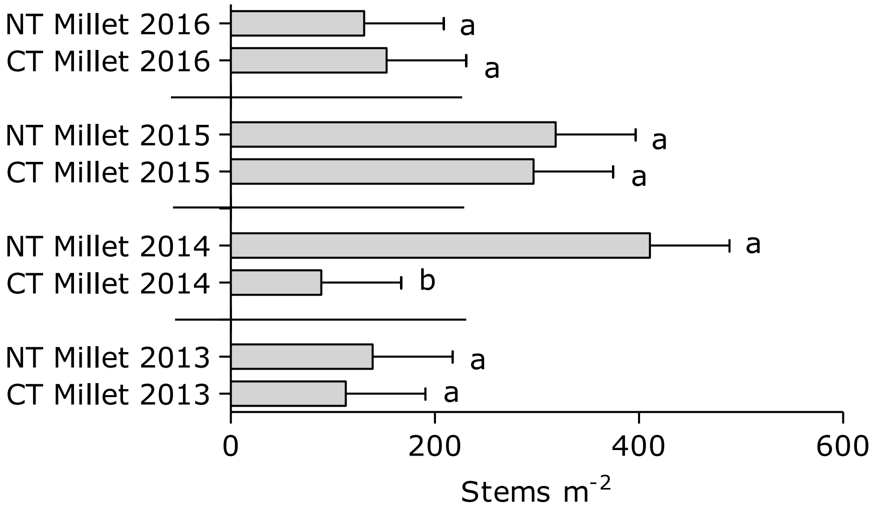

Figure 1.9. Mean (±S.E.) total weed density in proso millet as affected by management system, no-till plus grazing (NT) and clean till (CT). Bars labeled with different lowercase letters between system and in the same year differ (*P* ≤ 0.05) according to Tukey's HSD.

Proso Millet Results Synthesis

For proso millet plots, only data from 2015 and 2016 was analyzed due to lack of millet yield for both CT and NT systems during the 2013 and 2014 growing seasons. The fall of 2013 was abnormally wet, which could explain the millet stand during that year (Akyuz 2017). As for the 2014 growing season, early precipitation and persistent cold temperatures may have hindered development of this warm season crop, which requires a base air temperature of 50 F (Akyuz 2017; Baltensperger et al. EC137). Poor millet stands are more commonly associated with well-tilled soils (Baltensperger et al. EC137); however, poorer stands in the NT systems were observed in this study. Weed biomass during 2013 and 2014 was greater within the NT system compared to CT. In NT plots, weed biomass peaked during the second year of relatively cool weather, 2014, and declined thereafter as warmer weather resumed. Furthermore, the proso millet crop phase was associated with greater weed biomass during 2014 than field pea or wheat phases (data not shown). Weather better suited to proso millet growth occurred during 2015 and 2016 resulting in a more complete crop canopy better able to compete with weeds (Norris et al. 2001). Although yield loss to weeds was greater during the latter two years for the NT system, compared to CT, weed biomass and density were similar between systems.

Yield Loss Synthesis

Compared to field pea (~50 and ~20%) and wheat (~30 and ~5%) grown in this study, proso millet plots resulted in yield losses of ~90% and ~40% for NT and CT, respectively (Figures 1.1, 1.4, 1.7). Despite our study including a diverse system with a variety of cash crops, cover crops, and an application of composted fertilizer, resource niches, as discussed in Smith et al. (2009), did not mitigate the yield lost due to weed presence. With initial fertilizer applications being the same in NT and CT systems, the differences between NT and CT management systems, namely tillage action and grazing, altered the system so as to reduce yield. Results from our study align with findings reported by Benaragama et al. (2016), in that yields were reduced in the NT system regardless of the additional management decisions. Over a five-year study comparing organic and conventional management as well as comparing tillage and no-till, Halde et al. (2015) showed that tillage system, rather than management system, affected growth and yield of oat and spring wheat, with no-till having a negative effect on these measures. The hairy vetch and barley (*Hordeum vulgare* L.) cover crop grown by Halde et al. (2015) produced ~4.8 Mg ha^{-1} which is well below suggested rate of biomass accumulation for weed suppression; consequently, capability of the CC to control weeds was diminished (Teasdale and Mohler 2000). Halde et al. (2015) noted that an early-seeded oat crop was competitive with weeds, regardless of the depressed biomass accumulation in the organic no-till system. As demonstrated by Norris et al. (2001), a highly competitive crop canopy can effectively suppress weeds. In our study, CT plots generally resulted in less yield loss to weeds, and this could be due to a more competitive crop canopy. Canopy establishment may have been diminished because crops were planted into the existing stand of weeds in the NT system compared to freshly tilled soil in the CT system. McKenzie et al. (2016b) noted that the incorporation of sheep grazing, compared to mowing, resulted in no negative yield effects.

Total Weed Biomass Synthesis

The use of grazing sheep or mowing did not affect the biomass, density, or diversity of weed communities within a four-species cover crop (McKenzie et al. 2016a). A companion study, McKenzie et al. (2016b), showed that sheep grazing either met or further reduced weed biomass compared to mowing, citing temporal differences in the weed community for this departure. Menalled et al. (2001) showed that weed biomass associated with organic management was greater than conventionally managed no-till or tilled (109 vs. 58 and 18 g m^{-2}, respectively). Similarly, Halde et al. (2015) detected differences in above-ground weed biomass and weed species richness between organic and conventional management; although these differences were gleaned only during the fifth year of the experiment, divergent weed communities between systems created a situation in which biomass harvest timing confounded the results. In our study field pennycress was often desiccated during biomass harvest; however, this species was not predominant. Lehnhoff et al. (2017) noted that weed pressure and yield loss are not proportional (e.g., 11 times more weed biomass in the organic system only resulted in a 21% lentil (*Lens culinaris* Medik.) yield loss compared to conventional). This is similar to the wheat grown in our study during the years in which weed biomass differed between systems. In those years, NT wheat had 15 times more weeds than CT but the difference in yield loss between each system was only 28% (Figures 1.1, 1.2). Conversely, in wheat plots across the four years of our study, weed biomass in the NT system was only 3 times greater than in the CT system. Across the four years of our study, field pea and proso millet yield loss differences between management systems amounted to 39and 50%, respectively despite weed biomass being 4 times greater in field pea and 2 times greater in proso millet (Figures 1.2, 1.4, 1.5, 1.7, 1.8).

Total Weed Density Synthesis

Researching in a semi-arid region, Koocheki et al. (2008) found that an organically managed system resulted in 220 plants m^{-2} compared to a high-input conventional system with 66 plants m^{-2}; these weed densities are similar to those in our study. Norris et al. (2001) discovered that the presence of a highly competitive crop canopy lowers weed density. With similar weed species as our study (i.e., green foxtail, redroot pigweed, wild buckwheat, shepherdspurse) Vaisman et al. (2011) found weed density to be over 2.3 times greater in no-till than clean till. Similarly, Anderson et al. (1998) demonstrated using diverse rotations that weed densities in no-till were 5 times greater than in disk tilled plots. In our study, the hairy vetch CC was often injured during the winter season and, thus, was not a vigorous crop during the following spring and early summer. This period of time early in the growing season with little ground cover gave seedlings an opportunity to emerge. In the CT system, this flush of weeds was eliminated by a tillage passage before crop planting, conversely, emerged weeds remained in the NT system. Density differences with respect to time were not observed in our study, unlike Menalled et al. (2001), in which weed density decreased after seven years of organic management. As integrated management requires time to normalize, sometimes 10 years after adoption (Gebhardt et al. 1985), it is possible that the three additional years afforded to the study by Menalled et al. (2001) allowed the environment time to adjust to management.

Above Ground Weed Community Composition

Multi-dimensional scaling analyses showed that in 2013 weed community composition did not differ with respect to crop phase ($p = 0.520$). However, there were differences between management systems, CT and NT ($p = 0.005$) (Figure 1.10). Multi-dimensional scaling analyses showed that in 2016 weed community composition did not differ with respect to crop phase ($p = 0.335$) however, weed community composition did differ between management systems CT and NT ($p = 0.005$) (Figure 1.11).

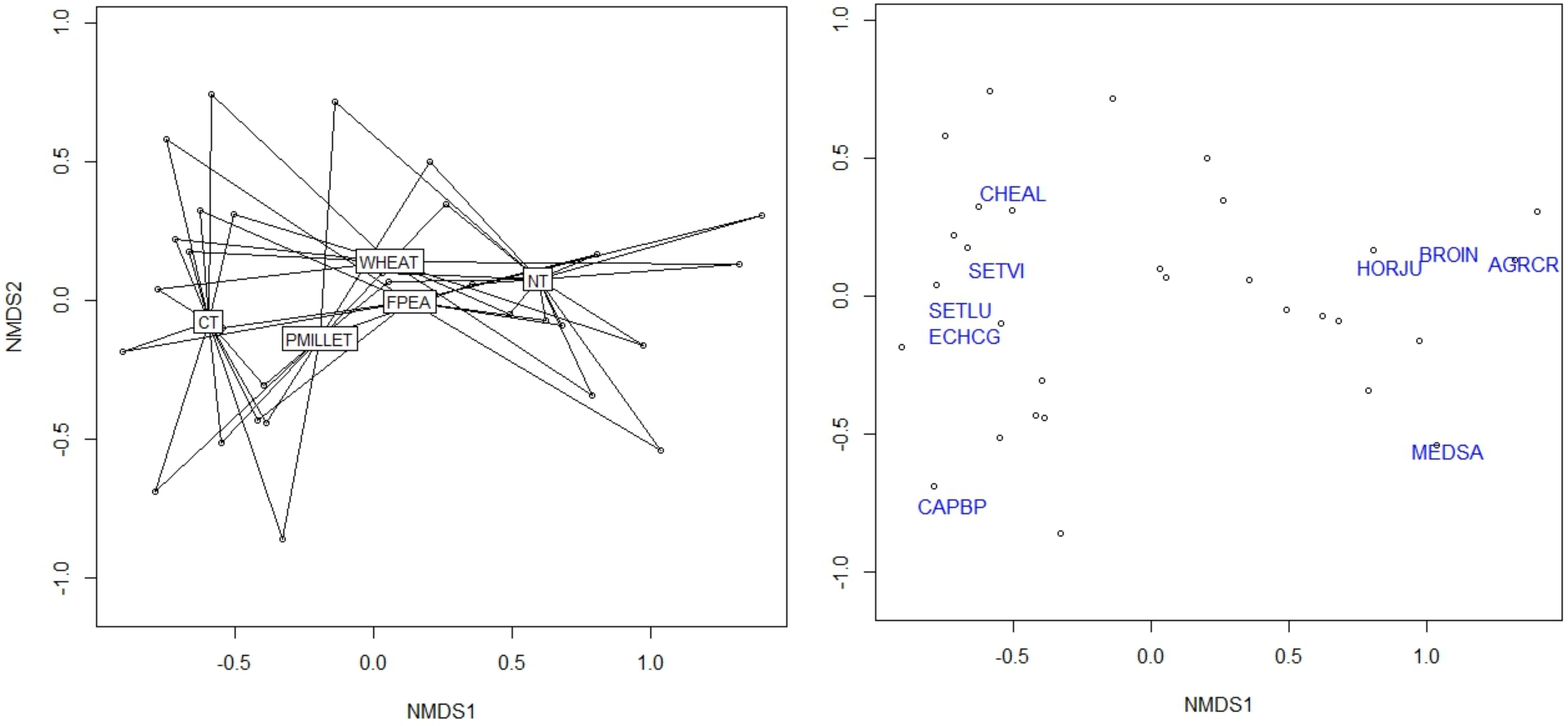

Figure 1.10. Non-metric multidimensional scaling (NMDS) ordination of above ground weed community during 2013 as associated with crop phases: proso millet, field pea, and spring wheat (PMILLET, FPEA, and WHEAT, respectively) and management systems: clean tilled and no-till plus grazing (CT and NT, respectively). Experimental treatments are labeled in chart A and weed species are labeled as Bayer Codes in chart B (reference Table 1.2 for common and scientific names). For purposes of visual clarity, only a portion of species are labeled. Stress = 0.1.

