COMBINING COVER CROPS, STRIP TILLAGE, AND NOVEL MULCHES TO MANAGE WEEDS IN VEGETABLE CROPPING SYSTEMS

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Jesse Jor-El Puka-Beals

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Title

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The Supervisory Committee certifies that this ***disquisition*** complies with North Dakota State University's regulations and meets the accepted standards for the degree of

MASTER OF SCIENCE

SUPERVISORY COMMITTEE:

Dr. Greta Gramig
Chair

Dr. Kirk Howatt

Dr. Tom Walk

Dr. Aaron Daigh

Approved:

3/30/2020
Date

Richard D. Horsley
Department Chair

ABSTRACT

Vegetable producers may benefit from integrating living mulches into their operations to manage weeds and improve soil quality. Living mulches, however, can reduce vegetable yield through competition. Here we investigate strip tilling into living mulches and then direct seeding a vegetable crop in the strip till zone as a production practice to limit competition. We further investigate the use of two surface-applied mulches, a newsprint hydromulch and a compost blanket, for weed control within the strip till zone. In field conditions, living mulches reduced vegetable yield by 49-84% and the use of the newsprint hydromulch and compost blanket reduced weed biomass by 84% and 85% respectively. In greenhouse conditions, a 50% reduction in the hydromulch application rate used in the field experiment achieved similar weed control, suggesting an application rate of 6.4 L m^{-2} or a mulch strength of 0.6 MPa may be sufficient for weed control with a hydromulch.

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CHAPTER 1: REVIEW OF LITERATURE

Introduction

Agricultural producers make decisions to manage the weeds, soils, and crops in their operations. An important component of agricultural research is determining the response of management actions so that agricultural producers can make more informed decisions. In North Dakota, increasing demand for locally grown vegetables has allowed entrepreneurs to begin small-scale vegetable production operations (Martinez et al., 2010). Many of these producers follow organic practices, resulting in unique challenges for managing weeds, maintaining soil fertility, and achieving acceptable yields. The owners of one local farming operation expressed interest in incorporating perennial living mulches into their vegetable operation, but the effects on the weeds, soils and vegetable crops in their operation were unknown (R. Lockhart, personal communication). This knowledge gap impacts the ability of other agricultural producers to make fully informed decisions about their operations as well. The objective of this thesis is to address this knowledge gap in a sufficiently robust manner to benefit all agricultural producers.

Living Mulches

Living mulches are plant species that grow simultaneously with the crop an agricultural producer intends to sell (i.e., cash crop). Most living mulch species are also cover crop species, and vice versa, but cover crops are typically not grown simultaneously with the cash crop. Living mulches are typically employed to reduce weed pressure and improve soil health (Masiunas, 1998).

Weed Responses

A recent meta-analysis aggregated results from 33 studies of weed responses to cover crops conducted in the United States, with 8 of these studies involving vegetable cropping systems (Osipitan et al., 2018). Weed response was reported using weed biomass in 33 of the studies, weed density in 16 of the studies, and percent control in 4 of the studies. Measurements of weed responses to cover crops were taken immediately before cover crop termination. The findings, therefore, provide an estimation of weed responses to cover crop species when employed as living mulches. The presence of cover crops was found to reduce weed biomass compared to production with no cover crops. Average weed biomass reduction was 43 g m^{-2} with a 95% confidence interval of 1 to 85 g m^{-2}. The presence of cover crops was also found to reduce weed density by an average of 6 weed plants m^{-2}, with a 95% confidence interval in weed reduction of 9 to 3 weed plants m^{-2}, in comparisons with crops grown in the absence of cover crops. Percent weed control was also greater where cover crops were present. In comparisons with treatments lacking cover crops, establishment of cover crops produced an average gain in weed control of 8% (95% confidence interval in weed control of 16 to 0.3%).

The overall findings of this meta-analysis were not surprising because beneficial weed management outcomes resulting from cover crop usage are well established (Masiunas, 1998). The extent of weed control provided by cover crops, however, was surprisingly smaller than anticipated. The 95% confidence intervals in weed biomass and percent control both very nearly approached 0 (1 and 0.3, respectively). The authors acknowledge that large confidence intervals in weed responses to cover crops indicate wide variability associated with both the cover crops assessed and weed responses measured among the observed systems. This response variability was expected since plant growth is dependent on many environmental cues, including the availability of water and nutrients, along with an assortment of other factors that affect plant growth in ways that vary widely among plant species (Teasdale, 1998). In instances where environmental conditions favored cover crop species over weed species, large reductions in weed biomass and weed density were observed. Conversely, when environmental conditions inhibited robust cover crop growth, weed control benefits from cover crops were minimized. This meta-analysis did not account for environmental effects on cover crop and weed dynamics, nor differences in initial weed density, yet despite the variability among the 33 studies, weed biomass, weed density and percent control of weeds were all consistently reduced when a cover crop species was present.

Interestingly, Osipitan et al. (2018) also detected differences in weed responses between broadleaf and grass cover crops. Broadleaf cover crop species reduced weed biomass by 22.0 g m^{-2} with a 95% confidence interval of 34.3 to 9.75. Grass cover crop species, in contrast, did not reduce weed biomass. Weed density did not differ between treatments with grass or broadleaf cover crop species. Taken together, these biomass and density observations suggest that grass cover crop species may be less suppressive of weed growth than broadleaf species. Additional research is needed to further broadly compare weed suppression between grass and broadleaf cover crops, though these initial results may be applicable when speculating on weed responses in different living mulch systems.

Whether a cover crop species is a grass or broadleaf is often considered an important characteristic for determining its effect on the weed community (Smith et al., 2015). Smith et al. (2015) hypothesized that cover crop species would compete more with weed species within the same functional group. Broadleaf weeds, for example, were expected to be less common when a broadleaf cover crop species was present. The investigators examined weed communities and their responses to six different cover crop species. The investigators used a relative neighbor effect index to quantify differences in competition between the six cover crop species examined in the study and the weed community. This index compares the biomass differences when weeds are grown with and without a cover crop. Differences in weed communities were detected among cover crop species treatments, but these differences were not associated with whether a cover crop was a grass or broadleaf. The investigators concluded that while competition varied among cover crop species and weeds, these differences in variation were not associated with whether the cover crop species was a broadleaf or grass.

The findings of Smith et al. (2015) highlight an additional complexity of cover-crop–weed dynamics, various plant life cycles. All of the weeds observed by Smith et al. (2015) were either summer annual or winter annual species, with summer annuals being the most common, likely due to the timing of measurements made during July and August in New Hampshire. Smith et al. (2015) did nonetheless find that, although no differences in weed community were found between broadleaf and grass annual cover crop species, weed community response may vary in perennial cover crop systems between grass and broadleaf treatments. The Osipitan et al. (2018) study also included perennial cover crop species and did detect a difference in weed responses to grass and broadleaf cover crop species. Both Smith et al. (2015) and Osipitan et al. (2018) emphasized that regardless of plant functional group, weed suppression was closely associated with cover crop biomass production.

Another study found that biomass production differed between red clover (*Trifolium pratense* L.) and white clover (*Trifolium repens* L.), two perennial legumes often used as cover crops (Ross et al., 2001). Ross et al. (2001) found that red clover produced more biomass than white clover in the first year (1.7 and 0.8 Mg ha^{-1}, respectively) and the second year (2.9 and 2.1 Mg ha^{-1}, respectively). The greater biomass production of red clover, however, was not associated with greater cover crop weed suppression. The weed of interest in Ross et al. (2001), mustard (*Sinapis spp.*), was more greatly suppressed by white clover treatments compared to red clover treatments during the first year (4.4 and 2.7 Mg ha^{-1}, respectively) and the second year (0.89 and 0.69 Mg ha^{-1}, respectively) of their study. Morphology differences between red and white clover may explain greater weed suppression being associated with white clover, despite its lower biomass production. The investigators identified ground cover and adaptability to mowing as key considerations clover weed suppressive action. Plant height and stem length were greater in red clover than white clover. The methods in Ross et al. (2001) included both mowed and unmowed treatments, which showed that mowing reduced the biomass of red clover biomass more than white clover. Red clover may be less resilient to mowing due to taller stature and, therefore, produce less consistent ground cover than white clover. These differences could explain why, relative to red clover treatments, weed reduction was greater in white clover treatments despite lower cover crop biomass production. In this regard, Ross et al. (2001) presented an exception to the general findings of Osipitan et al. (2018) and Smith et al. (2015), both of whom reported that greater cover crop biomass production resulted in greater weed suppression.

Only one grass species, rye (*Secale cereale* L.), was investigated in Ross et al. (2001). Although cereal rye is not a perennial species, the weed suppressive ability of this grass species in comparison to broadleaf clover species may allow for speculation on how perennial grasses might suppress weeds. Rye production in year one (3.4 Mg ha^{-1}) was greater than red clover and white clover, but no difference in biomass was detected in year two among rye, red clover and white clover (2.7, 2.9 and 2.1 Mg ha^{-1}). Weed biomass reduction, however, was greater in rye than in the red clover and white clover in both years (6.5 and 10.2 Mg ha^{-1} respectively). Compared to broadleaf cover crops, grass cover crop species exhibited greater weed suppression both when they produced more and equivalent biomass when compared to weeds. A perennial grass species like perennial ryegrass (*Lolium perenne* L.) may perform differently than rye, but the findings of Ross et al. (2001) do not support the conclusion of Ospitan et al. (2018) that broadleaf cover crop species tend to reduce biomass more than grass species. The difference in findings between Ross et al. (2001) and Osipitan et al. (2018) underscores the point that weed responses to cover crops are often determined by species specific interactions (Smith et al., 2015) that may not be easily generalizable to broad plant functional groups.

Soil Responses

Numerous soil benefits are associated with the use of cover crops. One benefit provided by clover species is an increase of soil nitrogen (Carlsson and Huss-Danell, 2003). Carlsson and Huss-Danell (2003) summarized 19 studies including white clover and 14 studies including red clover that reported varying ranges of soil nitrogen increases associated with clover species. Among those studies, four were from Minnesota and two were from North Dakota. The authors found that nitrogen fixation tended to be greater in red clover than white clover (23±24 kg N year^{-1}). The variability in this difference, however, is indicative of N fixation being influenced by many other factors, such as sowing date, number of production years, variety type, soil fertility and biomass production (Ross et al., 2001; Carlsson and Huss-Danell, 2003). Due to these large variations in N fixation, the impact of clover living mulches on soil N will vary likely across locations and/or years.

One important characteristic of white clover is its ability to increase soil nitrogen even in anaerobic conditions. Clover species can increase soil nitrogen via symbiotic relationships with rhizobacteria in the soil that fix atmospheric nitrogen. Legume-rhizobia symbioses are typically negatively impacted by saturated soils due to anaerobic conditions which reduce the activity of the rhizobacteria (James and Crawford, 1998). White clover, however, has been found to increase nitrogen fixation under long periods of saturated soil conditions (Pugh et al 1995). The white clover exception to the general rule of nitrogen fixation being negatively impacted by saturated soil conditions may be important to vegetable producers in soils susceptible to flooding such as those in the Red River Valley of ND.

Crop Responses

Despite the weed suppression and soil improvements provided by cover crops, yield reductions are often observed when cover crops are used as a living mulch (Masiunas, 1998; Pfeiffer et al., 2016), likely due to resource competition between the living mulch and the vegetable crop. In Pfeiffer et al. (2016), four cover crop species were compared as living mulches in three vegetable crop production systems, and yield reductions were observed in all cover crop treatments compared to weed-free controls. For broccoli (*Brassica oleracea* L.), red clover living mulches were associated with a 100% yield reduction during both years of the study. Similarly, red clover living mulches reduced bell pepper (*Capsicum annuum* L.) yield by 95% during the first year and 83% during the second year, and snap bean (*Phaseolus vulgaris* L.) yield by 67% during the first year and 82% during the second year. Yield reductions depend on a variety of factors impacting competition between crops and living mulches. In Pfeiffer et al. (2016), spacing between the crop and living mulch was very narrow because vegetable crops were punch-planted into the living mulches. The results of Pfeiffer et al. (2016) are consistent with an earlier review of living mulches in vegetable crop production (Masiunas, 1998), which concluded that vegetable yields were reduced by an average of 92% in red clover living mulch systems. In short, managing competition between living mulches and vegetable crops has long been discussed. One potential solution to living mulch competition with vegetable crops is the use of strip tillage. Strip tillage may terminate the living mulch in zones where vegetable crop production would occur. Strip tillage therefore allows for vegetable crop growth to occur at a distance from living mulch growth, thereby potentially reducing competition and consequent yield reduction.

The use of strip tillage in living mulches may be a useful practice for vegetable crops such as carrot (*Daucus carota* L.). Managing competition in carrot is vitally important as it may be one of the most susceptible crops to competition (Swanton et al., 2010). In commercial carrot production in the United States and Canada, competition occurs from weeds because living mulches are not used. In order to manage competition from weeds, the herbicide linuron is typically applied multiple times in a growing season to reduce weed competition with carrot. Swanton et al. (2010) suggested that the development of linuron-resistant pigweed was a consequence of the limited weed control options for carrot production. The use of living mulches and strip tillage may provide an alternative system for managing weeds that could reduce selection for linuron resistant weeds in commercial carrot production. Carrot production at smaller scales may also benefit from a living mulch and strip tillage system. The viability of using living mulches in carrot production hinges on (i) the extent to which competition from the living mulch is managed by strip tillage and (ii) the extent to which competition from weeds is managed in the strip till zone.