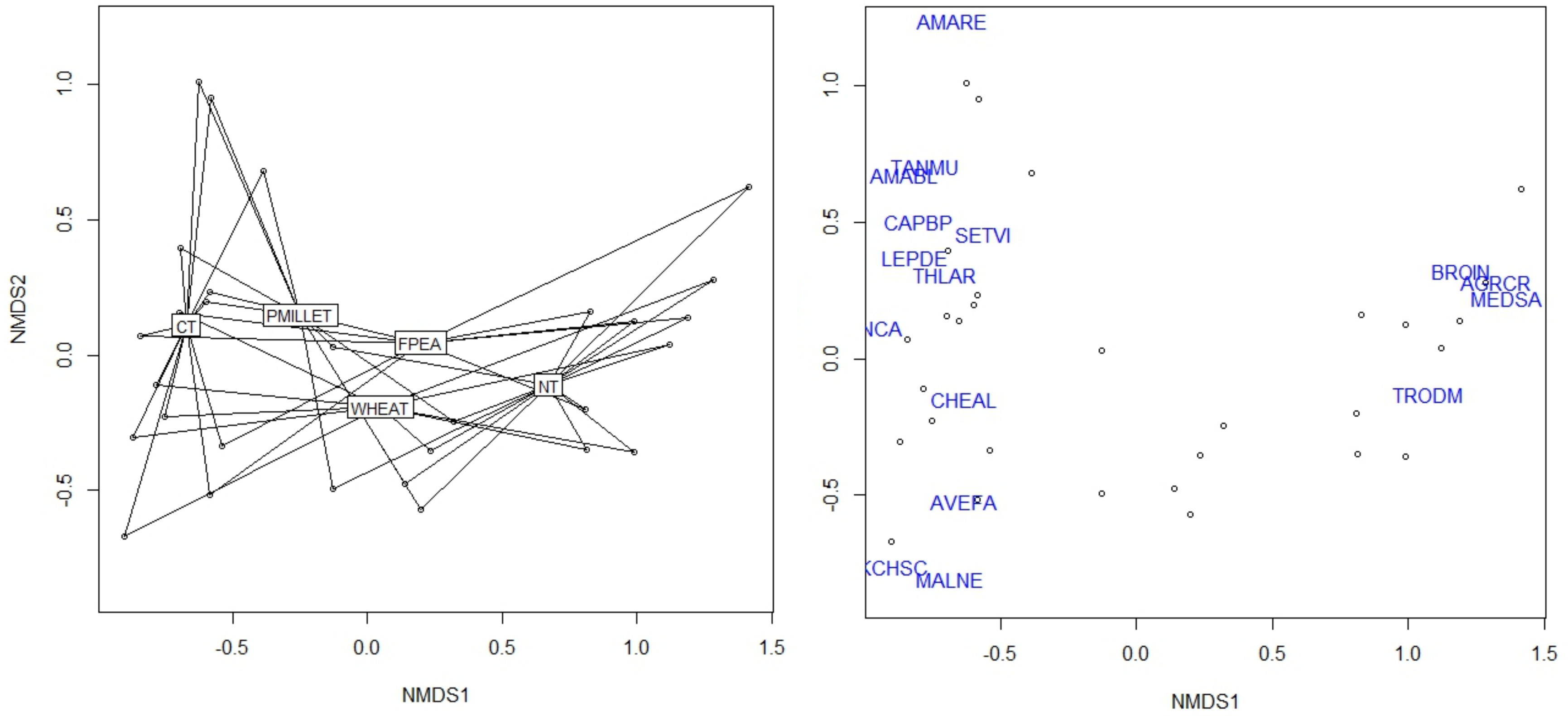

Figure 1.11. Non-metric multidimensional scaling (NMDS) ordination of above ground weed community during 2016 as associated with crop phase proso millet, field pea, and spring wheat (PMILLET, FPEA, and WHEAT, respectively) and management systems: clean tilled and no-till plus grazing (CT and NT, respectively). Experimental treatments are labeled in chart A and weed species are labeled as Bayer Codes in chart B (reference Table 1.2 for common and scientific names). For purposes of visual clarity, only a portion of species are labeled. Stress = 0.09.

Three warm-season annual grass species, green foxtail, yellow foxtail, and barnyardgrass, were associated with the CT system, whereas, three cool-season perennial species, crested wheatgrass, smooth brome, and foxtail barley, were associated with the NT system (Figure 1.10). Separation between annual and perennial species across tillage systems has been demonstrated elsewhere (Mulugeta and Stoltenberg 1997; Grime 1977), similarly to ours. Our data were gathered during the first year of sampling, at which time the tillage and cropping system had been in place for two years. Initiation of sheep grazing was concurrent with sampling; therefore, these data can act as a baseline for the grazing aspect of the management system.

As demonstrated in 2013, the above-ground weed community separated depending on the management system. The CT system was again associated with annual species, green foxtail, common lambsquarters, field pennycress, shepherdspurse, and greenflower pepperweed, with the latter three capable of growing as either a winter or summer annual (Figure 1.11). Similarly, the NT system was associated with crested wheatgrass and smooth brome, cool season perennial species (Figure 1.11). By utilizing NMDS ordination McKenzie et al. (2016a) demonstrated that the structure of weed communities do not differ between grazed and mowed land.

Weed community composition differed between clean till and no-till plus grazing management, these communities diverged to a greater degree over time. Similarly, Lehnhoff et al. (2017), using Curtis-Bray distances, found differences, which intensified with time, in weed community structure based on management. In the short-term, Vaisman et al. (2011) found that weed species did not differ between clean till and no-till management. The composition of the weed communities in corn, soybean (*Glycine max* (L.) Merr.), and wheat fields did not differ between conventional clean till or no-till management; however, a separation was discerned between communities under low-input and organic systems (Menalled et al. 2001). Annual broadleaf weeds accounted for 49 and 78 % of the weed population after six years of high-input and low-input conventional systems, respectively

(Koocheki et al. 2008). These results from Menalled et al. (2001) and Koocheki et al. (2008) imply that system inputs act as a filter for weed establishment and, thus, community composition along with tillage differences. The use of herbicides in conventional systems act as a blanket, stopping everything, as opposed to a filter, allowing escapes, which is demonstrated in the chemical-free systems. Our study showed that weed communities did not associate strongly with crop phase. This finding suggests that we were able to disrupt the weeds cycling along with the crop by the choice of management options like tillage and grazing. Long-term management decisions, like tillage, affect long-term effects with respect to weed community composition; in contrast to short-term decisions, like crop choice.

Weed Seed Bank Density and Diversity

For weed seed bank density there was a system by year interaction present ($p < 0.0001$). Entry point had a consistent effect on total seed bank density ($p = 0.0008$). For CT plots, weed seed bank density was greater during 2016 than during 2013 (1,129,407 vs. 445,707 weed seeds m^{-2} slice to 15 cm, respectively) (Figure 1.12). Likewise, for NT plots, weed seed bank density was greater during 2016 than during 2013 (549,761 vs. 322,763 weed seeds m^{-2} slice to 15 cm, respectively) (Figure 1.12). During 2013, CT and NT plots did not differ with respect to total weed seed bank density ($p = 0.0942$), while CT plots had greater weed seed bank density than NT plots (1,129,407 vs. 549,761 weed seeds m^{-2} slice to 15 cm, respectively) in 2016 (Figure 1.12). Sequence E was associated with greater weed seed bank density (768,159 weed seeds m^{-2} slice to 15 cm) than sequence C (445,496 weed seeds m^{-2} slice to 15 cm) (Figure 1.12).

Over the course of our study, each management system increased the density of seeds within the seed bank. During 2013, NT and CT seed banks were similar with respect to density but by 2016 weed seed density was greater in CT plots compared to NT plots. Koocheki et al. (2008) found greater differences within the 0 to 15 cm depth compared to the 15 to 30 cm depth between plowed and unplowed fields in a 6-yr study. The 0- to 15-cm depth had contained a greater proportion of the seeds than the 15- to 30-cm depth within the organic system while weed seed was evenly distributed among soil sampling depths in conventionally managed systems (Koocheki et al. 2008). Similarly, Cardina et al. (1991) demonstrated the relationship between depth, seed density, and tillage system, with no-till having a greater proportion of seeds within the top 5 cm of soil compared to minimum and conventional tillage. Barberi and Cascio (2000) noted that overall seed bank densities within a 0- to 45-cm depth were similar between differing tillage intensities, including no-till; however, seed distribution based on depth was present and correlated with depth of tillage. Buhler et al. (2001) attributed no-till seed bank heterogeneity to the lack of soil inversion, leading to seeds accumulating on the surface. Compared to high-, medium-, and low- input conventional systems, organic management resulted in greater seed bank densities in semi-arid regions (Koocheki et al. 2008). Additionally, the application of manure as a fertilizer may have affected densities across management systems by ushering in weed seeds secondary to those produced by weed plants at the site (Benoit et al. 1992).

Sequence E (spring wheat-proso millet-navy bean-field pea) increased seed bank density compared to sequence C (field pea-hairy vetch-winter wheat-proso millet). The winter termination of the winter wheat crop during the first year of the experiment, necessitating a sowing of spring wheat, eliminated what should have been the competitive crop stand associated with winter annual crops. This may have permitted increased weed emergence and persistence.

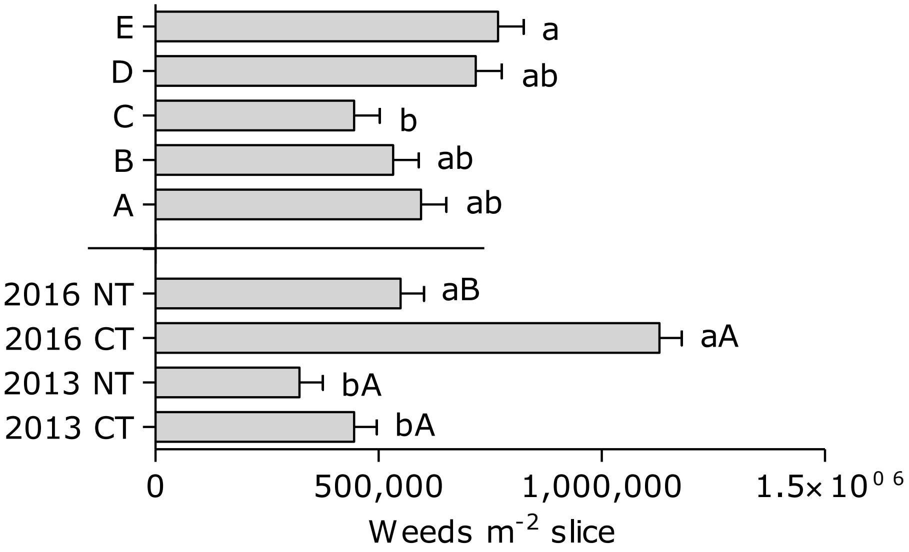

Figure 1.12. Mean (±S.E.) weed seedbank density as affected by cropping sequence (A, B, C, D, E) and tillage system (no-till plus grazing (NT) and clean till (CT)). Bars labeled with different lowercase letters among sequences or between years in the same management differ ($P \leq 0.05$) according to Tukey's HSD. Bars labeled with different uppercase letters between management systems in the same year differ ($P \leq 0.05$) according to Tukey's HSD.

A system by year interaction was detected for weed seed bank diversity (p = 0.0023). Clean till plots did not differ with respect to weed seed bank diversity between 2013 and 2016 (p = 0.1566) (Figure 1.13). Alternatively, plots under NT management had greater weed seed bank diversity during 2016 than during 2013 (1.76 vs. 1.51 H, respectively) (Figure 1.15). During 2016, NT plots had greater weed seed bank diversity than CT plots (1.76 vs. 1.23, respectively) (Figure 1.13). Entry point had a consistent effect on total seed bank diversity ($p < 0.0001$). Sequence A was associated with greater weed seed bank diversity than sequences D or E (1.70 vs. 1.27 or 1.37, respectively) (Figure 1.13).

Above ground weed diversity was greater in an organic no-till system than in conventionally managed tilled and untilled systems (Menalled et al. 2001). Conversely, seed bank diversity consistently showed that an increase in soil disturbance resulted in a decrease in the number of present species in a separate study (Cardina et al. 1991). Relative to other studies, the weed diversity at our site is great; this overall site diversity would be linked to field history and location of potential plant additions (Booth et al. 2011). Plots in our study were surrounded by large swaths of naturally occurring prairie grasses which could have acted as a source for weedy and non-weedy species (especially perennial species) to move into the plot area.

Sequence A did not include the wheat phase of the cropping rotation, conversely, wheat was grown in sequences D and E during one of the first two years in this study. Wheat was arguably a more competitive crop than proso millet or field pea. The lack of this competitive crop within the rotation may have led to an increase in diversity by permitting weeds to persist and grow.

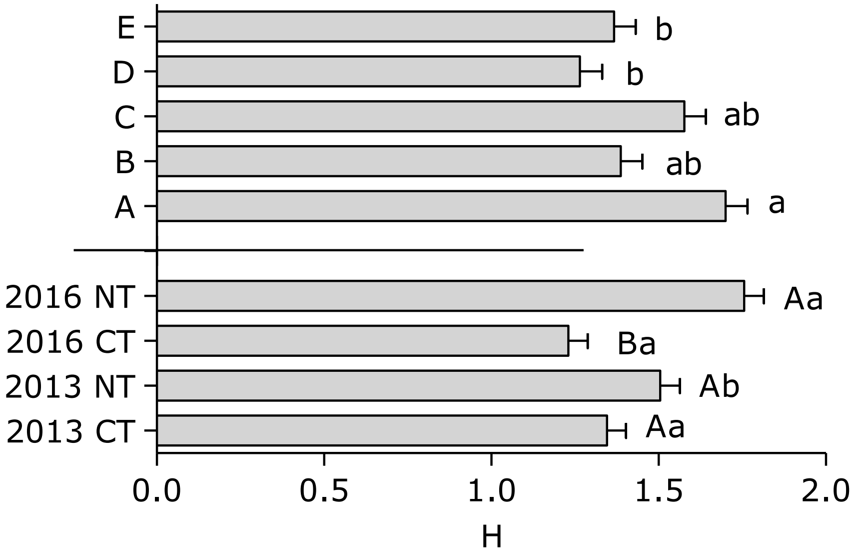

Figure 1.13. Mean (±S.E.) weed seed bank diversity as affected by cropping sequence, year, and tillage system. Bars labeled with different lowercase letters among sequences or between years and with the same management system differ (*P* ≤ 0.05) according to Tukey's HSD. Bars labeled with different uppercase letters between management systems in the same year differ (*P* ≤ 0.05) according to Tukey's HSD.

Seed Bank Composition

Multi-dimensional scaling analyses showed that in 2013 seed bank composition did not differ with respect to crop phase ($p = 0.065$), but did differ between management systems ($p = 0.02$) (Figure 1.14).

Multi-dimensional scaling analyses showed that in 2016 seed bank composition did not differ with respect to crop phase ($p = 0.135$) however, did differ between systems, CT and NT ($p = 0.02$) (Figure 1.15).

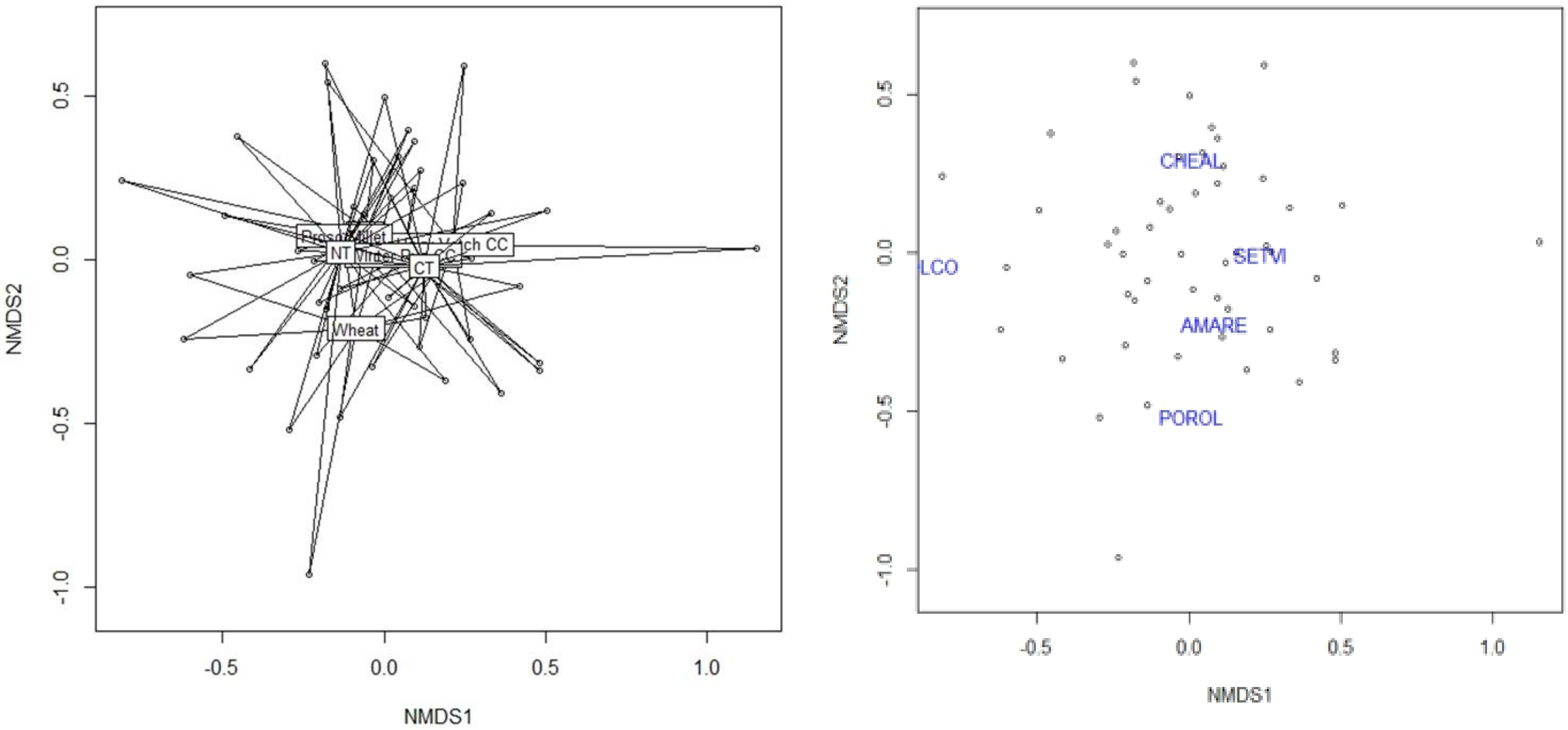

Figure 1.14. Non-metric multidimensional scaling (NMDS) ordination of weed seedbank community during 2013 as associated with crop phase proso millet, field pea, and spring wheat (PMILLET, FPEA, and WHEAT, respectively) and management systems: clean tilled and no-till plus grazing (CT and NT, respectively). Experimental treatments are labeled in chart A and weed species are labeled as Bayer Codes in chart B (reference Table 1.2 for common and scientific names). For purposes of visual clarity, only a portion of species are labeled. Stress = 0.12.

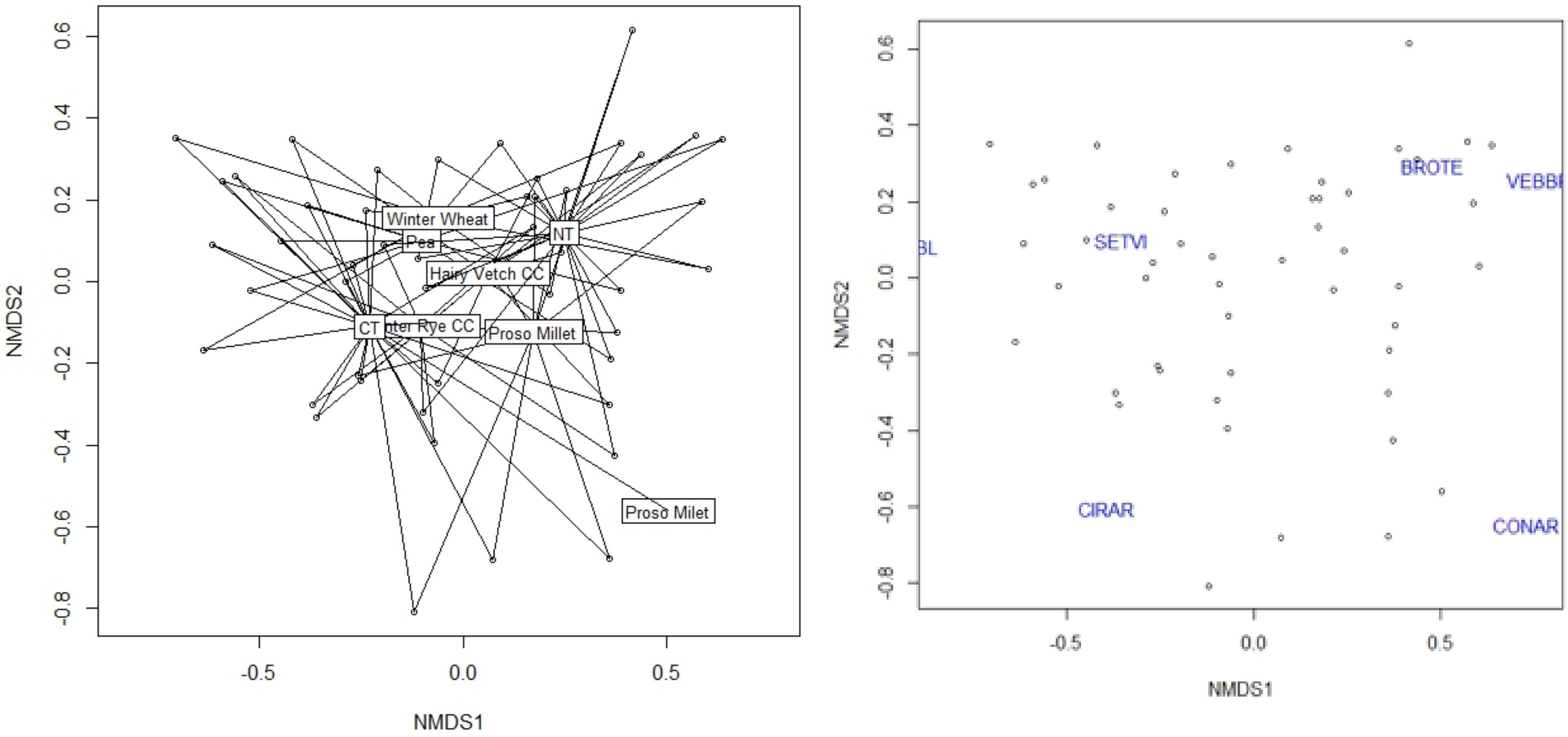

Figure 1.15. Non-metric multidimensional scaling (NMDS) ordination of weed seedbank community during 2016 as associated with crop phase proso millet, field pea, and spring wheat (PMILLET, FPEA, and WHEAT, respectively) and management systems: clean tilled and no-till plus grazing (CT and NT, respectively). Experimental treatments are labeled in chart A and weed species are labeled as Bayer Codes in chart B (reference Table 1.2 for common and scientific names). For purposes of visual clarity, only a portion of species are labeled. Stress = 0.12.

Despite the statistical difference between the NT and CT systems based on management (tillage and grazing), with respect to the 2013 seed bank, ordination did not reveal a clear community separation (Figure 1.14). Green foxtail and redroot pigweed, both annual species, aligned more with the CT than the NT system (Figure 1.15).

Ordination of the soil seed bank during 2016 revealed more distinct groups related to each management system when compared to the 2013 ordination (Figure 1.14). The CT system was associated with green foxtail, a summer annual, compared to downy brome, a cool-season winter annual, which was associated with the NT system (Figure 1.15).

Contrary to our results, NMDS ordination of weed communities that were previously mowed or grazed showed overlapping ranges, indicating similar species and distribution (Menalled et al. 2001). Similar to our study, Barberi and Cascio (2000) demonstrated that cropping rotation did not drive the differences in density or spatial distribution between seed bank communities, tillage had a greater effect. These prior findings may indicate that in our study, the tillage action had the greatest impact on seedbank composition, compared to addition of grazing or crop. Seed bank and flora evaluation by Ball and Miller (1989) demonstrated that seed bank composition can be a poor indicator of the assembled aboveground weed community.

Perennial Weed Presence

Canada Thistle and Field Bindweed

A major proportion of the plots had no Canada thistle or field bindweed presence, thus precluding formal statistical analyses. Hence, for these species, only observational results are possible. Over the course of this 4-yr study, Canada thistle presence increased in 5 CT plots and 6 NT plots. This increase was probably due more to organic management constraints than management. Canada thistle did not decrease in any of the plots. Sheep grazing has proved to be successful in the control of Canada thistle; however, grazing must be intensive and timely (Hartley et al. 1984). Field bindweed presence increased in 11 CT plots and 14 NT plots. This shows that field bindweed increased over time, but these increases were likely not associated with the management system. Only one bindweed plot showed a decrease over time, but this was likely due to sampling error. In a conventional system, Buhler et al. (1994) found that after 14 years field bindweed populations increased regardless of crop rotation, excluding corn monocrop, and did not consistently change with tillage system, including no-till. The prostrate growth habit of field bindweed may have contributed to its spread as growing near the soil surface allows escape from grazing or mowing action (McKenzie 2016a).

Dandelion

An entry point by management system interaction was detected for dandelion presence increase or decrease ($p < 0.0001$). In NT plots, dandelion increased in frequency within sequences B, C, and E (data not shown). For sequences A and D, in both NT and CT systems, dandelion presence decreased over time (data not shown).

Baseline presence of dandelion within sequences A and D were established during 2014 and baselines for sequences B, C, and E were established during 2013. The year in which the baselines were set may have affected these results. For example, during 2013, the first year of the experiment, low dandelion frequency may have been due to a lack of time for perennial weeds to become established. Conversely, during 2014, a year of experimental management, dandelion may have had time to become established and begun to proliferate.

ANOVA results for dandelion biomass data, gathered during the peak weed biomass harvest, showed that dandelion plants were consistently associated with NT plots compared to CT plots ($p = 0.003$) (3.65 vs. 0.02 g m^{-2}, respectively) (data not shown). This result lends further weight to the conclusion that the NT system led to an increase in dandelion presence in our study.

Halde et al. (2015) reported that an increase in dandelion establishment was responsible for the decrease observed in the species richness within no-till compared to disk till. Greater amounts of perennial weeds were associated with organic systems, and reached

66 percent of total weed density after six years, compared to conventional systems (Koocheki et al. 2008). Contrastingly, Menalled et al. (2011) found that most of the species found in organic and conventional managed plots were annual monocots. Demonstrations regarding weed functional groups associating with management system have been inconsistent. Our findings regarding dandelion align with the Grime (1977) model in that short lived, seed prolific species associate with disturbed sites while perennial species are more common in undisturbed sites. Furthermore, perennial species, in an effort to enhance longevity, allocate resources to enhancing vegetative structures; dandelions are particularly known for their deep taproot. This growth form improves regrowth potential if damage from grazing is incurred. Field bindweed and Canada thistle are able to reproduce via seed or rhizome, whereas dandelion only reproduces by seeds. Relying on seed production enables dandelion to spread more homogenously throughout and within the plots than field bindweed or Canada thistle, both of which spread primarily via vegetative reproduction (Weaver and Riley 1982; Becker et al. 2008). Species which disseminate seed by wind have been associated with no-till systems (Froud-Williams 1981).

Cover Crop Biomass

Because the roller-crimped CC acting as a weed suppressive mulch was an aspect of weed management in the NT system, CC biomass information will be briefly discussed. The above ground dry biomass produced by the hairy vetch CC peaked during 2015 at ~6,000 kg ha^{-1}; this was considerably greater than the biomass accumulated during 2013 and 2014 (~3,000 and ~1,000 kg ha^{-1}, respectively) (data not shown). The hairy vetch variety grown as a CC suffered from winter injury or was winterkilled during the first two years of the experiment. Feeser et al. (2014) recommended seeding cover crops to reach production of ~9,000 kg ha^{-1} of dry matter. Teasdale and Mohler (2000) found that over 7,000 kg ha^{-1} of above ground dry matter is needed for 80% suppression of annual broadleaf weeds. Carr et al. (2011) demonstrated that the cover crop with the least biomass accumulation, hairy vetch in their study, was associated with the greatest weed growth. Winter injury was the main reason that hairy vetch did not produce adequate cover, pointing to a need to develop hairy vetch varieties that are winter hardy at northern latitudes.

In our study, the CC did not provide a competitive crop canopy while growing nor did the hairy vetch planting amass the biomass necessary to create an even layer of mulch after being subjected to the roller-crimper. Inadequate biomass production may have permitted weed growth during the hairy vetch phase which, although being roller crimped along with the CC, would carry over into the next phase. These weeds may also have negatively affected the subsequent wheat crop. Following years when the hairy vetch CC phase produced < 3,000 kg ha^{-1} of biomass, weed density did not differ between systems and weed biomass was greater under NT only during 2014. Conversely, the NT winter wheat crop, which followed the vigorous 2015 hairy vetch CC, resulted in increased weed biomass and density compared to the CT system. However, hairy vetch was considered a weed species during biomass harvests, therefore, any escapes form termination with the roller-crimper would have contributed to measures of total weed biomass.