Surface Mulches

One tool for controlling weeds in strip till zones is a surface-applied mulch or surface mulch. Unlike a living mulch, a surface mulch is not a living organism, and can consist of multiple materials (i.e., bark, straw, plastic). In Teasdale and Mohler (2002), residue from rye, crimson clover (*Trifolium incarnatum* L.) and a landscape fabric were characterized as surface-applied mulches by their surface area and solid volume fraction before assessing weed suppression of redroot pigweed (*Amaranthus retroflexus* L.), common lambsquarters (*Chenopodium album* L.) and giant foxtail (*Setaria faberi* Herrm.). The findings of Teasdale and Mohler (2002) suggest that surface mulches can vary significantly both in their physical properties and suppression of weed species. For all surface mulches, increases in application rates resulted in greater weed suppression until mulch mass reached 200 g m^{-2}. Weed suppression by mulches was found to differ by species, with an inverse relationship occurring between weed seed size and weed suppression. Although the numerical responses provided by Teasdale and Mohler (2002) are primarily model parameters that varied by mulch properties and weed species, the findings of the paper underscore the importance of physical impedance for weed suppressive action associated with surface applied mulches.

The preferred mulching material for United States vegetable production is polyethylene plastic. Approximately 130 million kilograms of plastic mulch were applied in 2004 and annual plastic mulch usage has been increasing (Shogren and Hochmuth, 2004; Chen et al., 2018). Plastic mulches provide sufficient physical impedance for effective weed suppression, but also impose additional labor costs due to yearly disposal requirements ($250 ha^{-1}). The development of biodegradable mulches may eliminate the yearly disposal labor costs, but adoption is limited due to inconsistent weed suppression of biodegradable mulches and their prohibition for organic vegetable operations (Goldberger et al., 2015). The environmental costs associated with yearly disposal of plastic mulches is a strong incentive for some vegetable growers to seek biodegradable alternatives to plastic mulches (R. Lockhart, personal communication).

The use of paper mulches could provide a biodegradable alternative to plastic mulches. Paper mulches have been in use for almost a century and have been associated with beneficial agronomic outcomes (Clark and Elizabeth, 1931). Recent efforts to directly compare paper mulches and plastic mulches have suggested similar levels of weed control between these two mulch types (Brault et al., 2002; Shogren and Hochmuth, 2004). These studies have used a kraft paper that is coated in an oil and applied to soils using similar equipment as with plastic mulches.

Another limitation of plastic mulches is their inappropriateness for direct seeded vegetable crops like carrot. Unlike plastic mulches, paper mulches can be applied in a liquid form called hydromulch which is more appropriate for direct seeded crops due to improved soil coverage (Warnick et al., 2006). Warnick et al. (2006) provides the only published data comparing a hydromulch with a plastic mulch. In this study, weed control was reduced by a range of 57-63% in the hydromulch compared to 95-97% in the plastic mulch. These findings suggest that the hydromulch formulations used in Warnick et al. (2006) did not achieve acceptable weed suppression to be an adequate alternative to plastic mulches. The causes for poor hydromulch weed control in Warnick et al. (2006) are unclear. It's possible the thickness of the mulch was insufficient to create the necessary physical impedance. It's also possible the prevalence of nutsedge (*Cyperus spp.*) in the weed community led to a decline in hydromulch weed control. Nutsedge species are perennials that are notoriously difficult to suppress. Hydromulch weed suppression may have been comparable to the black plastic mulch if the weed community consisted primarily of small seeded annuals, like redroot pigweed, which have been shown to be sensitive to mulches (Teasdale and Mohler, 2000).

Another approach to creating a biodegradable surface mulch could be the use of compost blankets. Compost blankets are used as an erosion control tool for construction activities, but may have applications for weed suppression in strip till zones (Faucette et al., 2006). As previously discussed in Teasdale and Mohler (2000), any material applied on the soil surface at sufficient mass and coverage can suppress weeds via physical impedance and light extinction.

Composted materials typically have no viable weed seeds within the material due to the high temperatures achieved in the composting process (Bahman and Lesoing, 2000). Applying a compost material as a mulch may provide sufficient weed suppression for the weed seedbank in the soil. If the compost blanket consists of a mixture of materials that can support crop germination, then a vegetable crop could possibly be directly seeded into the compost blanket. No research is available on the weed, soil or crop responses to a compost blanket. However, weed responses to the bark and straw mulches employed by Teasdale and Mohler (2000) suggest that weed emergence may be reduced with compost applied at rates up to 200 g m^{-2}.

Barriers to Adoption

Previous research allows for estimation of weed, soil and crop responses that might be associated with the use of perennial living mulches for vegetable production in North Dakota and elsewhere. Results regarding combining strip tillage and surface mulches from other studies may further provide information that helps producers meet their weed management and crop production objectives. The true weed and crop response to these practices, however, is unknown and poses a challenge for both vegetable producers and agricultural researchers in North Dakota.

The variability and complexity of non-chemical management practices such as living mulches are representative of the unique challenges associated with organic production. Agricultural research in organic systems often does not translate to field-scale applications as accurately as with conventional systems (Kravchenko et al., 2017). As previously discussed in Osipitan et al. (2018), biologically based tools vary in their effectiveness due to environmental variation. The use of review articles that examine multiple studies is one way to help account for this variation, though determining weed and crop responses in specific agricultural practices remains an ongoing challenge.

Estimating labor requirements also remains a substantial challenge in determining the feasibility of management practices. Labor is an important cost of any management practice. Canali et al. (2017) found that the use of human labor and fossil fuel energy increased by 7% among farmers in Europe who adopted living mulches in their farming operations (Canali et al., 2017). Surveying multiple farm operations seems to be an effective approach to estimating the cost of management practices. Within an experiment, however, meaningfully measuring labor costs remains a challenge. In Shogren and Hochmuth (2004), the labor involved in applying their modified paper mulch is discussed as prohibitively expensive for a vegetable operation (Shogren and Hochmuth, 2004). However, an agricultural producer would not likely mimic the exact methods of these researchers. In Pfeiffer et al (2016), all the labor associated with maintaining the four living mulch treatments in the study was tracked and analyzed using mean separation to conclude that time involved in managing red clover was greater than spent on the cultivated control in 2013, but not 2012 on a hr ha^{-1} basis. These labor estimates from small plot research probably do not scale to a hr ha^{-1} basis because producers would not mimic the exact procedures used in early experiments. The challenge of assessing labor costs in agricultural research studies is just one example of the limitations involved in translating agricultural research in organic systems into practice.

In a recent survey of vegetable producers in the Midwest region of the United States, weed management was identified as one of the greatest challenges in organic production (DeDecker et al., 2014). The current practices allowable in organic agriculture pose a challenge from an agricultural research perspective, but also an opportunity because the more that is understood about biologically based agricultural practices, the more growers can effectively employ them in their operations to meet their objectives.

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CHAPTER 2: COMBINING LIVING MULCHES, STRIP TILLAGE AND NOVEL SURFACE MULCHES IN CARROT

Abstract

Direct seeding into strip tilled zones (STZ) of living mulches may require weed suppression tactics for soil surfaces exposed within the STZ. Surface mulches applied in the STZ could suppress weeds and improve crop performance. We evaluated three surface mulch treatments (hydromulch, compost blanket and a no-mulch control) applied on STZs seeded to carrot (*Daucus carota L.*). These STZs were located within one of five living mulch treatments [red clover (*Trifolium pratense L.*), white clover (*Trifolium repens L.*), perennial ryegrass (*Lolium perenne L.*), a weed-free control and a weedy control). In observations spanning two years and two North Dakota locations characterized by different soil types, weed biomass was lower in STZs where hydromulch or compost blankets were applied compared to the no-mulch control (12, 13 and 82 g m^{-2}, respectively). The presence of a living mulch adjacent to the STZ reduced carrot biomass by 49-84% compared to the weed-free control. Competition between the living mulch and the crop may be reduced by widening the STZ and further development of the surface mulches may provide a viable alternative to plastic mulches.

Introduction

Researchers and agricultural producers acknowledge the need for additional weed control tools and tactics (DeDecker et al., 2014; Jerkins and Ory, 2016). In organic vegetable production systems, living mulches are highly attractive due to weed control and soil fertility benefits (Kołota and Adamczewska-Sowińska, 2013). Yet efforts to integrate living mulches with vegetable crops often result in substantial vegetable yield reduction due to resource competition (Kolota and Adamczewska-Sowińska, 2004; Gómez et al., 2013; Pfeiffer et al., 2016).

Strip tilling into living mulches and then direct seeding a vegetable crop may limit yield reductions by limiting competition between the living mulch and vegetable crop (Masiunas, 1998). A secondary weed control tactic, however, may be required to control weeds within the strip till zone.

Surface-applied mulches provide weed control and can support crop growth through soil modification by forming a physical barrier over the soil surface. In organic production, polyethylene plastic is the most widely used surface mulch and biodegradable alternatives are needed (Goldberger et al., 2015). Some biodegradable materials may also be more appropriate for vegetable crops that cannot be transplanted and prefer cooler soil temperatures like carrot (*Daucus carota* L.). Carrot also has a long critical weed-free period and very limited weed control options; only one herbicide is registered for carrot and resistance is developing (Swanton et al., 2010).

To address these challenges, we adapted two erosion control tactics, hydromulching and compost blankets, and applied them as surface mulches for vegetable production (Faucette et al., 2006). Hydromulching involves suspending a mulch material in water so that it can be applied as a liquid on the soil surface before hardening into a physical barrier. Efforts to combine newspaper and other by-products into an agricultural hydromulch have had modest 57-63% impacts on weed control, while also promoting advantageous soil conditions for cool-season crops (Warnick et al., 2006). Compost blankets are composed of weed-free organic materials that can be applied onto the soil surface to reduce weed emergence. Unlike straw or bark mulches, compost blankets may have sufficient structure and fertility to be direct seeded into and support initial crop growth. In contrast, commercially available surface mulches can neither be applied in liquid form nor serve as a crop growing medium. Here, we investigate weed, crop and soil responses to novel surface mulches applied in strip till zones within plots harboring living mulches.

We hypothesized that weed density and biomass would be reduced by perennial living mulches, though the extent to which harsh winters in North Dakota would impact performance was unknown (Chase and Mbuya, 2008; Kołodziejczyk, 2015; Osipitan et al., 2018). Competition from living mulches was expected to reduce carrot yield, but we hypothesized that the use of strip tillage will limit yield reductions compared to the 67-100% yield reductions observed when strip tillage was not combined with living mulches (Pfeiffer et al., 2016). We also hypothesized that, in comparison with grass living mulch treatments, soil fertility would be improved in production with legume living mulches like clover (*Trifolium spp.)* (Carlsson and Huss-Danell, 2003). Lastly, we hypothesized that hydromulch and compost blanket treatments would reduce weed density and weed biomass in the strip till zone by increasing the physical impedance of weed emergence (Teasdale and Mohler, 2000).

Materials and Methods

Site Description

Field experiments were conducted near Absaraka, ND (46°59'16.1"N 97°21'08.6"W) and at North Dakota State University's main campus in Fargo, ND (46°53'38.4"N 96°48'37.8"W) in 2018 and 2019 (Table 1, Table 2 and Table 3).

The Absaraka site was certified organic during 2015 and was planted to a research project for the three years prior to the establishment of this experiment. The previous research project involved the use of different tillage intensities and an alfalfa (*Medicago sativa* L.) mulch application in four vegetable crops [snap pea (*Pisum sativum* L.), onion (*Allium cepa* L.), beet (*Beta vulgaris* L.) and butternut squash (*Cucurbita moschata* L.)]. The Fargo site was not certified organic. In 2015 it was planted to soybean (*Glycine max* L.), followed by hard red spring wheat (*Triticum aestivum* L.) in 2016 and was left fallow for 2017, with periodic cultivation applied to control weeds. Both sites were disked and cultivated in the first two weeks of May 2018 before the experiment was established.

Table 1. Soil properties of Absaraka ND and Fargo ND.