Limitations of Results Due to Management Choices

Our experimental plots were managed with respect to tillage for two years before sampling for this study began potentially giving weed communities time to change in response to tillage system.   The start of sheep grazing was concurrent with that of sampling, however, the grazing and tillage treatments are confounded, so no comment can be made regarding their independent effects.

Acetic acid was applied to all NT plots to limit the spread of especially troublesome weeds (Canada thistle, field bindweed). This was done not as an experimental treatment but rather as an overall management tactic to preserve the long-term viability of the plots for research purposes and to reduce highly patchy effects caused by these species. Therefore, study results may underestimate the pressure from these species that might not have occurred had these actions not been taken.

Sheep were not maintained on the plot land for the duration of the experiment. They were housed elsewhere, in places where their diet may have included weed seeds of species not initially present in the study plots. In particular, downy brome may have been introduced to the site via sheep. Such introductions may have influenced measures of weed community diversity. Also, the grazing strategy was not consistent throughout the experiment. Once researchers noted that weed populations were becoming unruly, mowing was used in conjunction with grazing. Although mowing has been shown to result in similar outcomes as grazing, this was a deviation from the experimental plan.

The seed bank data presented included readily germinating seeds only. This exclusion necessarily lowers the overall density of seeds in seed banks associated with either management system. However, the inclusion of seeds that remain in the seed bank may alter the relations demonstrated between management systems with respect to density and diversity.

Conclusion

Cover crop stands were unable to produce adequate biomass to suppress weeds during most years of the study, in part because of extensive winter injury. As a result, above-ground biomass produced by hairy vetch cover crop was limited and likely led to increased weed growth. Greater yield loss under no-till management, even with grazing was consistently observed during wheat and proso millet crop phases. In most instances, the no-till plus grazing system had greater weed biomass and density. The composition of the weed communities, both above ground and within the soil seed bank, were distinct between management systems. Tillage strategy, as opposed to the crop species being grown, was the main driver of changes in the weed community. Annual weed species more often aligned with the clean till system, whereas perennial species were more prevalent within the NT system. By the end of this study, no-till plus grazing plots were associated with greater seed bank diversity while clean till plots contained more seed comprising the weed seed bank.

Compared to the clean tilled plots weed biomass was greater in the NT system, this seems to contrast with the CT systems having increased weed seeds. Our results demonstrate that these two systems have different capacities for weed suppression. Developing organic continuous no-till small-grain production systems for the NGP region remains a formidable challenge.

As integrated management techniques require time to adapt to the environment, the differences gleaned across four years of this study may be stochastic, especially differences associated with entry point. As this study was the first to attempt continuous organic no-till for annual grain production in ND, improvements in this design can be made. Beyond the necessity of being long-term, future studies for organic no-till in the NGP should be designed in such a way that effects of treatment factors can be disentangled. Although several tactics may be integrated, region-specific knowledge regarding individual mechanisms will better enable producers to personalize a land management system.

CHAPTER 2. HEMP HURD MULCH, PAPER MULCH, AND BIOCHAR IMPACTS ON ORGANIC PERENNIAL STRAWBERRY ESTABLISHMENT AND PRODUCTION

Abstract

Effective weed management is crucial for organic perennial strawberry production and the common mulching products have limitations. Therefore, introducing novel mulch materials would benefit organic producers. Biochar soil amendment has previously been shown to improve growth of strawberry plants. Field trials were conducted over two years to investigate the ability of two novel mulch materials and pine-derived biochar to aid matted-row strawberry establishment and production. Biochar amendment was associated with increased soil organic matter and pH at both sites, but did not impact strawberry measures. The mulch materials, paper and hemp hurd, were associated with greater yields compared to alfalfa hay (5.8 and 4.7 vs. 3.0 kg m^2). Alfalfa hay, paper, and hemp hurd mulches demonstrated similar weed suppression during the establishment year while only hemp hurd sustained this capacity during the second year. This experiment demonstrated that paper and hemp hurd mulch provide effective weed control for perennial strawberry production.

Introduction

Organic Strawberry Production

According to the Nutrition Business Journal, fresh fruits and vegetables have been the top selling organically grown food category since the onslaught of organic retail sales (USDA-ERS 2017). Fresh market strawberries are consumed in the U.S. at a rate of over seven pounds per capita (USDA-ERS 2013). In 2016, 53,600 acres were planted to strawberry and the U.S. fresh market strawberry production was valued at over $2 billion (USDA-NASS 2016).

Strawberry is a member of family Rosaceae, genus *Fragaria* L.; the USDA PLANTS database (National Plant Data Team 2017) notes six species including two hybrids, *Fragaria* x *ananassa,* and *Fragaria* x *bringhurstii*, both of which are native to the U.S. *Fragaria x* *ananassa* is the most common species grown for production (Hoover et al. 2017). Strawberry species can further be divided based on their photoperiod sensitivities. There are three types of strawberry plants delineated by flowering photoperiod: Junebearing (one crop per year, flowering during late spring or early summer), everbearing (two crops per year, flowering during late spring and again during the fall), and day-neutral (continuous flowering) (Himelrick et al. 2002). Strawberries require insect pollination for fruit formation (Hancock 1999). Anatomically, the strawberry plant consists of a crown from which roots, leaves, axillary buds, and trusses arise (Hancock 1999). Runners or stolons are formed at the axillary buds and, at the distal end of each runner, a daughter or clonal plant develops (Hoover et al. 2017). Generally, daughter plants develop on the second node of the runner, leaving the first node to either remain dormant or produce a runner/daughter plant; furthermore, each daughter plant is capable of producing runners (Hancock 1999). The proliferation of daughter plants can be advantageous for production, depending on the type of production system employed.

Large-scale annual strawberry production is associated with the use of plastic as a mulch to cover the soil in high-density plantings (Himelrick et al. 2002). Annual production is common in warmer climates; plants are established in the fall and harvest takes place early in the spring and generally lasts 5-8 weeks, after which plants are destroyed (Himelrick et al. 2002). Plastic mulches have been studied extensively and have been found to be highly effective for preventing weed growth (Anzalone et al. 2010; Bakshi et al. 2014; Cirujeda et al. 2012). Furthermore, plastic is more consistent at suppressing weed growth than biomass or particulate mulches (Feeser et al. 2014). Consequently, polyethylene is a common treatment in mulch comparison studies (Anzalone et al. 2010; Cirujeda et al. 2012; Weber 2003). According to a Rodale Institute publication (Feeser et al. 2014), producers using black plastic mulch incur costs of \$200 to250 acre^{-1} for materials and an additional \$20 acre^{-1} for disposal. Since polyethylene plastic does not readily biodegrade, disposal also incurs an environmental cost (Barnes et al. 2009). Although black plastic mulch facilitates non-chemical weed management in organic production systems, these disposal issues are incongruent with the ideology of organic agriculture, which promotes environmental sustainability. As a possible solution to these issues, biodegradable plastic films, typically plant-derived and starch-based, have been developed for use as weed-suppressive mulches. Biodegradable film mulches have demonstrated varying degrees of success as some films break down rapidly and, thus, do not provide durable weed suppression (Greer and Dole 2003; Weber 2003). Despite the potential of biodegradable film mulches and availability on the market, none of these materials are yet approved by the USDA, National Organic Program for use in organic production systems (USDA-AMS 2017).

Perennial strawberry production systems, also termed matted-row systems, are widespread, but usually associated with short growing seasons and cool climates. Matted-row strawberry production relies on the establishment of clonal daughter plants for stand creation. Hence, this system requires lower planting densities coupled with early spring planting to ensure adequate space and time for runner production (Hoover et al. 2017). Flowers are removed during the establishment year to encourage vegetative growth (Hoover et al. 2017). Fruits are not harvested until the second year when berry maturation occurs over a 2- to 3-week period during late spring or early summer (Himelrick et al. 2002). Matted-row strawberry beds can last for 3 or 4 years with annual renovation; this includes narrowing plant rows, thinning out plants, and applications of pesticides and fertilizers (Himelrick et al. 2002). Because matted-row strawberry production relies on the establishment of daughter plants via runners, plastic mulches are unacceptable since they prevent root penetration into the soil. Nevertheless, effective weed control is paramount in matted-row systems.

Mulches for Weed Suppression

Organic strawberry producers in Salinas Valley CA spend 2.7 times more money per acre on weed control, 2.3 times more hours per acre hand laboring than their conventional counterparts (Klonsky 2011). Klonsky (2011) reported that organic strawberry production requires 427 person-hours per acre compared to conventional production, which requires 183 person-hours.

Pritts and Kelly (2001) showed that for strawberry, competition with weeds early in the season has a negative impact on yield whereas late season weed competition has little to no effect. Duration or persistence of weed pressure also impacts yield: in one study, Pritts and Kelly (2001) reported that one month of weed competition resulted in a 20% strawberry yield reduction while four months reduced yield by 90%, a similar long-term study demonstrated a 51% reduction in perennial plant productivity due to weeds across four years (Pritts and Kelly 2004). Weed-free plantings had greater yield potential than strawberry plants exposed to weeds (Lawson and Wiseman 1976). Contrastingly, yield was unaffected by increases in weed biomass one year after planting (Pritts and Kelly 2004). These studies demonstrate that weed control during plant establishment is more crucial than controlling weeds after plants are established. Pritts and Kelly (2001) produced a regression line demonstrating a linear relationship between strawberry yield and weed biomass during the establishment year (every 100 g m^{-2} of weed biomass reduces yield by 5.5%).

Effective weed control is essential during the establishment year of strawberry plants, especially early in the season. Pritts and Kelly (2004) advised that intensive, regular hand weeding and cultivation for weed removal can damage strawberry plants and negatively affect yield. Consequently, weed suppressive mulches are commonly used in matted-row systems. Additionally, it is crucial that the mulch material remains intact throughout, at least, the establishment season, as the crop is most sensitive to weed pressure during this period.

Hay mulches are commonly used for strawberry production as hay is a readily available product that can be made from several plant species. Compared to plastics, particle mulches, like hay or straw, allow for increased water infiltration (Teasdale and

Mohler 2000). Along with increased soil moisture, by decomposing, hay mulches add organic matter and other nutrients to the soil (Coleman 2012). Although hay is commonly recommended to strawberry producers (Hoover et al. 2017; Himelrick et al. 2002), there are problems with using this material as a mulch. Hay has been shown to harbor pests, including slugs, and may insulate cold soil from early spring warming, which delays growth (Grundy and Bond 2007; Ganmore-Neumann and Kafkafi 1981). The consistency and structure of hay mulch may leave it susceptible to wind displacement. Furthermore, unless the source field is well managed and relatively weed free, resulting hay may be infested with weed seeds. These weed seeds can lead to influxes of weeds in planting beds, as observed in Boyhan et al. (2006) and Sinkeviciene et al. (2009).

Flaws associated with commonly used mulch products like plastic and hay represent a research opportunity to advance novel mulch materials for use in strawberry production. Paper mulch is one material that may be effective for suppressing weeds in perennial matted-row strawberries. Paper mulches are commonly used in comparison studies, with moderate results (Li et al. 2013, 2014; Miles et al.2012). Mulches must remain on the soil surface in order to effectively manage weeds. Some paper mulches tested in Weber (2003) degraded as such that the soil cover became ineffective at suppressing weeds while others remained fully intact and, thus, did not permit daughter plant rooting and, furthermore, created a disposal issue. Miles et al. (2012) tested paper mulch which degraded fully within the first year and noted that the wind would blow the material up from the soil surface, resulting in many rips and tears throughout the season.

Hemp hurd is a novel material that may prove to be an effective alternative mulching material suitable for organic systems. Hurd is the soft, woody, inner core of the hemp (*Cannabis* L.) plant stalk. Hemp hurd is a byproduct of the fiber industry (Pecenka 2012). Fiber yields average 25% of total shoot biomass, compared to the hurd yield of 55% of total shoot biomass (Pecenka 2012). Economic analysis by Pecenka (2012) noted that hemp fibers garnered a price of \$0.55 kg^{-1}, whereas hurd prices range from \$0.15 to \$0.28 kg^{-1}.

Because of its relative abundance, low cost, and status as a crop byproduct, hemp hurd is an excellent candidate as a mulch material for matted-row strawberry production.

Hemp hurd is used for an array of applications including mulch, animal bedding, paper products, and building materials such as fiberboard and insulation (Salentijn et al. 2014). The companies that produce hemp hurd mulch tout several advantages. One claim is that the composition of the hurd (high in lignin and pectin) causes the fibers to knit together making the mulch less prone to wind erosion and better able to insulate the soil (Anonymous 2017a). The hemp hurd pieces are small and, thus, pack together tightly, compared to the long strands of hay mulch which create air pockets within the mulch matrix. Due to these properties, hemp hurd mulch reportedly creates an environment favorable to micro-organisms and earthworms while deterring unwanted pests such as slugs and snails; furthermore, the texture eases use as it is gentle on skin (Anonymous 2017a). Another attribute is the ability to fully degrade and add organic matter to the soil (Anonymous 2017a). Although hemp-based mulch has the potential for use in production systems, no research has yet been conducted to verify the claims about these benefits of hemp hurd mulch. Effective weed management is crucial for perennial strawberry production and the common mulching products exhibit limitations; therefore, introducing novel mulch materials would benefit producers.

Biochar as a Soil Amendment

Besides applying mulches, organic producers apply various soil amendments to aid plant productivity. Calcium carbonate (lime), is a common soil amendment added to increase soil pH and reverse the soil acidification that generally results following intensive crop production (Sims 1996). In a study on strawberry by Hargreaves et al. (2008), composted municipal solid waste, ruminant compost, and the non-aerated compost tea of these two compost sources were tested as organic soil amendments. Soil amendments are also used for insect control, immobilizing metals in the soil, managing soil-borne pathogens, alteration of the soil chemical makeup and availability of nutrients, bioremediation, etc. (Akhtar and Malik 2000; Park et al. 2011; Lazarovits 2010; Hanselman et al. 2004).

Biochar is a stable form of carbon with a high capacity for retaining nutrients; as such, it is of interest to researchers with regard to climate change, soil improvement, and environmental remediation (Lehmann 2007). During pyrolysis (i.e., heating of biomass in an anaerobic environment) mineralized or fixed carbon is not oxidized (becomes charcoal or biochar) while organic matter within the sample is decomposed into combustible gasses (i.e., biofuel) (Xie et al. 2015). Biofuel and biochar are products of pyrolyzing biomass; approximately 50% of the feedstock becomes biochar (Lehmann 2007). Various source materials have been used as biomass feedstock for pyrolysis: sweet chestnut (*Castanea sativa* Mill.) shells (Jay et al. 2015), hardwood, softwood, wheat middlings, pine (*Pinus* L.) chips, macadamia nut (*Macadamia integrifolia* Maiden & Betche) shells (Weyers and Spokas 2014), coconut (*Cocos* L.) shells, corn plant residue, peanut (*Arachis* L.) shells, pecan (*Carya illinoinensis* (Wangenh.) K. Koch) shells, rice (*Oryza* L.) straw, poultry litter, and sewage sludge (Atkinson et al. 2010) amongst others. Pyrolysis temperatures vary depending on the stability of the carbon in the source material and range from 220 to 1040 C (Xie et al. 2015). Pyrolysis duration varies from two seconds to 24 hours (Xie et al. 2015).

Because production methods and source materials can vary so greatly, the performance of biochar in field applications is variable (Xie et al. 2015). A review assessing the effects of biochar on crop productivity found that biochar application had a positive effect on production (Jeffery et al. 2011). The lack of effect of biochar applications on crop productivity in (various crops) was attributed by Jay et al. (2015) to the already fertile soil. A 2.5-year study by Weyers and Spokas (2014) found that a single biochar application did not increase the biodegradation of wheat residues. Atkinson et al. (2010) concluded that the effects of biochar on agricultural productivity are apparent in tropical regions but increased research is needed in the northern hemisphere. According to Harel et al. (2012), three foliar diseases of strawberry caused by fungal pathogens were reduced in severity due to the application of biochar. In addition to possible disease management, biochar has been shown to sequester carbon and improve soil health measures including cation exchange capacity, water and nutrient retention, and physical characteristics (Atkinson 2010).

Experiment Objectives and Hypotheses

In order to fill existing knowledge gaps regarding the use of novel mulch material, hemp hurd, and add to the current discussion regarding paper mulches and biochar in organic strawberry production systems, experiments were conducted to address the following objectives and hypotheses.

Objective 1: Quantify measures of strawberry plant growth as affected by mulch materials (alfalfa hay, paper, and hemp hurd) and soil applied biochar during establishment and harvest seasons at two locations with different climates.

Objective 2: Quantify weed biomass to assess weed suppressive capacity of alfalfa hay, paper, and hemp hurd mulches.

Objective 3: Evaluate strawberry yield data for impacts of mulch type or biochar application.

Objective 4: Track soil temperature to determine insulating properties of tested mulches.

Objective 5: Demonstrate that paper mulch and the novel mulch material, hemp hurd, are suitable for use in matted-row strawberry plantings.

Hypothesis 1: Hemp hurd mulch will provide greater weed suppression during the establishment year compared to bare soil (control) or alfalfa hay mulch.

Hypothesis 2: Paper mulch will provide greater weed suppression during the establishment year compared to bare soil and alfalfa hay mulch.

Hypothesis 3: Hemp hurd mulch will provide greater weed suppression during the harvest year than bare soil, alfalfa hay mulch, and paper mulch.

Hypothesis 4: Alfalfa hay and hemp hurd mulch will insulate soil with regard to soil temperature to a greater degree than paper mulch or bare soil.

Hypothesis 5: Biochar application will be associated with increased strawberry yield.

Hypothesis 6: Hemp hurd and paper mulches will be associated with increased strawberry yield.

Materials and Methods

Site Information

Absaraka is located at 46.987624, -97.352319 with an elevation of 285 m. Ten-year average rainfall is 46.2 cm. Soil at the Absaraka site is a Warsing sandy loam (WebSoilSurvey). During the time period over which the experiment was conducted, (1) maximum summer temperature was 33.6 C, (2) minimum summer temperature was 5.6 C, (3) average summer temperature was 20.2 C, (4) average summer wind speeds were 3.1 m/s and peaked at 20.8 m/s, (5) maximum winter temperature was 12 C, (6) minimum winter temperature was -31.9 C, (7) average winter temperature was -8.7 C, (8) winter wind speeds averaged 4.5 m/s and peaked at 21.1 m/s, (9) average dew point was -10.9 C, and (10) minimum wind chill was -44 C and averaged -15.1 C (Anonymous 2017b).

Dickinson is located at 46.893566, -102.819951 with an elevation of 779 m. Ten-year average rainfall is 34.8 cm. Soil at the Dickinson site is an Arnegard loam (WebSoilSurvey). During the time period over which the experiment was conducted, (1) maximum summer temperature was 38.4 C, (2) minimum summer temperature was 3.1 C, (3) average summer temperature was 20.6, (4) summer wind speeds averaged at 3.12 m/s with maximum wind speed of 28.13 m/s, (5) maximum winter temperature was 19.1 C, (6) minimum winter temperature was -31.4 C, (7) average winter temperature was -6.6 C, (8) winter wind speeds averaged 3.56 m/s and maximum wind speed was 20.79 m/s, (9) average dew point was -9.6 C, and (10) average wind chill was -11.7 C with a minimum wind chill of -41.2 C (Anonymous 2017b).

Experimental Design

Field trials were conducted during 2015 (establishment year) and 2016 (production year) at the NDSU Horticulture Research Farm in Absaraka, ND and at the Dickinson Research Extension Center in Dickinson, ND, to investigate the ability of mulch materials (paper, hemp hurd, alfalfa hay) and pine-derived biochar to test some of the previously noted benefits in perennial organic strawberry production. The experiment was designed as a 2 (biochar vs. no biochar) by 4 (alfalfa hay, paper, hemp hurd, or bare soil) factorial arranged in a randomized complete block. Each treatment block was replicated four times per site.

Prior to planting strawberries, experimental plot land was tilled at both sites to eliminate emerging weeds and soil fertility was improved by an application of pelletized composted poultry manure 4-3-5 (Ag Resource Inc; Detroit Lakes, MN) to the Absaraka site to achieve a N rate of 67.25 kg ha^{-1} and dried beef cow manure to the Dickinson site to achieve a N rate of 58.8 kg ha^{-1} during the first year (Christensen and Peacock NG7-97). Pine-derived biochar was applied at a rate of 11.25 m^{3} ha^{-1} per plot assigned treatment; biochar was tilled into the soil with a rototiller before the strawberry plants were transplanted. 'Cavendish' variety bare root strawberry plants (Ag Resource, Inc., Detroit Lakes, MN) were transplanted during early June into prepared beds at both sites in a staggered double row formation with 30.5 cm spacing between all plants, resulting in 17 plants per plot. Individual plot dimensions were 3.1 by 0.6 m with a 0.6 m alley separating adjacent plots. To ensure adequate water for strawberry establishment, a drip irrigation system was installed at the Dickinson site while hand watering was used at the Absaraka site to ensure that plants were adequately supplied with water. To reduce weed pressure along the edges of plots, alfalfa hay mulch was spread in the alleyways. Hemp hurd mulch (Hemp Technologies LLC; Asheville, NC) was applied at a rate of 0.13 m^{3} (equivalent to one bale) per plot. The hemp hurd mulch was wetted before application to plots to ease placement and prevent wind dispersal. This mulch is composed primarily of cellulose (44-

55%), hemicelluloses (16-18%), and lignin (4-28%) (Anonymous 2014). Hemp hurd mulch application required ~40 minutes per plot. Alfalfa hay was teased apart and applied until a depth of ~10 cm was covering the soil. Application of alfalfa hay mulch required ~30 minutes per plot. Paper mulch (WeedGuardPlus; Sunshine Paper Co. LLC; Aurora, CO) was applied by placing one 46 cm diameter circle around each plant and securing with wire field staples. Paper mulch application required ~8 minutes per plot. Plants were fertilized (27 DAP and 66 DAP) during the establishment year using a 5-1-1 fish emulsion (Alaska; Lilly Miller Brands; Walnut Creek, CA) at a rate of 0.6 kg N ha^{-1}. Plants were winterized in early November by covering with 1.5 oz. point bonded polypropylene fabric with 50% light transmission (Supreme Row Cover; DeWitt Company, Inc.; Sikeston, MO) and then alfalfa hay was placed on top for increased insulation.

Data Collection

Flower, leaf, and runner counts were determined throughout the establishment year. Production year measurements consisted of fruit number and weight. Weed biomass and soil temperature were measured during both years of the experiment. Weed density and weed species were recorded during the establishment year only. For dates of field activities reference Table 2.1.

Leaf number was determined by randomly selecting four plant positions and counting the number of leaves produced by these plants in each plot. To follow procedures typical of matted-row production systems, all flowers were removed during the establishment year to encourage vegetative growth and runner production. Flowers were counted and reported per plot during the removal process. Runners were counted and pruned so that transplanted plants were limited to four runners, or daughter plants, per plant. Maximum final plant density was 36 plants per 1 m^2.

Table 2.1. The timing of field and data collection activities.

	Absaraka	Dickinson
Bed Preparation	1 June 2015	8 June 2015
Biochar Application	4 June 2015	11 June 2015
Strawberry Planting	5 June 2015	11 June 2015
Mulch Application	16-18 June 2015	11-19 June 2015
Weed Removal	2 July 2015	14 July 2015
	21 July 2015	19 August 2015
	20 July 2016	27 July 2016
First Flowers	9 May 2016	
Harvest	16 June 2016	20 June 2016
	23 June 2016	27 June 2016
	28 June 2016	
	6 July 2016	
Soil Sampling	8 September 2016	16 September 2016

To measure soil temperature, data loggers (HOBO Pendant® Temperature/Light 64K; Onset; Bourne, MA) were installed to a depth of 10 cm and set to record temperature every six hours at Absaraka (4AM, 10AM, 4PM, 10PM UTC-5) and Dickinson (1AM, 7AM, 1PM, 7PM UTC-5). The soil temperature pendants remained in the soil until completion of the experiment in 2016. Daily average, minimum, and maximum values were calculated for each site over summer and winter time periods. Data subjected to analyses were limited to the average daily average, minimum, and maximum from 6 June 2015 to 31 August 2015 (Absaraka) and 1 June 2016 to 31 August 2016 (Absaraka and Dickinson) for the summer analysis, and 1 December 2015 to 29 February 2016 (Absaraka and Dickinson) for the winter analysis.

For the duration of the establishment year, weed population biomass and density were quantified via destructive harvest of all weed shoots, with subsequent sorting and counting of the weeds by species. The weeds were placed in paper bags, dried at 70 C to a constant mass, and weighed. During the establishment year, weeds were removed on a timely basis such that plant establishment should not have been affected by differential weed pressure among plots and experimental treatments. During the production year (2016), weeds remained in the plot until harvest was complete. Weeds were then collected via destructive harvest, sorted into categories: broadleaves or grasses, dried at 70 C to constant mass, and weighed. Although weed species or category is not an aspect of the statistical analyses presented herein, this step provided information regarding the weed community at each site. At Absaraka, broadleaf weeds were more prevalent than grass weeds during both years of the experiment. Notable weeds from this site during the establishment year included, (1) common lambsquarters, (2) common purslane, (3) stink grass (*Eragrostis cilianensis* (All.) Vign. ex Janchen), (4) hairy vetch, and (5) redroot pigweed. At Dickinson, grass weeds were more prevalent than broadleaf weeds during the establishment year whereas, during the production year, broadleaf weeds were predominant over grass weeds. Notable weeds during the establishment year at the Dickinson site included, (1) green foxtail, (2) barnyard grass, (3) field bindweed, (4) common lambsquarters, and (5) common purslane.

Statistical Analyses

Analysis of variance (ANOVA) tests ($p < 0.05$) were performed using PROC MIXED in SAS 9.2 (SAS Institute Inc., Cary, NC) to understand the effects of treatment factors biochar, mulch, site, and their interactions on several response variables. Before conducting ANOVA tests, data were assessed for homogeneity of variance (Levene's test) and normality (Shapiro-Wilk test) to determine whether the data meet ANOVA assumptions for each response variable within each univariate treatment factor. Soil temperatures were only tested for effects of mulch, site, and their interaction. Data were transformed appropriately to improve conformation to assumptions. Post-hoc multiple comparisons were made using Tukey's HSD and the Bonferroni adjustment. Tests of simple effects ('slice' option in PROC MIXED lsmeans) were used to assess treatment effects in the event of higher-order interactions.

Results and Discussion

Soil Temperature

Because extremes of temperature can better elucidate the ability of mulch materials to buffer soil temperature extremes, only summer maximum temperature and winter minimum temperature were examined.

At Absaraka during 2015, the simple effect of mulch on maximum soil temperature was highly significant (p < 0.0001). The average maximum daily temperatures during the summer were 2.2 to 4.2 C warmer for bare soil plots (26.1 C) than for mulched plots (Table 2.2). Alfalfa hay mulch and hemp hurd mulch were associated with the coolest daily maximum soil temperatures (21.9 and 22.5 C, respectively) (Table 2.2). Paper mulched plots were intermediary with regard to average maximum temperature (23.9 C) (Table 2.2). Sensors were not installed at the Dickinson site during this time period.