Site	Soil Series†	Soil Texture	Soil Taxonomy	Slope
				%
Absaraka	Warsing Loam	Sandy Loam	Fine-loamy, mixed, superactive, frigid Oxyaquid Hapludoll	0-3
Fargo	Fargo Silty Clay	Clay	Fine, smectitic, frigid Typic Epiaquerts	0-1

† Soil properties obtained from USDA-NRCS soil survey (Soil Survey Staff, 2000, 2016)

Table 2. Mean monthly air temperature and precipitation for 2018 and 2019 growing seasons from a weather station near Absaraka, ND as obtained from North Dakota Agricultural Weather Network (NDAWN)

	Air Temperature†			Total Precipitation		
Month	Normal‡	2018	2019	Normal§	2018	2019
	———Celsius———			————mm————		
May	13.4	16.8	10.6	77.5	53.9	60.0
June	19.7	20.5	19.2	101.1	80	122.0
July	21.3	20.3	21.9	87.6	65	156.1
August	20.4	19.4	18.4	66.6	78.5	102.4
September	14.8	14.1	15.5	65.5	70.9	147.7

† Average air temperature
‡ Average air temperature over a 30 year period; 1980-2010
§ Average total precipitation over a 30 year period; 1980-2010

Table 3. Mean monthly air temperature and precipitation for 2018 and 2019 growing seasons from a weather station in Fargo, ND as obtained from North Dakota Agricultural Weather Network (NDAWN)

	Air Temperature†			Total Precipitation		
Month	Normal‡	2018	2019	Normal§	2018	2019
	———Celsius———			————mm————		
May	13.9	17.9	11.4	71.3	43.6	69.6
June	19.0	21.4	19.7	99.1	123.2	82.8
July	21.6	21.9	22.5	70.9	80.9	121.3
August	20.7	20.8	19.8	65.0	100.9	89.7
September	15.0	14.9	16.9	65.1	64.4	106.8

† Average air temperature
‡ Average air temperature over a 30 year period; 1980-2010
§ Average total precipitation over a 30 year period; 1980-2010

Field Preparation

In April of 2018, both sites were rototilled. Dry, pelletized, composted poultry manure (4-3-2) was broadcast at a rate to achieve 100 kg N ha^{-1} (Cashton Farm Supply, Cashton WI). The composted poultry manure was then incorporated using a Ford 3600 tractor with a disc attachment in Absaraka, ND and a BCS tractor (BCS 749 with Rinaldi R2 power harrow, BCS America, Portland, OR) in Fargo.

Experimental Procedures

Research plots were 1.5 m wide and 4.57 m long and arranged in a randomized complete block design with four replications. Plots first received one of five living mulch treatments: red clover (*Trifolium pratense* L.), white clover (*Trifolium repens* L.), perennial ryegrass (*Lolium perenne* L.), a weed-free control and a weedy control. The weed-free control was cultivated and hand weeded throughout the season to remove all weeds. The weedy control was left unmanaged.

Seeding rates were 16.8 kg ha^{-1} for all three living mulch treatments. White clover and red clover were inoculated with PREVAIL (Verdesian Life Sciences, Cary NC). Living mulch seed was broadcasted with an oat (*Avena sativa* L.) nurse crop at a rate of 36 kg ha^{-1}. Living mulches were hand weeded and reseeded two weeks after seeding because atypical hot and dry weather impaired living mulch establishment (Figure A1).

One month after living mulch seeding, strip till zones were created in the center of each plot at a width of 0.2 meters using a rototiller (FG110 Mini Tiller Cultivator, American Honda Motor Co, ND). Strip till zones were raked to remove debris and ensure a flat seedbed for carrot planting and mulch application.

The three surface mulch treatments applied in the strip till zones were hydromulch, compost blanket, and a no-mulch control. The hydromulch consisted of shredded newspaper (Fargo Forum, Fargo ND) and water mixed at a ratio of 1 kilogram of newspaper to 35 L of water. The newspaper and water were combined using a hydroseed mixer (TurboTurf Hydroseeding Unit Model# HS-100, Beaver Falls PA). Mixing occurred until a homogenized slurry formed, usually requiring 10 minutes on high power for the TurboTurf engine. A steel C-channel bar approximately 4 cm wide and 5 m long was placed over the carrot planting zone within the strip till zone after the carrot was planted and before the hydromulch was applied (Figure 1). Hydromulch was gravity fed from a modified 4-gallon backpack sprayer onto the soil at an application rate of 12.7 L m^{-2} within the strip till zone (Chapin Home & Garden, Chapin NY). Hydromulch application nozzles were kept less than 5 cm above the soil surface to reduce disturbance of the freshly tilled soil in the strip till zone. The hydromulch mixture was left to dry for 1 minute after application before the C-channel bar was removed. Typical thickness of the hydromulch mixture was 2 cm when wet immediately after application.

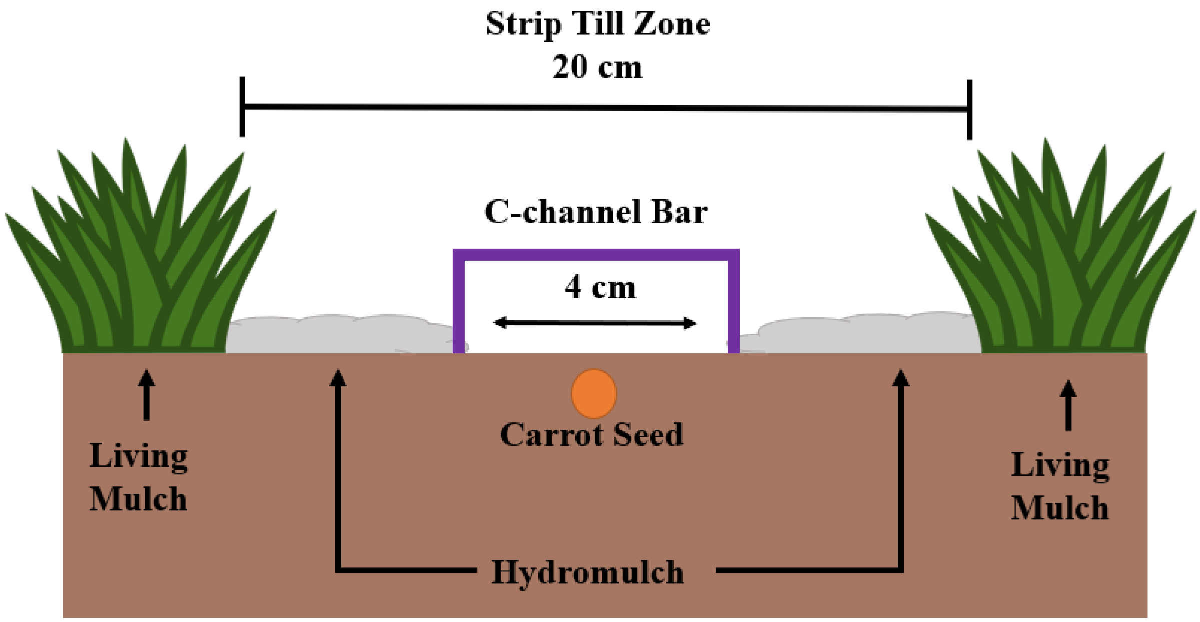

Figure 1. Cross-sectional diagram of the strip till zone after a hydromulch application. The strip till zone is flooded with hydromulch but the area of soil directly above the carrot seed is protected by a bar during hydromulch application.

The compost blanket consisted of hemp hurd and composted cow manure in a 2:1 ratio by volume and was applied at a rate of 108 L m^{-2} in the strip till zone. The hemp hurd was a byproduct of hemp production and contained cellulose (44% to 55%), hemicelluloses (16% to 18%) and lignin (4% to 28%) (DunAgro, Oude Pekela NL). The composted cow manure was sourced from a dairy farm that was managed in compliance with NOP 205.203 (Cowsmo, Cochrane WI). Compost blankets were applied and compressed by hand. The approximate height of the compost blanket was approximately 10-15 cm above the soil surface after application.

Carrot was seeded into the soil for the hydromulch and no-mulch treatments; carrot was seeded directly into the compost blanket for compost blanket treatments (Figure 2). Carrot was seeded in a single row at a depth of 0.6 cm and a rate of 77 seeds m^{-1} using a JP Jang-1 seeder (JangAutomation, Seoul KOR). Drip tape was installed after planting using a medium flow drip tape with emitter spacing of 10.1 cm (DripWorks, model#TDE804100, Willits CA). The irrigation schedule ensured the greatest carrot emergence and adequate soil moisture for crop establishment (Table 4).

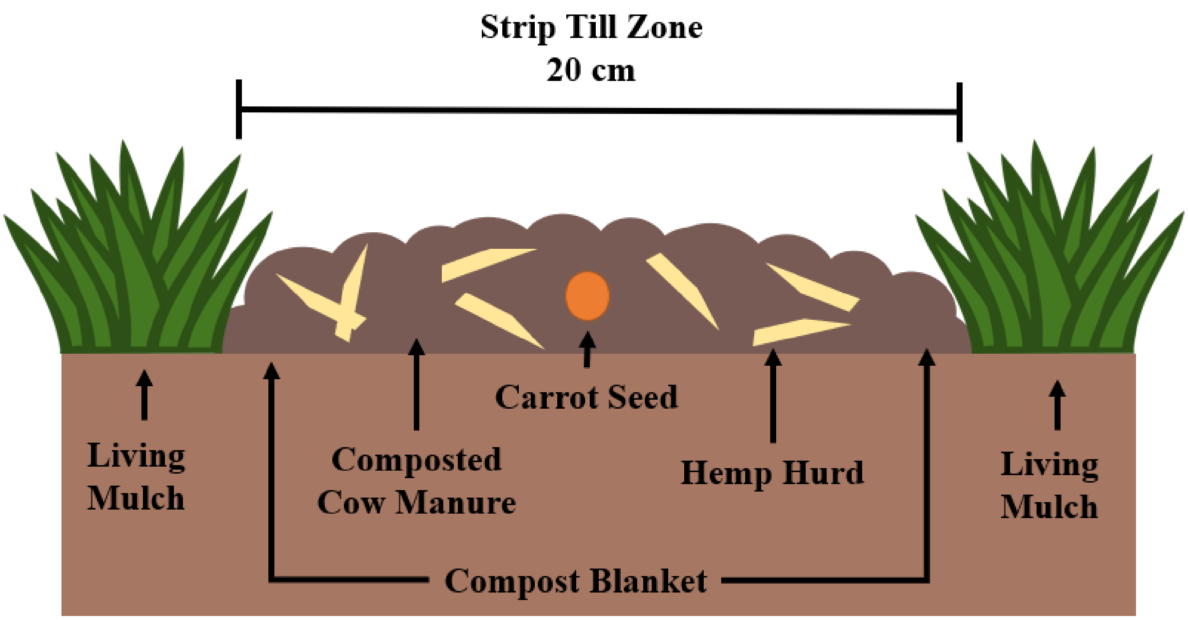

Figure 2. Cross-sectional diagram of the strip till zone in a compost blanket treatment after carrot seeding. The carrot seed is planted into the compost blanket mixture of composted cow manure and hemp hurd.

Table 4. Irrigation timetable and estimated output in Absaraka ND and Fargo ND in 2018 and 2019

		Daily irrigation specifications			
Weeks after planting	Irrigation frequency	Morning†	Afternoon‡	Cumulative	Rate
		——hours——		—L—	L hr^{-1} m^{-1}
0-2	Daily	2	1	4088.2	7.4
2-4	4 per week	2	0	2739.0	7.4
5-14	None	0	0	0	0

† Morning irrigation began at 6am
‡ Afternoon irrigation began at 1pm

Living mulches were mowed throughout the growing seasons to reduce aboveground interference with the carrot crop (Figure 3). Mowing height was 10 cm and was accomplished using a push mower (Cub Cadet model 25A-262J756, Cub Cadet, Cleveland OH) in Fargo and a deck mower (Kubota Kommander model Z121S-48, Kubota Tractor Corporation, Grapevine TX) in Absaraka. Living mulch aboveground biomass that encroached into the strip till zone was removed by hand after mowing. Key experimental dates are provided (Table 5).

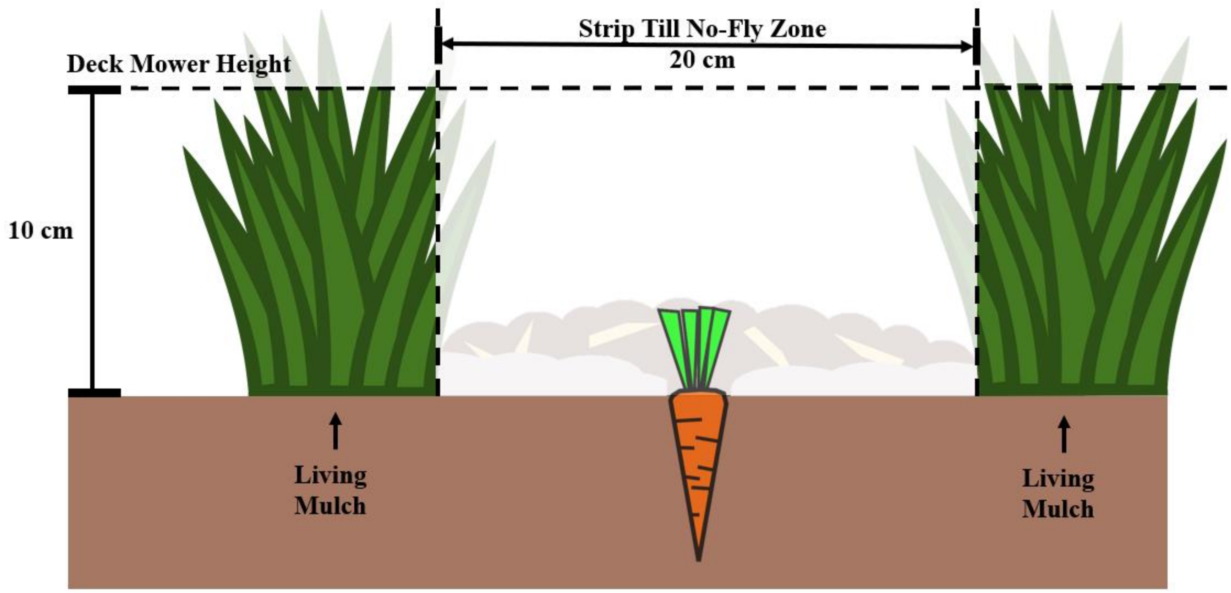

Figure 3. Cross-sectional diagram of the strip till zone during the growing season in all plots. Living mulches were mowed to 10 cm and maintained by hand to prevent living mulches from creeping into the strip till zone.