Table 2.2. Mean 2015 summer maximum soil temperature at Absaraka as affected by mulch.

	°C	
Alfalfa Hay	21.9	c[a]
Hemp Hurd	22.5	bc
Paper	23.9	b
Bare Soil	26.1	a

[a] Means followed by different lowercase letters within site and year differed at $P \leq 0.05$ according to Tukey's HSD.

For average minimum daily temperature during the winter, a mulch by site interaction was present (*p* = 0.0176). At Absaraka, alfalfa hay and hemp hurd mulches kept the soil warmer throughout the winter compared to bare soil and paper mulch (average minimum temperatures of 2.2 and 2.3 vs. 1.7 and 1.6 C, respectively) (Table 2.3). At Dickinson, alfalfa hay mulch kept the soil slightly warmer than hemp hurd, paper, or bare soil (-0.1 vs. -0.7, -1.0, -1.1 C, respectively) (Table 2.3).

These differences occurred even though all plots were equally covered with thermal row cover and a layer of alfalfa hay during the winter. Alfalfa hay and hemp hurd mulches created a layer over the soil several cm thick. Paper mulch was comparatively thin, and did not differ from bare soil.

Table 2.3. Mean (± S.E.) winter minimum soil temperature as affected by mulch type.

	Absaraka		Dickinson	
	°C			
Alfalfa Hay	2.2	a[a]	-0.1	a
Hemp Hurd	2.3	a	-0.7	b
Paper	1.6	b	-1.0	bc
Bare Soil	1.7	b	-1.1	c

[a] Means followed by different lowercase letters within site differed at $P \leq 0.05$ according to Tukey's HSD.

For average maximum summer soil temperatures recorded during 2016, a mulch by site interaction was present (*p* = 0.004). At Absaraka in 2016, hemp hurd and paper mulched plots differed with regard to soil temperature (19.6 vs. 20.4 C, respectively); all other mulch comparisons were similar (Table 2.4). In Dickinson during 2016, alfalfa hay and hemp hurd mulches kept the soil cooler (19.8 and 20.0 C, respectively) than paper mulch and bare soil (21.1 and 21.5 C, respectively) (Table 2.4).

Table 2.4. Mean 2016 summer maximum daily soil temperature as affected by mulch.

	Absaraka			Dickinson		
	°C					
Alfalfa Hay	19.7	ab[a]	A[b]	19.8	b	A
Hemp Hurd	19.6	b	A	20.0	b	A
Paper	20.4	a	B	21.1	a	A
Bare Soil	20.1	ab	B	21.5	a	A

[a] Means followed by different lowercase letters within site and year differed at $P \leq 0.05$ according to Tukey's HSD.

[b] Means followed by different uppercase letters across site and within year and mulch type differed at $P \leq 0.05$ according to Tukey's HSD.

Hemp hurd and alfalfa hay mulch kept the soil cooler in the heat of the summer and warmer in the cold of the winter. Differences, especially in the winter, were slight (~ 1 degree) (Figure 2.3). Hemp hurd and alfalfa hay buffered soil temperatures better than paper mulch and bare soil. More differences were found in Dickinson with respect to soil temperature in 2016 than in Absaraka, where temperatures were more similar among mulch types than during 2015 (Tables 2.4, 2.2). This could be due to the mulch treatments degrading to an extent that the mulch is no longer moderating soil temperature or the strawberry canopy is effective in moderating soil temperature. The Absaraka site did receive a greater amount of its water via natural rainfall vs drip irrigation compared to the Dickinson site, which could have led to greater mulch degradation. However, the Dickinson site was less protected from wind which could have displaced or torn the mulch materials. Because canopy cover was more complete in Absaraka than in Dickinson and because, observationally, there was little mulch degradation, the strawberry canopy is credited with mediating soil temperature in 2016.

High soil temperatures and reduced water availability in the rooting zone can affect gas exchange rates, namely a decline in stomatal conductance and transpiration (Hancock

1999; Prakash and Ramachandran 2000). During the first two years of cucumber (*Cucumis sativus* L.) growth studied by Haapala et al. (2015), fewer differences in soil temperature among mulch types were observed as the summer season progressed and the plants contributed to soil shading. Similarly, plastic, hairy vetch, and rye mulches exhibited fewer differences in soil temperature at the end of the season compared to early in the growing season (Feeser et al. 2014). Early season soil temperatures for mulched plots ranged from 1 to 3 degrees cooler than those of bare soil plots (Haapala et al. 2015). Wheat straw mulch lowered the soil temperature 2 to 4 C degrees compared to bare soil in watermelon (*Citrullus* Schrad. ex Eckl. & Zeyh.) and potato (*Solanum tuberosum* L.) plantings (Johnson et al. 2004). Compared to bare soil, chopped wheat straw, fen peat, sawdust, and grass mulches each lowered soil temperature; wheat had the greatest cooling impact, with a maximum difference of 1.6 C (Sinkeviciene et al. 2009).

Soil Chemical Properties

Soil Nitrogen

For the soil nitrogen analysis, an interaction between site and mulch type was present ($p < 0.0001$), therefore sites were analyzed separately. Dickinson soil N did not differ among mulch types ($p = 0.7118$) (Table 2.5). At Absaraka, plots mulched with alfalfa hay contained greater soil N (175 kg ha^{-1}) compared to bare soil, paper mulch, and hemp hurd mulch (72, 54, and 46 kg ha^{-1}, respectively). Bare soil and hemp hurd mulch differed from one another but neither differed from paper mulch (Table 2.5). Biochar did not impact soil N ($p = 0.0959$).

The hemp hurd mulch had a C:N ratio of 54:1 and the paper mulch had a C:N ratio of 121:1 (NDSU Soil Testing Lab). Young alfalfa hay typically has a C:N ratio of 13:1 and mature alfalfa hay has a C:N ratio of 25:1 (USDA-NRCS 2011). The C:N ratio affects nutrient cycling by either immobilizing N (high C:N ratio) or providing N (low C:N ratio) to the system (USDA-NRCS 2011). Due to the high C:N ratio, both hemp hurd and paper mulches have the potential of immobilizing nitrogen in the soil. Conversely, the C:N ratio of alfalfa hay indicates the likely release of nitrogen into the soil solution for uptake by crop plants. Schonbeck and Evanylo (1998) credited differences in soil N between mulch types to the dynamics of soil N with organic mulches and to leaching under plastic and oiled paper. Nitrogen mineralization can be increased during the fall under a mulch application compared to bare soil due to increased soil temperature and conserved soil moisture (Berglund et al. 2006); yet the C:N ratio of these mulches must be considered as a high C:N ratio may mitigate the effects of temperature and moisture.

The Absaraka site was subject to more rain during the growing season than the Dickinson site. Moist conditions favor mulch degradation and subsequent N mineralization in the soil if the C:N ratio of the mulch is low (Schonbeck and Evanylo 1998). The humid conditions may explain the increased N observed with the alfalfa hay mulch at the Absaraka site.

Table 2.5. Mean soil nitrogen (N) as affected by mulch type and site.

	Absaraka			Dickinson		
	kg N ha^{-1}					
Alfalfa Hay	175	a[a]	A[b]	20	a	B
Hemp Hurd	46	c	A	10	a	B
Paper	54	bc	A	11	a	B
Bare Soil	72	b	A	9	a	B

[a] Means followed by different lowercase letters within site differed at $P \leq 0.05$ according to Tukey's HSD.

[b] Means followed by different uppercase letters across site and within mulch type differed at $P \leq 0.05$ according to Tukey's HSD.

Soil Phosphorus

With regard to soil *P*, an interaction was present between site and mulch type ($p < 0.0001$). Dickinson soil P was greater than the soil P at Absaraka, but only when plots were mulched with paper (15 vs. 10 ppm); for all other mulch types, soil P did not differ between sites (Table 2.6). Plots at Dickinson did not differ in terms of soil P with regard to mulch type (*p* = 0.1669) (Table 2.6). At Absaraka, alfalfa hay mulch was associated with the greatest soil P (18 ppm), which exceeded soil P associated with hemp hurd, paper, or bare soil (13, 10, and 11 ppm, respectively) (Table 2.6). Soil P in plots mulched with hemp hurd had an intermediary soil P content of 13 ppm (Table 2.6). Paper and bare soil were associated with the least amounts of soil P (10 and 11 ppm, respectively) (Table 2.6). Biochar did not affect soil phosphorus at either site (*p* = 0.3242).

Soil phosphorus levels at both sites were well below recommendations from the University of Minnesota Extension production guide (Hoover et. al, 2017). Jay et al. (2015) found that soil extractable P decreased with applications of biochar. Phosphorus is less available when pH is less than 5.5.

Table 2.6. Mean soil phosphorus (P) parts per million (ppm) as affected by mulch type and site.

	Absaraka			Dickinson		
	P ppm					
Alfalfa Hay	18.3	a[a]	A[b]	16.3	a	A
Hemp Hurd	12.8	b	A	15.5	a	A
Paper	10.1	c	B	15.3	a	A
Bare Soil	10.6	bc	A	14.3	a	A

[a] Means followed by different lowercase letters within site differed at $P \leq 0.05$ according to Tukey's HSD.

[b] Means followed by different uppercase letters across site and within mulch type differed at $P \leq 0.05$ according to Tukey's HSD.

Soil Potassium

For soil potassium, a site by mulch type interaction was present (*p* < 0.0001). Soil K was greater at Dickinson than at Absaraka, except for plots mulched with alfalfa hay (Table 2.7). At Absaraka, plots mulched with alfalfa hay had the greatest amount of soil K (290 ppm) (Table 2.7). Soil in plots mulched with hemp hurd had an intermediary amount of soil K (196 ppm) (Table 2.7). Bare soil and paper mulch were associated with the least amounts of soil K (119 and 113 ppm, respectively) (Table 2.7). At Dickinson, soil mulched with hemp hurd and alfalfa hay had the greatest amount of soil K (390 and 366 ppm, respectively), while bare soil and soil mulched with paper had the least amount of soil K (316 and 318 ppm, respectively) (Table 2.7). Biochar did not impact soil potassium (*p* = 0.4438) (data not shown).

Based on the University of Minnesota strawberry production guide K recommendations, the Dickinson site and alfalfa hay mulched plots in Absaraka provided a surplus of potassium compared to the other treatments at the Absaraka site. (Hoover et. al, 2017). Increased soil K was associated with a biochar application in a study by Jay et al. (2015).

Table 2.7. Mean (± S.E.) soil potassium (K) parts per million (ppm) as affected by mulch type and site.

	Absaraka			Dickinson		
	K ppm					
Alfalfa Hay	290.0	a[a]	A[b]	365.5	a	A
Hemp Hurd	195.6	b	B	389.6	a	A
Paper	113.1	c	B	318.3	b	A
Bare Soil	118.9	c	B	316.4	b	A

[a] Means followed by different lowercase letters within site differed at $P \leq 0.05$ according to Tukey's HSD.

[b] Means followed by different uppercase letters across site and within mulch type differed at $P \leq 0.05$ according to Tukey's HSD.

Soil pH

Simple effects of site ($p < 0.0001$), mulch type ($p = 0.0007$), and biochar application ($p=0.0016$) were all significant with respect to soil pH. Soil pH was much greater at Absaraka than at Dickinson (8.00 vs. 5.73, respectively) (Table 2.8). Soil mulched with alfalfa hay had reduced soil pH compared to soil mulched with hemp hurd or bare soil (6.71 vs. 6.94 and 6.96, respectively) (Table 2.8). Soil mulched with paper had an intermediary soil pH of 6.86, which did not differ from the soil pH values associated with other mulch types (Table 2.8). Biochar application was associated with a slight increase in soil pH (6.94 vs. 6.79) (Table 2.8).

Other than the site effect, these differences in soil pH are minor and differences are not likely biologically relevant, in spite of differences being significant statistically. Jay et al. (2015) reported that an increase in soil pH was associated with an increase in biochar application in barley, potato, and strawberry plantings. As in our study, after 18 months, no differences in pH were found between bare soil and paper mulch (Li et al. 2013).

Table 2.8. Mean (± S.E.) soil pH as affected by site, mulch, and biochar.

		pH	
Site	Absaraka	8.00	a[a]
	Dickinson	5.73	b
Mulch	Alfalfa Hay	6.71	b
	Hemp Hurd	6.94	a
	Paper	6.86	ab
	Bare Soil	6.96	a
Biochar[b]	-	6.79	b
	+	6.94	a

[a] Means followed by different lowercase letters within factor (site, mulch, or biochar) differed at $P \leq 0.05$ according to Tukey's HSD.

[b] (-) indicates that no biochar was added to the soil and (+) indicates that biochar was added to the soil.

Soil Organic Matter

Simple effects of site (p = 0.0011) and biochar (p = 0.0105) were significant regarding soil organic matter; mulch had no impact on soil organic matter (p = 0.8714) Dickinson soil has greater soil organic matter than Absaraka soil (2.8 vs. 2.3 %, respectively) (Table 2.9). Biochar application was associated in increased soil organic matter (2.6 vs. 2.5% OM) (Table 2.9).

The site at Dickinson had been managed organically for a longer period of time than the Absaraka site, however not long enough for differences in soil organic matter to develop. Soil organic matter results might also be related to soil type or soil water content (Nelson and Sommers 1996). The minor increase associated with biochar is not unexpected as biochar is an additional source of carbon.

Table 2.9. Mean (± S.E.) percent soil organic matter (SOM) as affected by site and biochar treatment.

		%	
Site	Absaraka	2.30	b[a]
	Dickinson	2.84	a
Biochar[b]	-	2.52	b
	+	2.63	a

[a] Means followed by different lowercase letters within factor (site or biochar) differed at $P \leq 0.05$ according to Tukey's HSD.