Table 5. Dates of important experimental field activities in Absaraka ND and Fargo ND in 2018 and 2019

	2018		2019	
Activity	Absaraka	Fargo	Absaraka	Fargo
Sites establishment: Tillage and disking	14 May	Early May (exact date unknown)	---	---
Soil Sampling	7 May	21-22 May	9 Sep	9 Sep
Fertilization: composted poultry manure + incorporation	14 May	22 May	---	---
Living mulch seeding	16 May	23 May	---	---
Strip tillage + carrot planting + surface mulch application	19-21 Jun	27-28 Jun	17-19 Jun	26-27 Jun
Carrot emergence counts and thinning	17 Jul	24 Jul	8 Jul	15 Jul
Strip till zone weed counts: peak emergence	17 Jul	24 Jul	15 Jul	16 Jul
Living mulch weed counts: peak emergence	---	---	22 Jul	25 Jul
Strip till zone weed counts and biomass: peak vegetative growth	29-30 Aug	5-6 Sep	15 Aug	16 Aug
Living mulch weed counts and biomass: peak vegetative growth	---	---	7-8 Aug	13-14 Aug
Carrot harvest	11-12 Sep	18-19 Sep	4,6 Sep	8,16 Sep§
Living mulch assessment: stand counts, percent weed control	10 Sep†	17 Sep	28 May, 17 Oct	28 May, 19 Oct
Light interception measurements	---	---	7 Aug, 4 Sep	14 Aug, 5 Sep
Living mulch mowing dates	1 Jul, 1 Aug, 16 Aug, 30 Aug‡, 10 Sep, 17 Oct	29 Jun, 5 Jul, 24 Jul, 21 Aug, 31 Aug, 16 Oct	7 Jun, 17 Jun, 2 Jul, 8 Jul, 15 Jul, 29 Jul, 5 Aug, 15 Aug	10 Jun, 19 Jun, 1 Jul, 8 Jul, 15 Jul, 30 Jul, 14 Aug, 5 Sep

† While all living mulches were assessed, stand counts were not recorded for living mulches since tillering and rhizome growth complicated data collection.
‡ Living mulches at both sites were mowed using a cub cadet until 30 Aug 2018, when a Kubota deck mower replaced the cub cadet at Absaraka ND for the remainder of the experiment.
§ Block 1 was harvested on September 8th, but the remaining blocks could not be harvested until September 16th due to wet field conditions.

Data Collection and Analysis

Collection

Weed measurements were performed in the strip till zone and living mulch zone during peak weed emergence and peak weed vegetative growth. Four quadrats were systematically placed in the strip till zone (0.0175 m^2) and living mulch zone (0.0625 m^2) to estimate the weed community (Figure 4). Weed counts by species were recorded to estimate peak emergence. For peak vegetative growth, weeds were separated by species, washed, counted and then dried to constant mass in an oven (~70 °C) before being weighed to determine weed dry biomass.

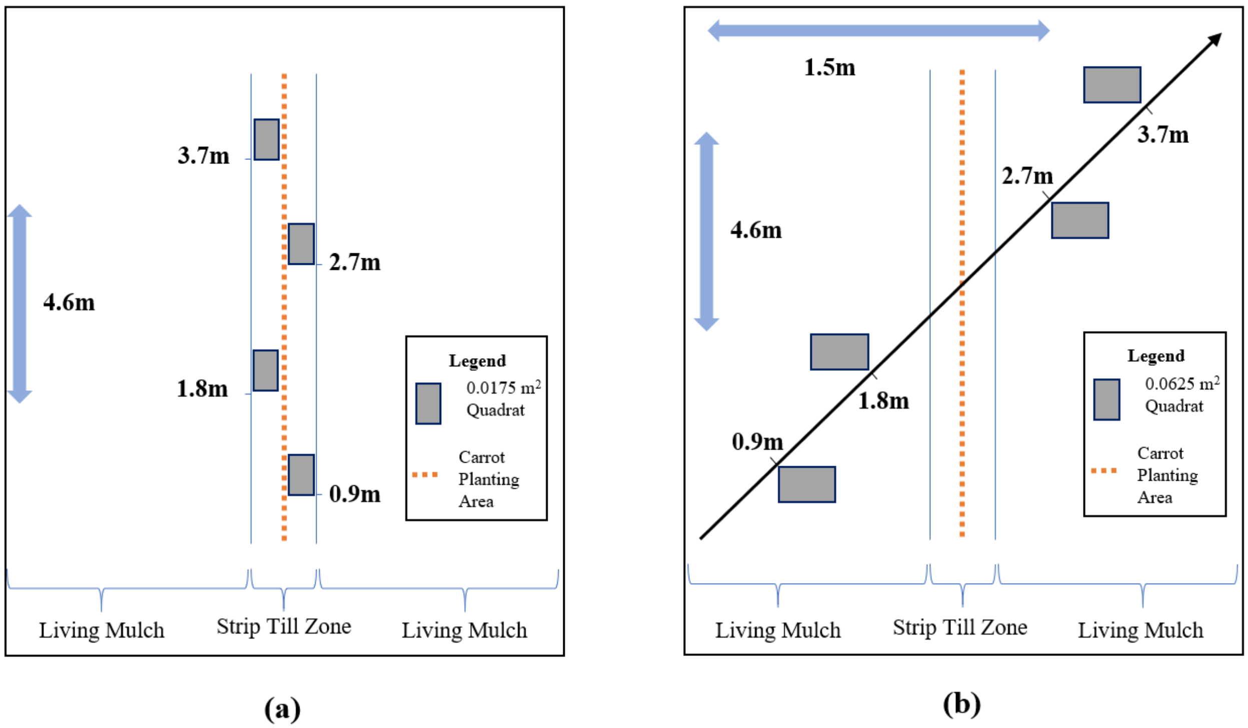

Figure 4. Quadrat location for weed sampling in experimental units in Absaraka ND and Fargo ND in 2018 and 2019. Figure (a) demonstrates sampling methods in the strip till zone. Figure (b) demonstrates sampling in the living mulch zone.

Crop response was measured after emergence and at harvest (Table 5). Emergence counts occurred 3 weeks after planting and immediately before carrot thinning. Emerged plants were counted in two 0.3-meter samples along the 4.6-meter length of carrot row in the strip till zone.

All carrots within the 4.6-meter strip till zone were harvested by hand using digging forks. Carrot roots were washed and sorted into three classes: misshapen, marketable or small. Misshapen carrots had bifurcation or obvious damage such as discoloration or rot. Marketable carrots had a diameter greater than 2 cm and were longer than 13 cm (Agricultural Marketing Service, 2018). Remaining carrots were classified as small.

Soil samples were taken at the beginning and end of the experiment (Table 5). Each plot was sampled 10 times in a zig-zag pattern in the living mulch area (Figure A2) at a depth of 0-15 cm using a soil probe with an inside diameter of 1.6 cm (AMS Inc., American Falls ID). Soil cores were then homogenized and sent to North Dakota State University soil testing lab for determination of nitrate, phosphorous and potassium content.

Analysis

Weed response was analyzed using univariate and multivariate techniques. Univariate responses (i.e., weed density) were analyzed using PROC GLIMMIX (SAS institute, Cary NC). Model effects were a full factorial of surface mulch and living mulch. Efforts were made to detect main effects across years using a repeated measures statement. Multiple method statements, adjustments, covariance structures and distributions within GLIMMIX were evaluated for acceptable fit statistics by their proximity to 1 for the chi-square divided by degrees of freedom (Schabenberger, 2005). If fit statistics were poor or if an interaction was detected between years or locations, data was sliced within an interaction and a Bonferonni correction was applied for determining differences.

In order to improve the fit of the model, multiple approaches were taken to avoid data transformation. Weed response expressed as a percent reduction from a control often resulted in a better fit of the data to Poisson or negative binomial distributions.

Multivariate responses (i.e., weed counts by species) were analyzed using the vegan package in R (Oksanen et al., 2010; R Development Core Team, 2018). Multidimensional scaling was used with a Euclidian distance matrix because all count data was on an equal scale so their geometric distances were meaningful. Ordinations were analyzed and plotted in two dimensions; stress values never exceeded 0.2. Ultimately, rare species were grouped into either a broadleaf or grass category. For strip till zone weed community analysis, the three most abundant broadleaf species [purslane (*Portulaca oleracea* L.), redroot pigweed (*Amaranthus retroflexus* L.) and venice mallow (*Hibiscus trionum* L.)] and the three most abundant grass species [barnyardgrass (*Echinochloa crus-galli* (L.) P. Beauv.), yellow foxtail (*Setaria pumila* (Poir.) Roem. & Schult.) and stinkgrass (*Eragrostis cilianensis* (All.) Vignolo ex Janch.)] were plotted along with the rare species grouped into either the grass or broadleaf category. For the living mulch weed community, only the two most abundant broadleaf and grass species were plotted due to lower abundance of Venice mallow and stinkgrass.

Fixed effects such as surface mulch and living mulch treatments were fitted onto the ordination and pairwise comparisons were conducted to determine whether differences existed among the treatments using envfit (Oksanen et al., 2010). Ordinations containing differences among treatments were plotted using ordibar (Oksanen et al., 2010).

Typically, the weedy control treatment would be excluded from multivariate analyses, but its inclusion within the strip till zone weed community data reduced the stress of the model and allowed for maintaining a two-dimensional model. When the weedy control treatment was included, differences were detected between the red clover and weedy control treatment, though this difference was not highly significant ($p=0.03$), nor meaningful when further explored (Figure 13).

Emergence counts were analyzed using multiple approaches, but high variability and multiple interactions complicated the analysis. Total carrot count data at harvest mirrored the emergence data, but with less variability due to the greater precision of the measurement method.

Total carrot count data was analyzed using PROC GLIMMIX. In order to achieve an acceptable model fit without interactions, carrot count response was separated by year and location.

Carrot yield response was determined using total average carrot biomass. Analyzing within carrot classes like misshapen or marketable carrots was complicated by high frequency of zero counts in certain treatments. Total carrot biomass was confounded by the variability in total carrot counts as can occur with direct seeded crops (Reid et al., 2018). While an acceptable model was achieved using total carrot biomass as a response and total carrot count as a covariate, total average carrot biomass (i.e., total carrot biomass ÷ total carrot count) presented similar results and with a better model fit so total average carrot biomass was selected as the carrot yield response variable. Percent reductions of average total carrot biomass compared to the weed-free control further improved model fit statistics. The objective of the analysis was to determine how living mulch treatments differed from a weed-free control; weedy controls were not included in the analysis as carrot response to unmanaged weedy controls was not deemed meaningful.

The 2018 soil nutrient data was analyzed to detect potential artifact spatial differences in fertility at each location. Data were analyzed using PROC GLIMMIX using a normal distribution with living mulch as a fixed effect and block as a random effect. Differences in soil nitrate and phosphorous were detected among blocks in Fargo; however, these differences were controlled by the randomized complete block design. The absence of differences in soil fertility among the living mulch treatments allowed for analysis of the soil fertility response at the end of the experiment among treatments. The 2019 soil nutrient data was log transformed before analysis in order to achieve acceptable fit statistics. Log transformed means were compared using Tukey's honest significant differences (α=0.05).

Results and Discussion

Weed Responses

Strip Till Zone

The weed biomass response in the strip till zone was consistent among surface mulches across years and locations (Figure 5). Both the hydromulch and compost blanket were associated with lower weed biomass than the no-mulch control (12, 13 and 82 g m^{-2} respectively).

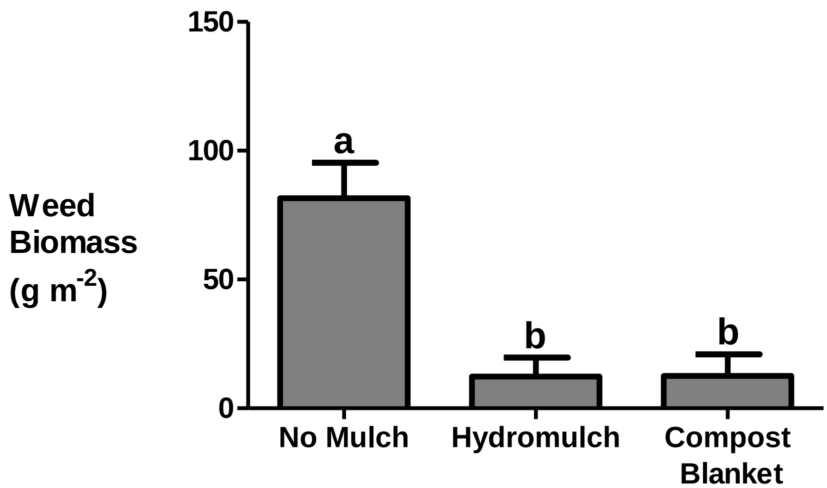

Figure 5. Weed biomass in the strip till zone at peak vegetative growth among surface mulches at Absaraka ND and Fargo ND during 2018 and 2019. Bars with the same letters do not differ according to Tukey's HSD (α=0.05).

The weed biomass response in the strip till zone at peak vegetative growth was consistent among living mulches across years and locations as well (Figure 6). Weeds in the strip till zone had lower total biomass when a living mulch was present compared with a weed-free control treatment. No differences in weed biomass were detected among red clover, white clover and perennial ryegrass (21, 11, and 10 g m^{-2} respectively), but all were lower in weed biomass than the weed-free control (130 g m^{-2}).

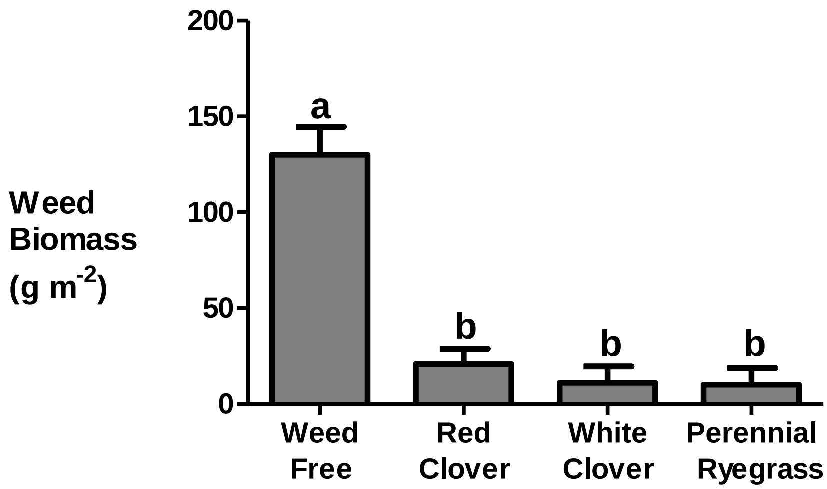

Figure 6. Weed biomass in the strip till zone at peak vegetative growth among living mulch treatments at Absaraka ND and Fargo ND during 2018 and 2019. Bars with the same letters do not differ according to Tukey's HSD (α=0.05).

The weed density in the strip till zone was not consistent across years or locations nor strongly associated with mulch treatments. Even within a given year and location, main effects were only present in Fargo 2018 where weed density was greater in the no-mulch control compared with the hydromulch and compost blanket, but no differences between the hydromulch and compost blanket were detected (16, 4, 7 weeds m^{-2} respectively) (Table 6). No differences in strip till zone weed density were detected among perennial ryegrass, red clover, white clover or the weed-free control in Fargo 2018.

Table 6. Weed density in the strip till zone at peak vegetative growth among the surface mulch and living mulch treatments at Absaraka ND and Fargo ND during 2018 and 2019.

	2018 Total weed density in strip till zone		2019 Total weed density in strip till zone	
Main effects	Absaraka	Fargo	Absaraka	Fargo
Surface Mulch†	——plants m^{-2}——		——plants m^{-2}——	
Compost blanket	3	7 b	7	26
Hydromulch	9	4 b	32	17
No-mulch control	30	16 a	404	160
Living Mulch				
Perennial ryegrass	9	8 a	28	64
Red clover	10	7 a	60	31
White clover	6	8 a	30	45
Weed-free control	14	9 a	77	34
GLIMMIX ‡	——*p value*——		——*p value*——	
Surface mulch	<0.0001	<0.0001	<0.0001	<0.0001
Living mulch	0.0088	0.8248	0.0241	0.0781
Surface mulch * Living mulch	0.0226	0.6538	0.0295	0.0337

† Due to interactions between surface mulch and living mulch, the only instance where mean separation can be performed within a main effect is in Fargo 2018. Values with the same letter do not differ according to Tukey's HSD where α = 0.05
‡ Generalized linear mixed model with a negative binomial distribution and a chi-square / df fit statistic range of 0.97 to 1.03 for all four models.

Of the three location-years where an interaction between surface mulch and living mulch was detected, the weed density was sliced by living mulch in order to assess simple effects among surface mulch treatments. In Absaraka 2018, weed densities were greatest in the no-mulch and least in the compost blanket within the perennial ryegrass and white clover living mulches (Figure 7). The no-mulch and hydromulch did not differ in weed density within the red clover treatments. The hydromulch and compost blanket did not differ in the weed-free control in Absaraka 2018. In Absaraka 2019, weed density was greatest in the no-mulch and least in the compost blanket only in the white clover treatments (Figure 8). In perennial ryegrass and red clover, weed density was greatest in the no-mulch and did not differ between the hydromulch and compost blanket. In the weed-free control, weed density is least in the compost blanket and does not differ between the no-mulch and hydromulch. In Fargo 2019, weed density was greatest in the no-mulch for perennial ryegrass, red clover and white clover (Figure 9). In perennial ryegrass and red clover, weed density did not differ between hydromulch and compost blanket. In white clover, weed density was lower in the hydromulch than the compost blanket. In the weed-free check, weed density was greater in the no-mulch than compost blanket, but neither the no-mulch nor compost blanket differed from the hydromulch in weed density.

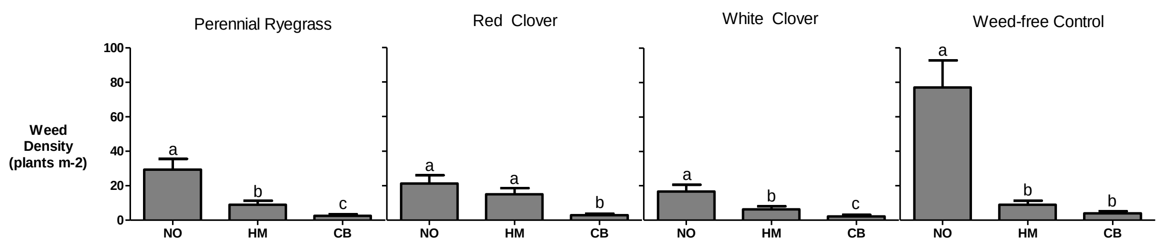

Figure 7. Weed density in Absaraka in 2018 sliced by living mulch treatment and compared among the surface mulches [no-mulch (NO), hydromulch (HM), and compost blanket (CB)]. Bars with the same letters do not differ according to a Bonferonni correction ($P \leq 0.005$).

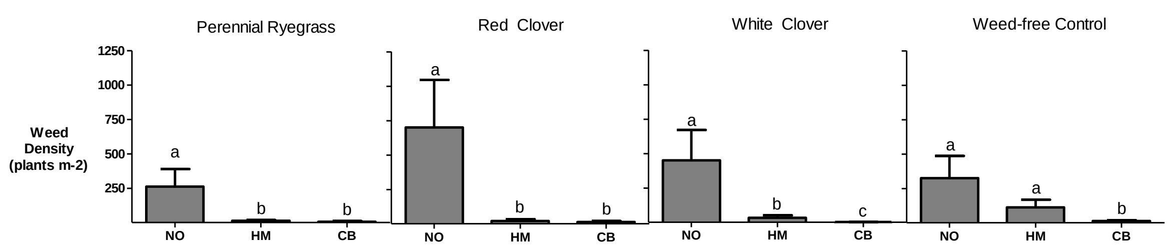

Figure 8. Weed density in Absaraka in 2019 sliced by living mulch treatment and compared among the surface mulches [no-mulch (NO), hydromulch (HM), and compost blanket (CB)]. Bars with the same letters do not differ according to a Bonferonni correction ($P \leq 0.005$).

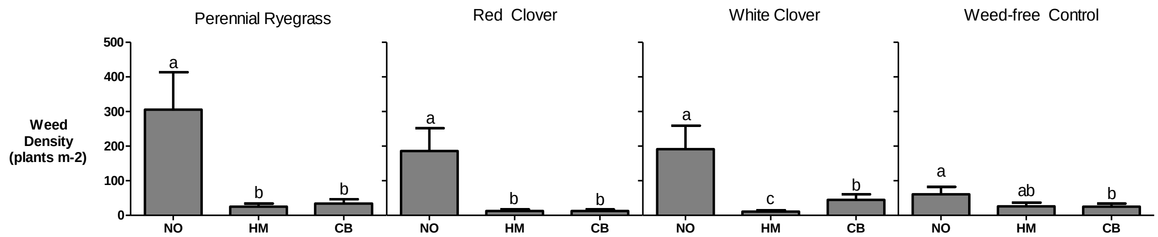

Figure 9. Weed density in Fargo in 2019 sliced by living mulch treatment and compared among the surface mulches [no-mulch (NO), hydromulch (HM), and compost blanket (CB)]. Bars with the same letters do not differ according to a Bonferonni correction ($P \leq 0.005$).

Treatment effects on average weed biomass at peak vegetative growth in the strip till zone were consistent across both years and locations. Results mirror the weed biomass response in the strip till zone, where the presence of living mulches reduced average weed biomass compared to the weed-free control (Figure 10). Specifically, the weeds in the weed-free control (5 g plant^{-1}) were larger than the weeds in red clover, white clover and perennial ryegrass (1, 0.6 and 0.4 g plant^{-1} respectively) though no differences were detected among the living mulch species. Average weed biomass at peak vegetative growth was greater in 2018 than in 2019 (4 and 0.3 g plant^{-1} respectively) (Figure 11). Average weed biomass at peak vegetative growth was lower in Absaraka than in Fargo (0.4 and 3 g plant^{-1} respectively) (Figure 12).

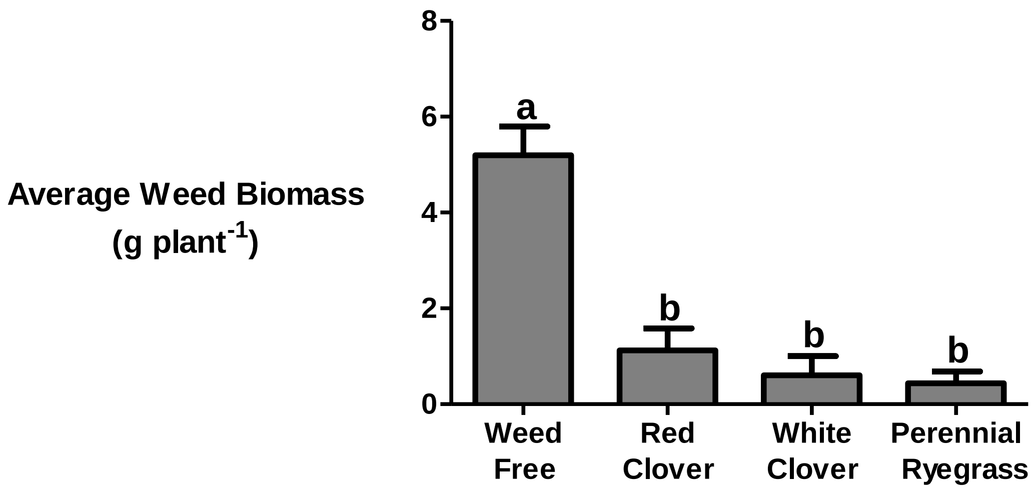

Figure 10. Average weed biomass in the strip till zone among living mulch treatments in Absaraka ND and Fargo ND during 2018 and 2019. Bars with the same letters do not differ according to Tukey's HSD (α=0.05).

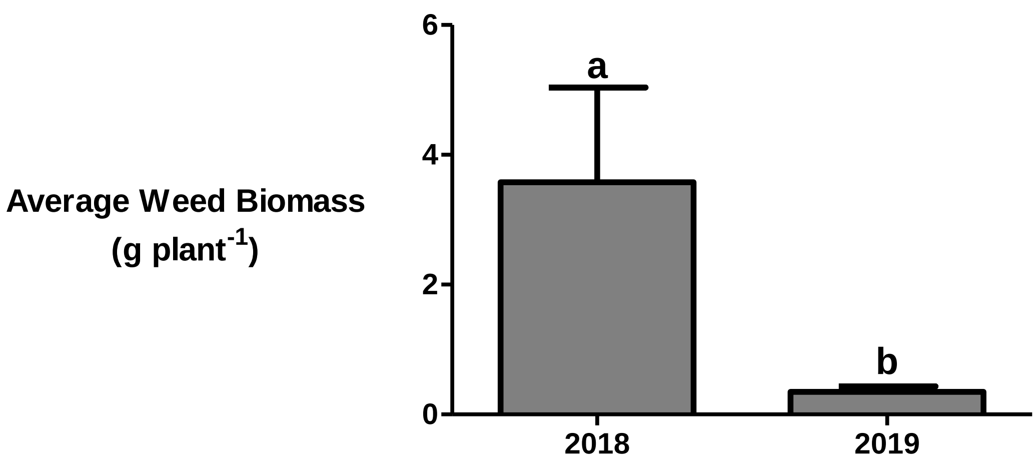

Figure 11. Average weed biomass in the strip till zone in Absaraka ND and Fargo ND. Bars with the same letters do not differ according to Tukey's HSD (α=0.05).