[b] (-) indicates that no biochar was added to the soil and (+) indicates that biochar was added to the soil.

Establishment Year Weed Pressure

Weed Biomass

Simple effects of site ($p = 0.0036$) and mulch type ($p < 0.0001$) were highly significant. Plots at Absaraka contained greater weed biomass than plots at Dickinson (22 vs. 11.1 g m^{-2}) (Figure 2.1). Regardless of site or biochar application, bare soil plots were associated with the greatest weed biomass (52.3 g m^{-2}) compared with plots mulched with alfalfa hay, paper, or hemp hurd (6.1, 6.1, and 1.7 g m^{-2}, respectively) (Figure 2.1). Paper and hemp hurd mulched plots were different from each other but neither was different from plots mulched with alfalfa hay (Figure 2.1). Weed biomass during 2015 did not differ with respect to biochar treatment ($p = 0.9414$) (data not shown).

Within the hemp hurd and alfalfa hay mulch treatments, soil was completely covered by the mulches, greatly reducing weed growth. In the paper mulch treatment, weed growth occurred in the bare soil exposed along the scalloped border of the plot created by the paper circles and directly adjacent to the strawberry plants via the space cut out of the paper for the strawberry plants. The relationship between physical mulch properties (biomass, height, light extinction, etc.) and weed emergence was examined by Teasdale and Mohler (2000) where they found greater weed emergence occurred as the fraction of uncovered soil area increased.

Schonbeck (1999) reported that weed biomass was reduced by paper and hay mulch treatments compared with bare soil early in the season during tomato (*Solanum lycopersicum* L.) establishment, but that only hay mulch resulted in less weed biomass later in the season because of decomposition of the paper treatment. Similar to our study, during the establishment year of organic pumpkin (*Cucurbita* L.) and throughout three years of tomato growth, all mulch materials tested (rice straw, barley straw, maize residue, absinth wormwood (*Artemisia absinthium* L.), biodegradable plastic, paper, polyethylene, wood chips, newspaper, and newspaper plus grass) resulted in reduced weed density and biomass compared to bare soil (Splawski et al. 2016; Anzalone et al. 2010).

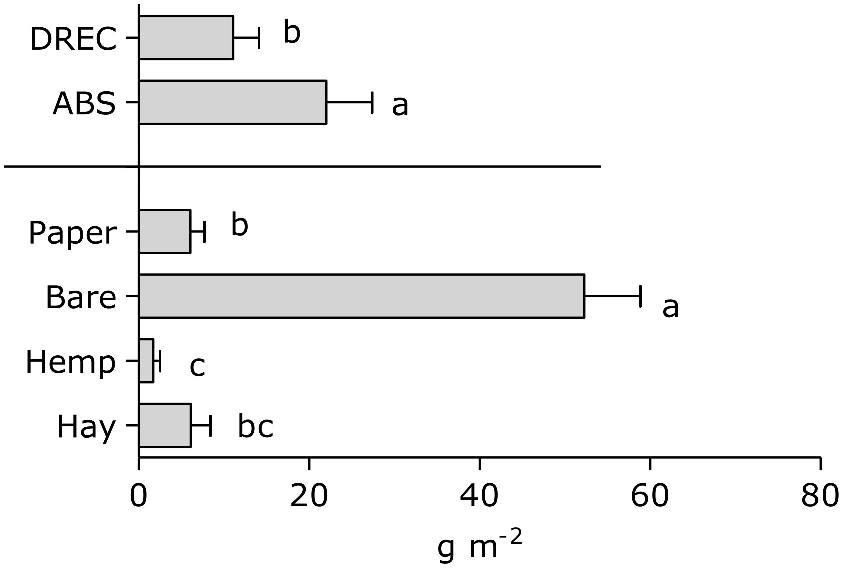

Figure 2.1. 2015 mean (± S.E.) total weed biomass as affected by mulch type and site. Bars labeled with different lowercase letters within site or mulch differ at $P \leq 0.05$ according to Tukey’s HSD.

Weed Density

Interactions between mulch type and site ($p < 0.0001$) as well as between mulch type and biochar application ($p = 0.0257$) occurred for weed density. Consequently, mulch effects on weed density were determined separately for each site and for each level of biochar application. At Absaraka, all mulches differed from one another except alfalfa hay and hemp hurd, which were associated with the least weed density (Figure 2.2). Bare soil plots were associated with the greatest weed density (211.5 m^{-2}) (Figure 2.2). At Dickinson, the greatest weed density occurred in bare soil plots (103.0 m^{-2}); the mulch materials did not differ with respect to weed density (Figure 2.2). When biochar was applied to the soil, bare soil was associated with the greatest weed density (162.7 m^{-2}) followed by paper, hemp hurd, and alfalfa hay (21.8, 12.8, and 7.9 m^{-2}, respectively); although paper and alfalfa hay mulches differed with regard to weed density, neither differed from hemp hurd mulch (Figure 2.2). Mulch treatments differed except hemp hurd and alfalfa hay mulches in the absence of biochar (1.5 and 10.8 m^{-2}, respectively). Greatest weed density occurred in bare soil (151.8 m^{-2}), while paper mulch was associated with moderate weed density (30 m^{-2}) (Figure 2.2). Sinkeviciene et al. (2009) reported that weed density was 2.8 to 6.4 times lower in straw mulched plots compared to bare soil, demonstrating that hay is an effective weed barrier.

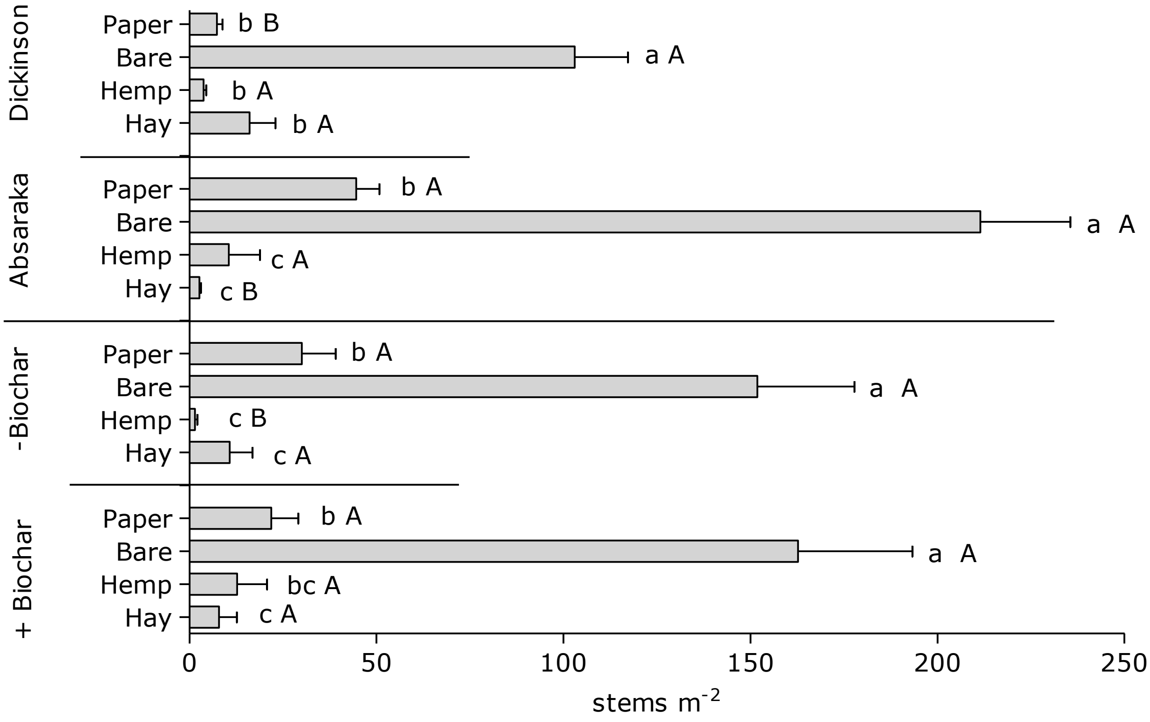

Figure 2.2. 2015 mean (± S.E.) weed density as affected by the site (A) or biochar (B) interaction with mulch type. Bars labeled with different lowercase letters within site or biochar application differ at $P \leq 0.05$ according to Tukey's HSD. Bars labeled with different uppercase letters across site or biochar treatment and within mulch type differ at $P \leq 0.05$ according to Tukey's HSD.

Establishment Year Strawberry Growth and Reproduction

Leaf Number

Strawberry plant leaf numbers per plant were consistently affected by the mulch treatments ($p < 0.0001$) pooled across sites with paper mulched plots producing the greatest number of leaves (3.9 leaves plant^{-1}) compared to bare soil (3.3 leaves plant^{-1}), and hemp hurd (3.3 leaves plant^{-1}) plots; the fewest leaves per plant were associated with those plants in alfalfa hay mulched plots (2.6 leaves plant^{-1}) (Figure 2.3). Biochar application did not affect the leaf numbers compared to non-amended soil ($p = 0.2572$).

Since weeds were removed from all plots in a timely manner, the differences among mulches with regard to leaf number are likely due to some other factor besides weed pressure that varied with mulch type. Research assessing the effects of paper and hemp hurd mulch on strawberry vegetative growth during establishment is lacking, with most research focused on fruit yield. Bakshi et al. (2014) found no differences between plastic, cut grass, and chopped wheat straw with respect to leaf number, while all mulches increased leaf number compared to the weedy control. Shading associated with the alfalfa hay mulch may have affected leaf production in the first year of growth as light capture is correlated with photosynthetic assimilation rates, which decreases under low light (Hancock 1999).

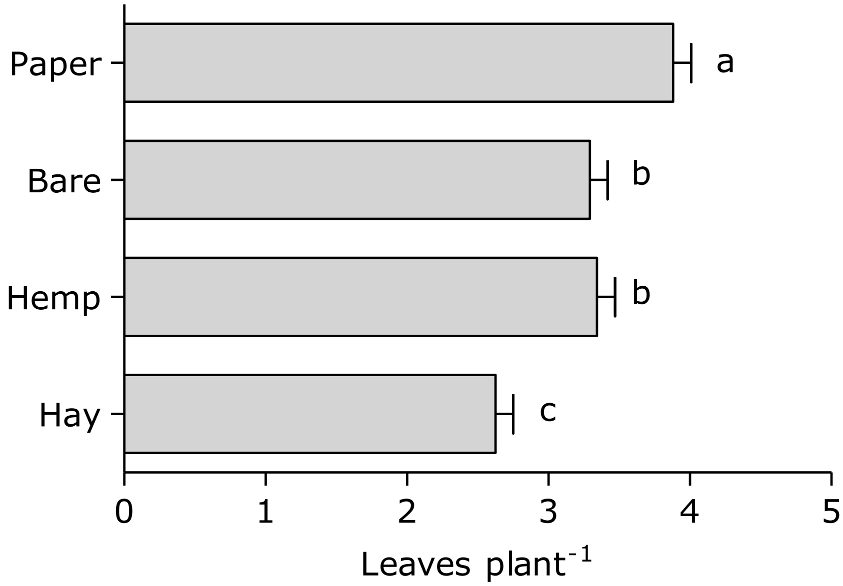

Figure 2.3. Mean (± S.E.) strawberry leaves as affected by mulch type. Data was pooled across sites. Bars labeled with different lowercase letters differ at *P* ≤ 0.05 according to Tukey's HSD.

Flower Number

For flower numbers, a site by mulch type interaction was present (*p* = 0.0032) as was a site by biochar application interaction (*p* = 0.0049). Consequently, mulch and biochar effects on strawberry flower number were analyzed separately by site. At Absaraka, alfalfa hay mulch was associated with the fewest number of flowers per plant (3.6 flowers plant^{-1}) compared to hemp hurd mulch, bare soil, and paper mulch (5.0, 5.1, and 5.9 flowers plant^{-1}, respectively) (Table 2.10). Biochar did not impact number of flowers at Absaraka (p = 0.0546). At Dickinson, hemp hurd mulched plots produced the greatest number of flowers per plant (5.4 flowers plant^{-1}), compared with paper, alfalfa hay, or bare soil (3.7, 2.9, and 3.2 flowers plant^{-1}, respectively) (Table 2.10). At Dickinson, biochar application was associated with fewer flowers per plant than non-amended plots (3.4 vs 4.2 flowers plant^{-1}) (Table 2.10). Since weeds were removed from all plots in a timely manner, the differences among mulches with regard to flower number are likely due to some other factor besides weed pressure.

Hay mulch was associated with the fewest flowers and fewest leaves per plant during the establishment year (Figure 2.3, Table 2.10). The lowest leaf count also was associated with fewest flowers in another study comparing the effects of mulches on strawberry establishment and yield (Bakshi et al. 2014).

Table 2.10. Mean (± S.E.) number of flowers as affected by mulch and biochar.

		Absaraka			Dickinson		
		flowers plant^{-1}					
Mulch	Alfalfa Hay	3.6	b[a]	A[b]	2.9	b	A
	Hemp Hurd	5.0	a	A	5.4	a	A
	Paper	5.9	a	A	3.7	b	B
	Bare Soil	5.1	a	A	3.2	b	B
Biochar[c]	-	4.5	a	A	4.2	a	A
	+	5.2	a	A	3.4	b	B

[a] Means followed by different lowercase letters within site and factor (mulch or biochar) differed at $P \leq 0.05$ according to Tukey's HSD.

[b] Means followed by different uppercase letters across site and within treatment (mulch type or biochar application) differed at $P \leq 0.05$ according to Tukey's HSD.

[c] (-) indicates that no biochar was added to the soil and (+) indicates that biochar was added to the soil.