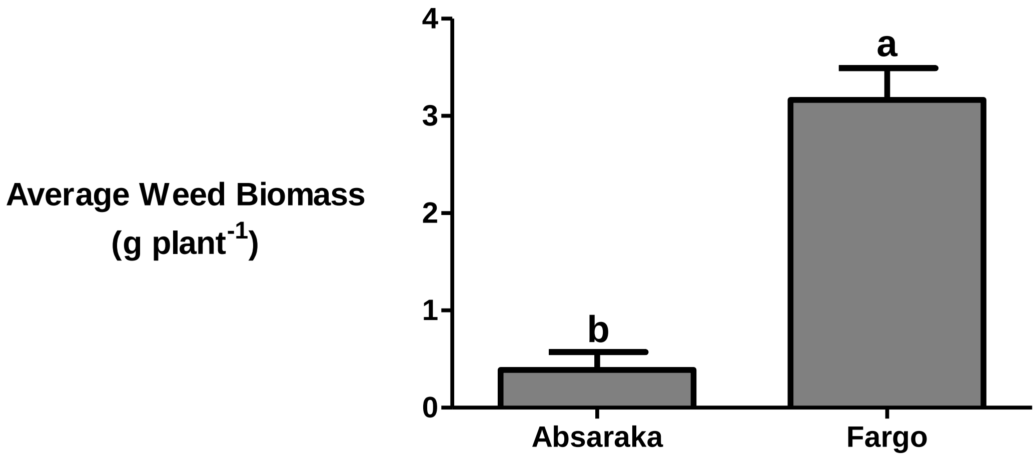

Figure 12. Average weed biomass in the strip till zone in 2018 and 2019. Bars with the same letters do not differ according to Tukey's HSD (α=0.05).

Weed species abundance differed among surface mulch treatments across both years and locations (Figure 13; stress = 0.143, rmse = 0.007). The compost blanket weed community differed from both the hydromulch and no-mulch weed communities ($P \leq 0.05$), though no difference was detected between the hydromulch and no-mulch strip till zones. Grass weeds were more abundant in the compost blanket and broadleaf weeds were more abundant in the no-mulch and hydromulch. Specifically, barnyardgrass, yellow foxtail and stinkgrass were all more commonly associated with the compost blanket treatment. Purslane, redroot pigweed and Venice mallow were more common with hydromulch and the no-mulch control.

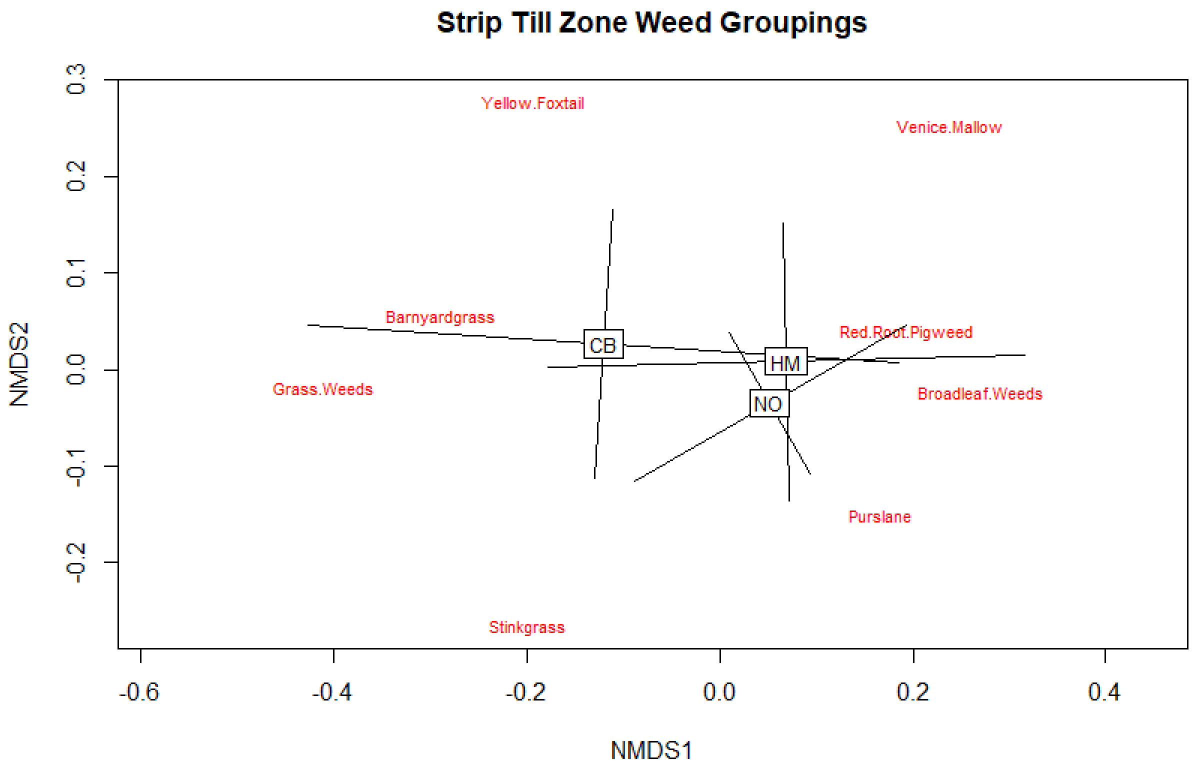

Figure 13. Weed community ordination during peak vegetative growth in the strip till zone in Absaraka ND and Fargo ND during 2018 and 2019. Surface mulch treatments [compost blanket (CB), hydromulch (HM) and the no-mulch control (NO)] are fitted within the ordination. Unlike a principle component analysis, axes in non-metric multidimensionsal scaling do not explain different amounts of variation and are only meant to show distance between the centroids.

Living Mulch

In the living mulch zone, weed biomass percent reduction from the weedy control in 2019 differed by location (Figure 14). In Absaraka, excellent weed suppression was observed in the white clover (99%) and perennial ryegrass (97%) treatments while good weed suppression was observed in the red clover treatment (81%). In Fargo, excellent weed suppression was observed in the white clover (99%) and red clover (96%) treatments while poor weed suppression was observed in the perennial ryegrass (69%).

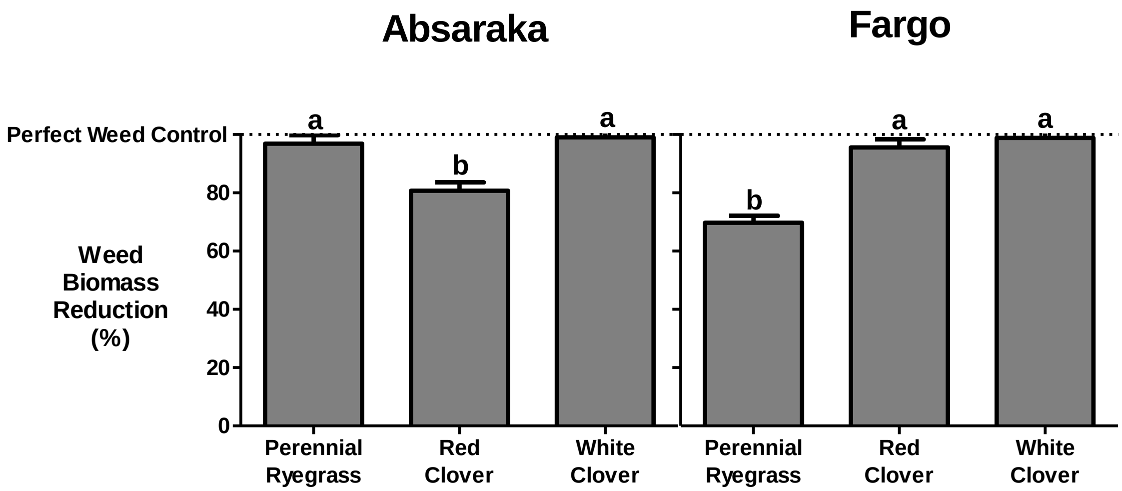

Figure 14. Weed biomass percent reduction from the weedy control at peak vegetative growth in the strip till zone in Absaraka ND and Fargo ND in 2019. Bars with the same letters do not differ according to Tukey's HSD (α=0.05).

Weed density percent reduction compared to the weedy control was separated by location due to an interaction (Figure 15). In Absaraka, weed control was excellent in perennial ryegrass (96%), red clover (94%) and white clover (100%) treatments and no differences were detected among the living mulch species. In Fargo, weed control was fair in perennial ryegrass (73%) and excellent in red clover (95%) and white clover (98%). The percent reduction in weed density was lower in perennial ryegrass plots than in red clover and white clover plots.

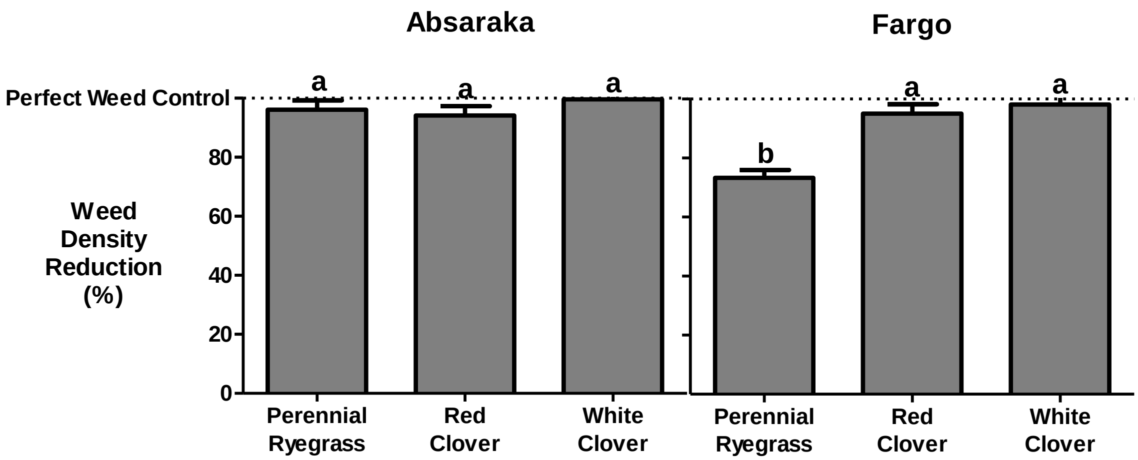

Figure 15. Weed density percent reduction from the weedy control at peak vegetative growth in the living mulch zone in Absaraka ND and Fargo ND during 2019. Bars with the same letters do not differ according to Tukey's HSD (α=0.05).

Differences in living mulch zone weed communities were detected among living mulch treatments (Figure 16). In this model, the weed-free controls were removed as they all contained zero weeds and their removal reduced the stress of the ordination (stress = 0.1135, rmse = 0.007). Pairwise comparisons indicated that red clover and white clover weed communities differed from each other and from the weedy control ($P \leq 0.05$). Red clover weed communities contained more grass species than the white clover and weedy control. Among grass species, yellow foxtail was particularly dominant in the red clover treatments compared to the other living mulch treatments.

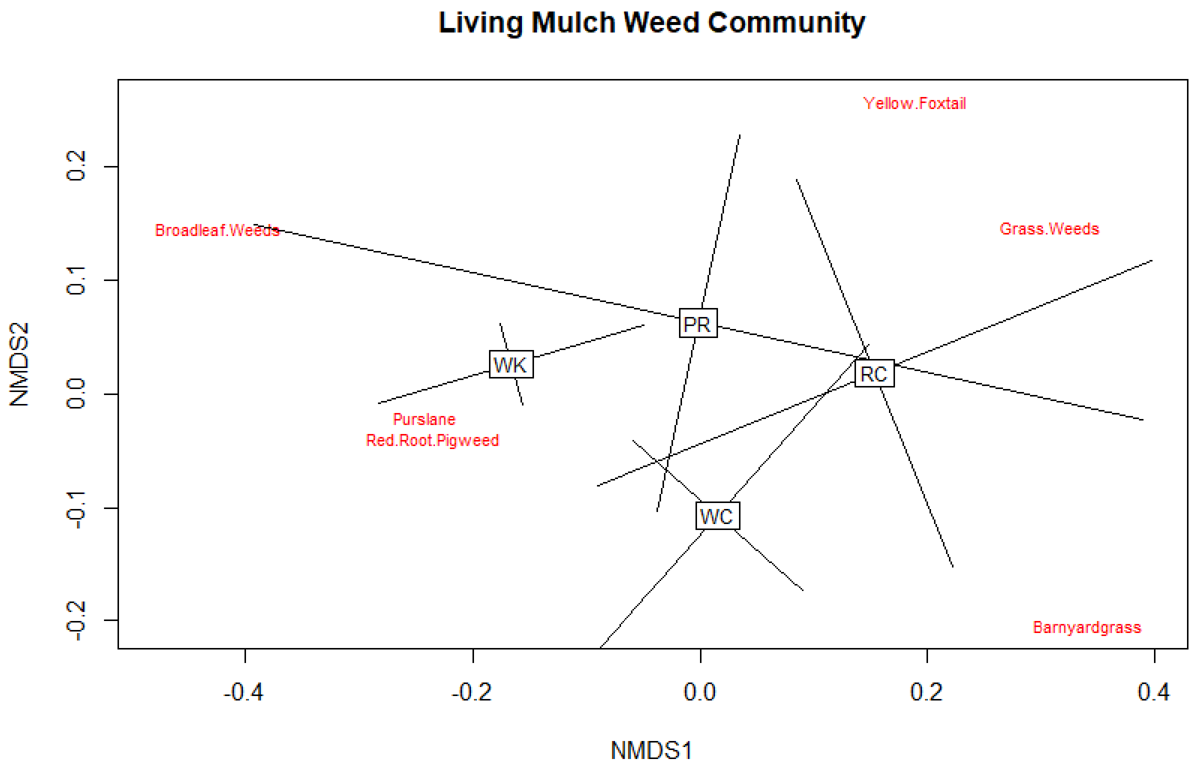

Figure 16. Weed community ordination during peak vegetative growth in the living mulch zone in Absaraka ND and Fargo ND during 2018 and 2019. Living mulch treatments [weedy control (WK), perennial ryegrass (PR), white clover (WC) and red clover (RC)] are fitted within the ordination. Unlike a principle component analysis, axes in non-metric multidimensionsal scaling do not explain different amounts of variation and are only meant to show distance between the centroids.