Runner Number

For strawberry runner production during the establishment year, simple effects of site and mulch type were significant ($p < 0.0001$). Strawberries grown without mulch or with alfalfa hay produced fewer runners per plant than those grown with hemp hurd or paper mulch (2.4 and 2.7 vs. 4.5 and 4.9 runners per plant, respectively) (Figure 2.4). Strawberry plants grown at Dickinson produced more runners than those grown at Absaraka (4.3 vs. 2.9 runners per plant) (Figure 2.4). Strawberry plant runner numbers were not affected by the biochar treatment ($p = 0.9776$).

According to Hancock (1999), vigorous strawberry plants produce 10 to 15 runners annually. Lawson and Wiseman (1976) discovered that when weeds persist throughout the establishment year, runner growth can be nearly eliminated. Since weeds were removed from all plots in a timely manner, the differences among mulches with regard to runner number are likely not due to weed pressure. Runner production was the only vegetative growth factor measured in Berglund et al. (2006) that was increased by mulch application compared with bare soil.

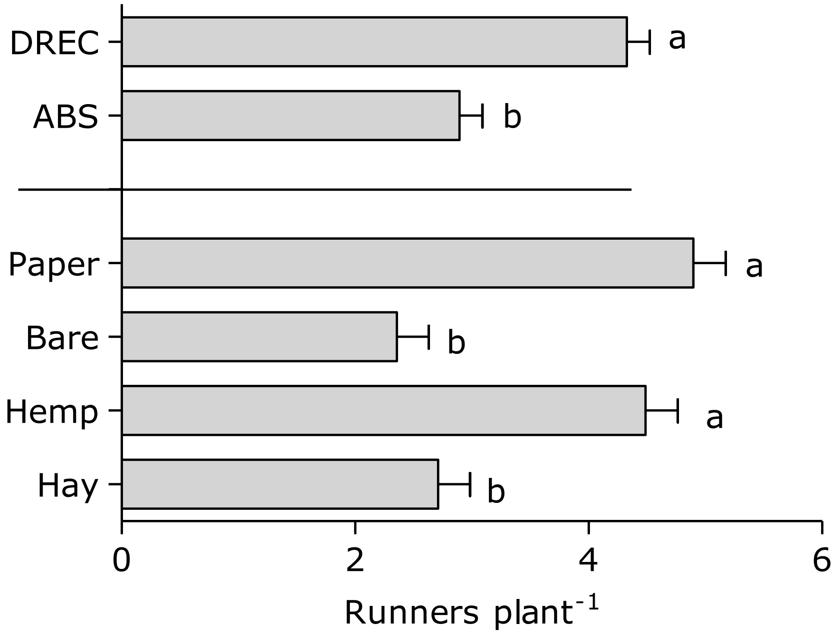

Figure 2.4. Mean (± S.E.) runners per plant as affected by mulch type and site. Bars labeled with different lowercase letters within treatment factor (site or mulch) differ at $P \leq 0.05$ according to Tukey's HSD.

Production Year Weed Pressure

Weed Biomass

Simple effects of site ($p = 0.0029$) and mulch type ($p < 0.0001$) were highly significant. Plots at Absaraka contained greater weed biomass than plots at Dickinson (199.6 g m^{-2} vs. 72.8 g m^{-2}) (Figure 2.5). Regardless of site or biochar application, hemp hurd mulched plots were associated with the least weed biomass (23.7 g m^{-2}) compared to all other mulch treatments (Figure 2.5). The biochar treatment did not affect weed biomass in 2016 ($p = 0.9183$).

During 2016, the production year, weeds were not removed; therefore, treatment effects are the results of combined impacts of weed suppression (or lack thereof) and other effects caused by the various treatment factors. Our results regarding hay effects are similar to a grass mulch treatment reported by Sinkeviciene et al. (2009), where, during the first years of the study, grass mulch reduced weeds 3.4 to 5.4 times compared to bare soil but, by the final year of the study, grass mulched plots produced more weeds than even the bare soil plots because of weed seed contamination in the hay mulch. Because these plants had been in place for a full year, yield may not have been affected by the increased weed growth in 2016 as mature strawberry plants less more susceptible to competition from weeds than young plants (Pritts and Kelly 2004).

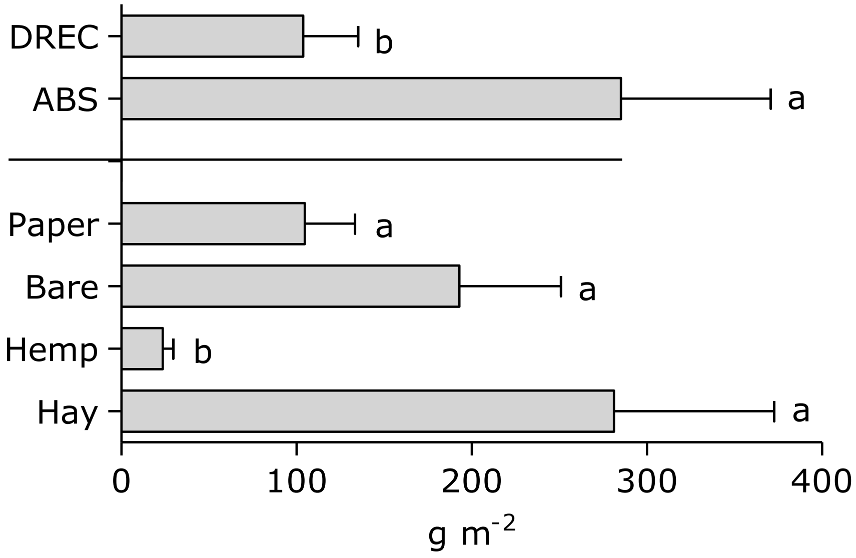

Figure 2.5. 2016 mean (± S.E.) total weed biomass as affected by mulch type and site. Bars labeled with different lowercase letters within treatment factor (site or mulch) differ at $P \leq 0.05$ according to Tukey's HSD.

Strawberry Yield

<u>Fruit Number</u>

A site by mulch type interaction was detected for fruit number ($p = 0.0252$). Consequently, sites were analyzed separately to determine mulch effects on fruit number. At Dickinson, strawberry number was not affected by the mulch treatment ($p = 0.7248$)

(data not shown). At Absaraka, strawberry fruit numbers were greatest for paper and bare soil (840 and 935 fruits m^{-2}, respectively). Fewest fruits occurred in alfalfa hay mulched plots (506 fruits m^{-2}). Differences were not detected between the two other mulch treatments (Table 2.11). A greater number of strawberry fruits were produced by plants at Absaraka compared to Dickinson, regardless of mulch type (data not shown). The biochar treatment did not affect strawberry number at either site (p = 0.2782).

During the establishment year, alfalfa hay mulch was associated with the least number of leaves and flowers, among the treatments for fewest runners, and among the treatments for least number of fruits. Mulch treatments in with the lowest leaf counts and flower counts were also associated with the fewest number of fruits per plant in a separate study (Bakshi et al. 2014).

Table 2.11. Mean number of strawberry fruits at Absaraka as affected by mulch type.

	fruits m^{-2}	
Alfalfa Hay	272	b[a]
Hemp Hurd	396	ab
Paper	481	a
Bare Soil	503	a

[a] Means followed by different lowercase letters differed at $P \leq 0.05$ according to Tukey's HSD.

Fruit Weight

A site by mulch type interaction was present when testing the fruit yield response variable (p = 0.0111). At Dickinson, strawberry fruit yield was not affected by mulch treatments (p = 0.4148) (data not shown). At Absaraka, greater strawberry yield was associated with hemp hurd, bare soil, and paper compared to alfalfa hay (4.7, 5.5, and 5.8

vs. 3.0 kg m^{-2}, respectively) (Table 2.12). Absaraka strawberry yields were greater than Dickinson strawberry yields regardless of mulch type (data not shown). Biochar treatment did not affect strawberry fruit yield ($p = 0.6738$).

Reduced tomato yields were associated with straw mulch compared to plastic, paper, or biodegradable plastic (Anzalone et al. 2010). However, in contrast to our findings with strawberry, bare soil plots were associated with lower tomato yields than any mulch treatment. Similarly, pumpkin was found by Splawski et al. (2016) to yield less in bare soil compared with mulch treatments that included plastic, newspaper, wood chips, and a combination of newspaper and grass clippings. In a matted-row strawberry study by Berglund et al. (2006) the use of biodegradable plastic mulch resulted in a 61% greater yield compared to bare soil during the final three of five harvest events. Our study had a relatively high strawberry planting density (~91,500 plants ha^{-1}) compared to Berglund et al. (2006) (~66,700 plants ha^{-1}) and Hargreaves et al. (2008) (25,000 plants ha^{-1}). This high-density planting may have mitigated the yield differences between bare soil, hemp hurd, and paper mulches. No strawberry yield differences were detected by Weber (2003) when using different mulch materials; strawberry was planted at a density of ~47,500. Our data did not conform to the regression equation developed by Pritts and Kelly (2001) which described the inverse relationship between weed biomass during the establishment year and subsequent strawberry yield. Accordance with their findings would demonstrate that greater first year weed biomass would result in lesser strawberry yield in the second year. Our study did not conform to the Pritts and Kelly (2001) regression as bare soil had the greatest weed biomass during 2015 and yet was among the highest yielding treatments. Comparatively, alfalfa hay was among the treatments with the least weed biomass during 2015 yet is the lowest yielding. Jay et al. (2015) applied biochar at rates of 0, 20, and 50 tons per hectare to aid strawberry growth and no yield differences were found among biochar rates.

The per berry weight of strawberries harvested at Dickinson (7.6 g berry^{-1}) was greater than per berry weight at Absaraka (5.2 g berry^{-1}) (data not shown). Pritts and Kelly (2001) found that lower yielding plots tended to have larger fruits.

A proportion of berries at the Absaraka site were “buttoned” or “catfaced” (apical seediness). This type of damage can result from poor pollination or insect feeding and is determined by the appearance of the achenes; small, green achenes indicate pollination issues whereas large achenes that brown before the fruit is ripe indicate insect feeding (Allen and Gaede 1963). At the Absaraka site during June 2016, sweep netting revealed a population of tarnished plant bug (*Lygus lineolaris*). To assess possible treatment interactions with the insect pest damage, insect damaged and undamaged berries were separated during the 28 June harvest. Strawberry fruits were affected by tarnished plant bug feeding; however, neither mulch nor biochar treatments affected the proportion of damaged fruit (data not shown).

Table 2.12. Mean (± S.E.) strawberry fruit weight at Absaraka as affected by mulch type.

	kg m^{-2}	
Alfalfa Hay	3.0	b[a]
Hemp Hurd	4.7	a
Paper	5.8	a
Bare Soil	5.5	a

[a] Means followed by different lowercase letters differed at $P \leq 0.05$ according to Tukey’s HSD.

Alfalfa Hay Synthesis

Fewest leaves and flowers and relatively limited number of runners occurred among strawberry plants in plots receiving alfalfa hay mulch, despite these plots having the lowest weed biomass during the establishment year. Alfalfa hay mulch also was associated with greatest amounts soil N, as well as greater amounts of weed biomass during 2016 compared to the other mulch treatments. Soil N may have been increased by the decomposition of hay mulch in the soil. The increased weed biomass can be attributed to either the hay mulch harboring weed seeds that germinated after the first year, or increased soil N aiding soil seed bank germination rates, or a combination of these reasons. Despite being associated with increased soil N, the lowest yield also was associated with alfalfa hay mulch. The reduced growth of strawberry plants during the establishment year in the alfalfa hay system, compared to the other treatments, led to reduced yield during the second year.

Paper Mulch Synthesis

Paper mulch has been shown to rapidly decompose (Miles et al. 2012). However, the mulch material remained relatively intact for the duration of the experiment in our study. Despite the material maintaining in place, paper mulch was among the treatments with the greatest weed biomass in 2016, as well as the greatest leaves, runners, and yield in terms of count and weight; conforming to the idea that establishment year weed competition is a greater factor than during the second year.

Hemp Hurd Mulch Synthesis

Hemp hurd mulch was associated with the lowest soil N and was among treatments with the greatest yield; this directly contrasts to the relationship in this study between alfalfa hay, soil N, and yield as alfalfa hay was associated the greatest soil N and lowest yield. Hemp mulch was also associated with relatively weed density as well as greatest leaf number and runner number.

Conclusion

Strawberry plants grown at the Absaraka site, compared to those at the Dickinson site, elucidated more differences between mulch types. The greater rainfall, and greater soil N at the Absaraka site may have been better suited to strawberry production. More temperature differences between the mulch materials were discovered during the establishment year than the production year, suggesting that the crop canopy contributes to soil temperature buffering. Greater soil N under the alfalfa hay may have contributed to the productive capacity of each plant, however, growth measures of associated strawberry plants revealed less vigorous plants. The literature suggested that plants are more susceptible to weed pressure during the establishment year. Compared to bare ground, all mulch materials effectively suppressed weeds. However, plants competing with the greatest weed biomass during establishment were among the plants that produced the greatest yield. Alternately, while among the lowest weed biomass during establishment, alfalfa hay resulted in lower yields than the other treatments, including bare ground. The influx of weed pressure during the second year and the diminished growth during the first year were factors in alfalfa hay mulched plants yielding less regardless of N availability and low weed pressure in the first year. Paper mulch met and hemp hurd mulch exceeded the ability of alfalfa hay mulch to suppress weeds during each year of the study. Furthermore, compared to alfalfa hay mulch, the novel mulch materials, paper and hemp hurd, were associated with greater strawberry yield. Application of paper mulch required the fewest number of person-hours, hemp hurd and alfalfa hay mulches required 5 and 4 times more person-hours, respectively, to apply. The application of biochar did not consistently influence any of the variables in this study, and did not interact with mulch type. This experiment demonstrated that hemp hurd and paper mulch provide effective weed control for perennial strawberry production and, thus, are viable options for mulching.

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