Discussion

Results are consistent with the hypothesis that weed biomass and density would be reduced in the hydromulch and compost blanket treatments compared to the no-mulch control. These findings are not surprising since materials that provide physical impedance to weeds reduce weed emergence (Teasdale and Mohler, 2000). More surprising was the similarity of weed biomass reduction in the hydromulch and compost blanket treatments. The material composition of hydromulch and compositions are quite different. Hydromulch is more similar to a landscape fabric with a high area-to-mass ratio and a low solid volume fraction, whereas a compost blanket is more similar to bark mulch with a low area-to-mass ratio and a high solid volume fraction. Teasdale et al. (2000) found that materials with high area-to-mass ratios tend to provide better weed suppression due greater soil coverage and strength. Heterogeneous mulches similar to the compost blanket with low area-to-mass ratios and high solid volume fractions were also found to provide less weed suppression due to incomplete soil coverage even when appearing to completely cover the soil surface. As a result, weeds typically face less physical impedance when emerging into a mulch like a compost blanket. One explanation for why weed biomass was not greater in the compost blanket treatments despite the lower area-to-mass ratio and higher solid volume fraction was due to the large application rate. In Teasdale et al. (2000), weed emergence through mulches was found to be reduced in the absence of light. Although the compost blanket may not have provided similar soil coverage and physical impedance as hydromulch, a weed that did emerge would need to grow 10-15 cm before being able to photosynthesize. Many annual weed species may not have sufficient energy reserves in their seeds to emerge through the compost blanket. Although the weed biomass responses to hydromulch and compost blanket treatments were expected, the specific mechanism governing weed suppression occurred is unclear.

The strip till zone weed density responses observed in this study were too variable to clearly determine whether it was consistent with the expectation that weed density would decline with a hydromulch or compost blanket present. Weed density was typically greatest in the no-mulch control and lowest in the hydromulch and compost blanket treatments. However, weed density did not always differ between the no-mulch and hydromulch treatments and these exceptions often occurred in strip till zones adjacent to weed-free controls. One possible explanation is that the hydromulch tended to degrade more rapidly when not protected by an adjacent living mulch. These findings suggest that the hydromulch provided a less consistent reduction in the number of weeds than the compost blanket.

Despite variable weed density among years and locations, the average weed biomass in the strip till zone did not differ among surface mulches across years and locations. Unexpectedly, average weed biomass in the strip till zone did differ among living mulch treatments. The largest weeds in strip till zones were adjacent to weed-free controls and the smallest weeds were adjacent to red clover, white clover or perennial ryegrass. Weed suppression from living mulch resource competition was expected to occur in the living mulch zone, but the results herein suggest that living mulches also compete with weeds in adjacent strip till zones.

One explanation for greater average weed biomass in 2018 is more favorable growing conditions, especially the abnormally warm temperatures after strip tillage in 2018, which resulted in a large flush of summer annual weeds (Figure A1). One explanation for larger average weed biomass in Fargo could be that weed densities were simply lower compared to Absaraka due to previous management of the weed seed bank. Total weed biomass in the strip till zone did not differ across locations, but weed densities were much lower in Fargo than Absaraka, which resulted in greater average weed biomasses.

The 2019 findings support the hypothesis that weed count and biomass would be lower where living mulches were established. White clover provided almost perfect weed control and weed suppression at both locations. After two growing seasons, white clover also appeared more consistent in weed suppression than red clover or perennial ryegrass, which both varied by location. Red clover performed worse in weed suppression than white clover at Absaraka, possibly due to the lower tolerance of red clover to mowing (Ross et al., 2001). Perennial ryegrass performed worse in both weed control and weed suppression in Fargo possibly due to winterkill between 2018 and 2019 (Figure A3). Overall, the weed suppression observed was far greater than observed in Ross et al. (2001), which reported a 39% weed biomass reduction in white clover plots and a 67% weed biomass reduction in red clover plots. The weed control of these living mulches was also far greater than that observed by Gruszecki et al. (2015), who observed 26% weed control in white clover treatments and 1% weed control in perennial ryegrass treatments compared to the weedy control. One possible explanation for the comparably high levels of weed control and weed suppression observed at peak vegetative growth in 2019 is the combination of ensuring a robust establishment of the living mulches in 2018 and the high frequency of mowing in 2019.

The living mulch treatments were hand weeded during establishment in the 2018 season to prevent annual weeds from impairing establishment during atypically hot weather. This intervention prevented a 2018 assessment of weed response to the living mulches compared to the weedy controls which were not hand weeded. This intervention may have been avoided had the living mulches been seeded in the fall of 2017 or if environmental conditions during establishment were different. The living mulch stands in our study were likely more robustly established than in other studies due to the hand weeding intervention during establishment and reseeding, which may have contributed to the strong weed suppression and weed control results observed in thein living mulch treatments employed in this study.

Weed biomass reduction in the living mulches was also confounded by the effect of mowing throughout the season. The weedy controls were not mowed and the living mulch treatments were mowed. This inconsistency existed because we conceived of the living mulch treatments as a farming practice that included mowing, not just a seeding rate as in Ross et al. (2001). The comparison of interest in our study was whether different living mulch species would provide different levels of weed control within a managed living mulch system. As a result, the primary comparison was not between the living mulches and the weedy check, but differences among the living mulch species. Due to the nature of this study, the management of the living mulches differed from the management practices reported in Ross et al. (2001) and Gruszecki et al. (2015). If the weedy controls were mowed, the weed density would likely be greater and the percent reduction from the weedy check among the living mulch treatments would likely be less and more similar to values reported in Ross et al. (2001) and Gruszecki et al. (2015).

Speculating on the weed density of a mowed weedy control is possible within the 2019 Fargo location, because 6 of the 12 perennial ryegrass treatments experienced more than 70% winterkill and 4 of the 12 plots experienced less than 30% winterkill (Figure A3). When comparing the differences in weed control with the differences in percent winterkill, 43% of the difference in weed control can be associated with winterkill, meaning the remaining 57% was attributable to mowing. These approximations suggest that weed density may have been twice as great if the weedy checks were mowed which would reduce the percent weed control values presented in our findings to levels similar with Ross et al. (2001) and Gruszecki et al. (2015).

The weed community shifts observed in the living mulches were not expected. Clover treatments have previously been associated with weed community shifts towards grass weeds, but it remains unclear whether these shifts were confounded by other factors in the studies, such as fertilization rates, crop rotation and tillage intensity (Bàrberi and Mazzoncini, 2001; Davis et al., 2005). Differences in aboveground biomass production may also have explained the shift in the weed community. In 2019, red clover treatments contained a considerable amount of red clover debris after the first mow in the early summer. Similar to growth through compost blankets, grass weeds may have been able to find an advantageous path through this clover mulch better than broadleaf weeds, resulting in weed species filtering (Teasdale and Mohler, 2000). Although previous research has found no more than weak associations between annual living mulches and weed community shifts, our findings suggest that perennial living mulches may be more effective at shifting weed communities (Smith et al., 2015). The perennial ryegrass weed communities were quite variable as seen in the variable ordibar lengths (Figure 16). The winterkill in the perennial ryegrass may explain this variation as filtering would be expected to be lower in the living mulch with less biomass production and soil coverage.

Crop Responses

Carrot emergence and stand counts at harvest were not consistent across years or locations (Table 7). When separated by year and location, main effects were present for both years in Fargo, but interactions between the surface mulch and living mulch treatments at Absaraka necessitated the slicing of the carrot count response (Figures 17, 18).

Table 7. Total carrot counts at harvest for 2018 and 2019 at Absaraka ND and Fargo ND.

	Total carrot counts at harvest			
	2018		2019	
Main effects	Absaraka	Fargo	Absaraka	Fargo
Surface Mulch	carrots m^{-1}		carrots m^{-1}	
Compost blanket	9	11 a†	9	4 b
Hydromulch	14	4 b	17	11 a
No-mulch control	21	5 b	18	8 a
Living Mulch				
Perennial ryegrass	12	8 ab	12	12 ab
Red clover	16	9 a	15	5 c
White clover	13	10 a	15	10 b
Weed-free control	18	4 bc	14	17 a
Weedy control	11	3 c	14	2 c
GLIMMIX	*p value*		*p value*	
Surface mulch	<0.0001	<0.0001	<0.0001	0.0001
Living mulch	0.0100	<0.0001	0.6682	<0.0001
Surface mulch * Living mulch	0.0285	0.8330	0.0022	0.3311

† Carrots counts values with the same letter are not different according to Tukey's HSD (α=0.05).

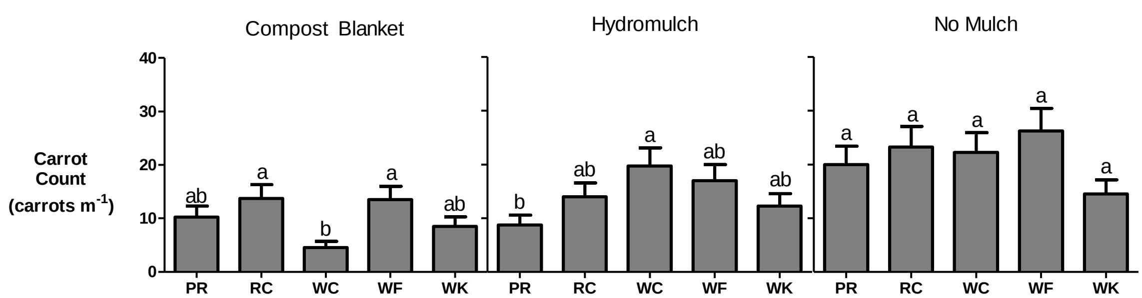

Figure 17. Carrot stand counts at harvest in 2018 at Absaraka ND. Living mulch treatments [perennial ryegrass (PR), red clover (RC), white clover (WC), weed-free control (WF) and weedy control (WK)] with the same letter do not differ according to Bonferroni groupings (α=0.05).

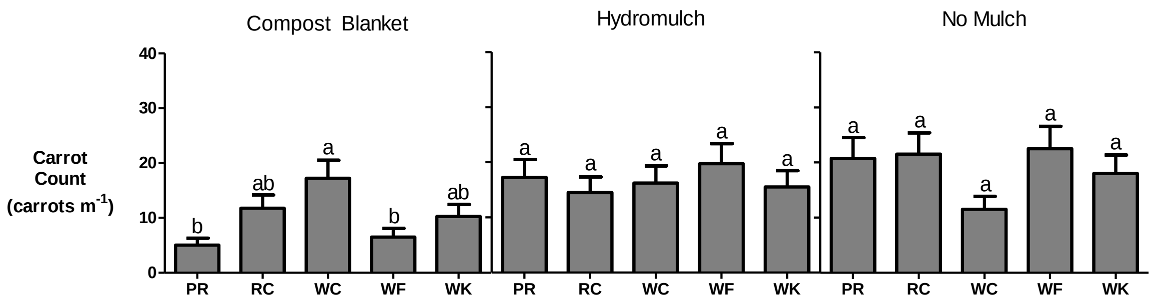

Figure 18. Carrot stand counts at harvest in 2019 at Absaraka ND. Living mulch treatments [perennial ryegrass (PR), red clover (RC), white clover (WC), weed-free control (WF) and weedy control (WK)] with the same letter do not differ according to Bonferroni groupings (α=0.05).

At Fargo in 2018, carrot counts were greater in the compost blanket treatment (11 carrots m^{-1}) compared to the hydromulch and no-mulch control (4 and 5 carrots m^{-1}, respectively). At Fargo in 2019, this pattern was reversed; carrot counts were lower in the compost blanket (4 carrots m^{-1}) compared to the hydromulch and no-mulch control (11 and 8 carrots m^{-1}, respectively). Among living mulch treatments in Fargo in 2018, carrot counts were greater in the red clover and white clover treatments (9 and 10 carrots m^{-1}, respectively) compared with the weedy and weed-free controls (3 and 4 carrots m^{-1}, respectively). Carrot counts in perennial ryegrass (8 carrots m^{-1}) were only greater than the weedy control. In Fargo in 2019, the weedy control remained the treatment associated with the lowest carrot count (2 carrots m^{-1}), but the weed-free control was now associated with the highest carrot count (17 carrots m^{-1}). Carrot counts were greater in white clover (10 carrots m^{-1}) than red clover (5 carrots m^{-1}), and perennial ryegrass carrot counts were greater than red clover (12 carrots m^{-1}), but not greater than white clover.

At Absaraka in 2018 and 2019, no differences were detected among living mulches when no surface mulch was present. When hydromulch was present, only one difference was detected in 2018 within hydromulch strip till zones where carrot counts were lower with perennial ryegrass compared to white clover (8.8 and 19.8 carrots m^{-1} respectively). When the compost blanket was present, differences among all living mulches except the weedy control were detected. In Absaraka in 2018, carrot counts were lower in compost blanket treatments where white clover was present compared with the red clover and weed-free controls (4.5, 14 and 13.5 carrots m^{-1} respectively). In Absaraka in 2019, carrot counts were greatest in compost blanket treatments where white clover was present compared with the perennial ryegrass and weed-free controls (17, 5, 6.5 carrots m^{-1} respectively).

Carrot yield was best represented as the percent reduction of average total carrot biomass in living and surface mulch plots compared to the weed-free control. Using this measure, differences between locations and among living and surface mulches were detected but no interactions were present. Overall, carrot biomass reduction was greater at Absaraka (75%) than in Fargo (49%) over both years (Figure 19).

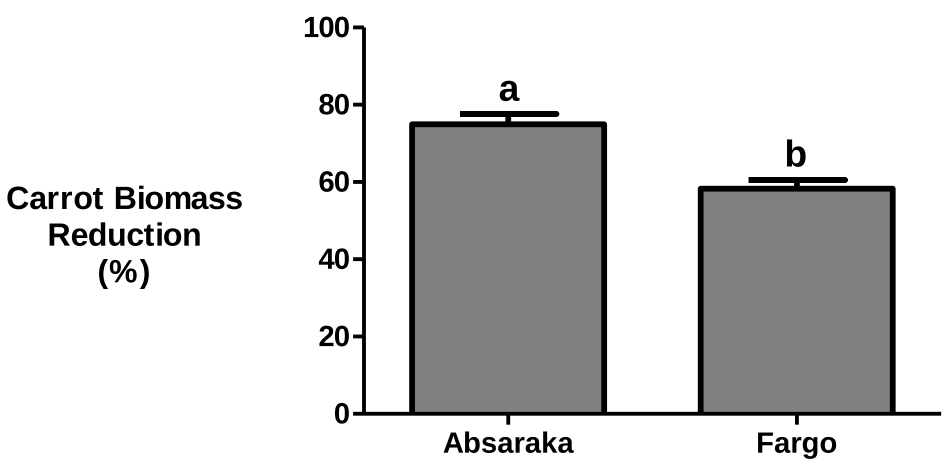

Figure 19. Average carrot biomass reduction from the weed-free control in 2018 and 2019. Bars with the same letters do not differ according to Tukey's HSD (α=0.05).

Carrot yield reduction was lower in compost blanket treatments compared to the no-mulch controls (62% vs. 72%) regardless of whether red clover, white clover or perennial ryegrass were the living mulch (Figure 20). These differences were consistent across both locations and years.

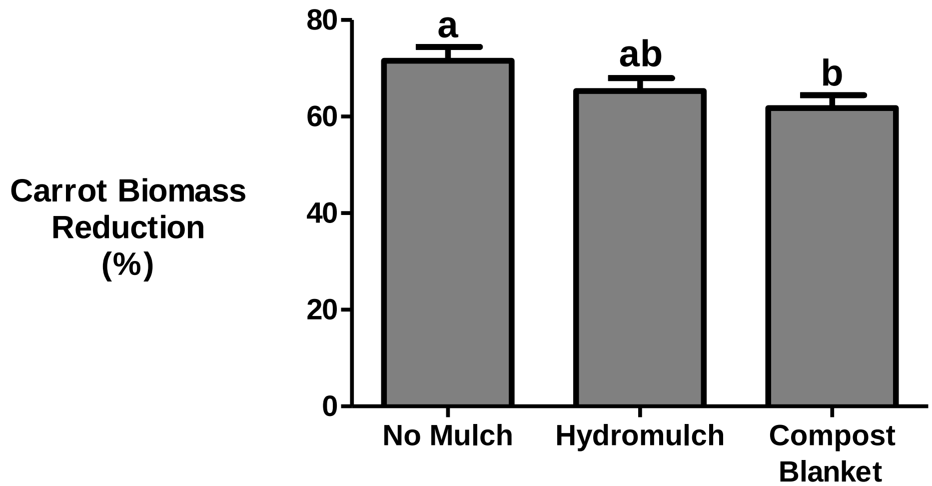

Figure 20. Average carrot biomass reduction from the weed-free control among surface mulch treatments in Absaraka ND and Fargo ND in 2018 and 2019. Bars with the same letters do not differ according to Tukey's HSD (α=0.05).

Carrot biomass reductions from the weed-free control also differed among living mulches and were consistent across years but not locations (Figure 21). In both locations, average carrot biomass was most greatly reduced when grown within a perennial ryegrass living mulch (84% in Absaraka and 65% in Fargo). White clover treatments had lesser carrot biomass reduction than the perennial ryegrass treatments in both sites (78% in Absaraka and 49% in Fargo). Carrot biomass reduction in red clover was less than perennial ryegrass in Absaraka (67% vs. 84%) but not in Fargo (62% vs. 65%).

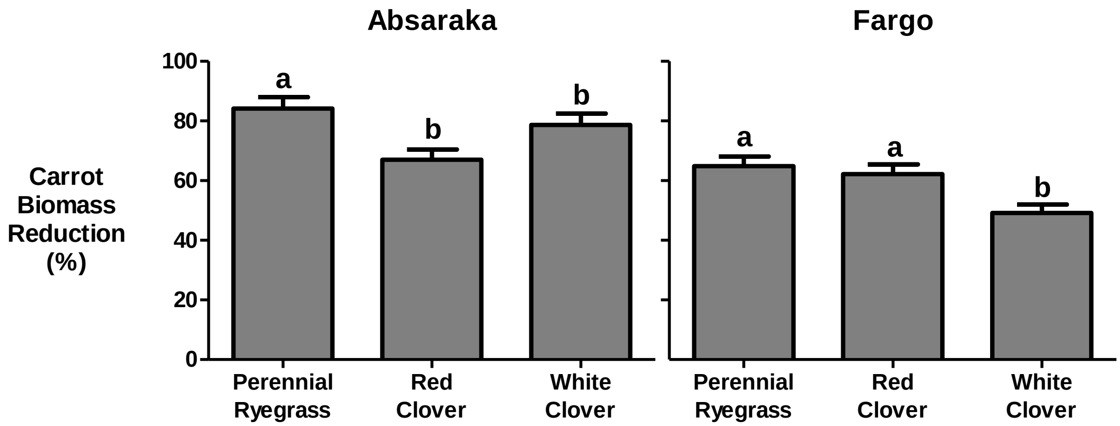

Figure 21. Average carrot biomass reduction from the weed-free control in 2018 and 2019. Bars with the same letters do not differ according to Tukey’s HSD (α=0.05).

Discussion

Findings support our hypothesis that yield reductions would occur in carrots grown adjacent to living mulches. Resource competition is well established as a mechanism by which living mulches reduce crop yields, but whether the competition was higher aboveground or belowground was not clear. We expected that aboveground resource competition for light could occur if mowing was not timely. In 2018, mowing was less consistent and carrot yield reductions were large among living mulch treatments. In 2019, mowing was more timely and light measurements were taken in the strip till zone using a ceptometer both before and after mowing. Nevertheless, despite more timely mowing, the yield reduction in living mulch treatments remained consistent in 2019, as evidenced by our ability to combine the two years of carrot biomass percent reduction observations. The ceptometer measurements indicated that slightly more light interception may have been occurring in clover treatments compared to the perennial ryegrass right before mowing, but after mowing these differences were no longer present (Figure A4).

Given the lack mowing impacts, living mulch competition with carrot crops likely occurred primarily belowground, which is consistent with observations in Pfeiffer et al. (2016) and Gruszecki et al. (2015). Carrot yield reductions in our work ranged from 49-84%, which is greater than the 18-26% yield reduction ranges reported in Gruszecki et al. (2015). One explanation for differences between our findings and Gruszecki et al. (2015) is that they used ridge tillage to manage competition rather than strip tillage. The ridge tillage system likely was more effective at reducing belowground resource competition, but their mowing methods may have been less effective at controlling aboveground resource competition. Specifically, white clover is more capable of lateral growth into the crop production zone and compete for aboveground resources. In our study, we managed white clover by hand to prevent its encroachment into the strip till zone, but there is no indication of the practice in the methods of Gruszecki et al. (2015). Living mulch competition likely occurred primarily belowground, as is consistent with observations in Pfeiffer et al. (2016) and Gruszecki et al. (2015).

Differences in carrot yield reductions among surface mulches were not expected, but logical. Compost blanket treatments tended to have less yield reduction than the no-mulch control, but this difference accounted for less than 10% of the total yield reduction. Differences in weed control could explain the differences in carrot yield between the compost blanket and no-mulch control (Figure 5), but the absence of a difference in yield between the hydromulch and no-mulch suggests that additional factors may allow for better carrot growth in compost blankets than hydromulch treatments. While the compost blanket and hydromulch treatments did not differ from one another, their impact on soil fertility may explain their difference or lack of difference from the no-mulch control. The compost blanket contained composted cow manure that likely contributed to carrot growth over the course of the growing season. By contrast, the hydromulch contained a very high carbon to nitrogen ratio and its degradation over the growing season may have contributed to the immobilization of nutrients important for carrot growth (Richard, 1996). The thickness of the compost blanket, and its ability to store water may also have contributed to the detectable difference from the no-mulch control. Attempts to measure differences in soil temperature and moisture were made in 2018 using a GS-3 spot measurement sensor and a continuous datalogger with a GS-1 sensor, but data was not sufficiently robust to present (Figure A5). Data that was collected suggested that the compost blanket tended to lower soil temperatures and increase soil moisture relative to soil under hydromulch, but these findings had inconsistencies due to instrumentation errors. Mulch modification of soil moisture and temperature and the impact of these factors on crop growth are well established, but these responses could not be sufficiently quantified in this study (O'Brien et al., 2018; Braunack et al., 2020). Compost blanket improvements to carrot yields compared to the no-mulch control were modest in comparison to the effect of living mulches on yield, but further investigation of the fertility, moisture and temperature modifications provided by compost blanket may explain the findings of this study.

Differences in carrot biomass reduction by site were interesting. One simple explanation was soil texture. As clay content increases in soils, the bulk density at which root development is restricted also increases (Jones, 1983). Absaraka had a sandier soil that is more conducive to carrot production than Fargo (Table 1). The carrot yield potential was likely greater in Absaraka as a result of soil texture. The weed-free controls in Absaraka, therefore, tended to produce larger average carrots than the same treatments in Fargo. Living mulch productivity also appeared greater in Absaraka compared to Fargo. The sandier soil in Absaraka may have allowed for greater growth by the living mulches than in the clayey Fargo soil. As a result, the living mulches in Absaraka may have competed belowground with carrots more easily, resulting in greater carrot biomass percent reduction in Absaraka. Differences in soil fertility may also explain differences in yield reduction, as will be discussed later.

The variability of carrot stand counts was not expected. Neither carrot emergence nor carrot count data at harvest present a clear and consistent picture of carrot responses response to the experimental treatments. Although differences were detected among surface mulch treatments in both years at Fargo, the effects were reversed between years, with the compost blanket being associated with the highest carrot count in 2018 and the lowest carrot count in 2019. The interactions at Absaraka and inconsistencies at Fargo suggest that detected differences were likely not meaningful and may be type I errors resulting from the need to separate analyses by location and year. In Absaraka 2018 and 2019, carrot counts appeared to be more variable in the compost blanket treatments than the hydromulch and no-mulch treatments (Figure 17, 18). Inconsistent results may also be explained by a failure to control sources of error such as soil preparation, seeder, seed storage, soil moisture, soil temperature, and drip tape modification of soil temperature. Intriguingly, inconsistent carrot stands have been previously reported and are typically accepted as a covariate when determining carrot yield response, but better statistical fits were achieved in our study when average carrot biomass was used versus carrot biomass with carrot count as a covariate (Reid et al., 2018).

Soil Nitrate Response

Differences in nitrate content were detected among living mulch treatments at the end of the 2019 growing season. When combined across locations, white clover plots had the greatest soil nitrate content of 30 kg ha^{-1} and weedy control plots had the least soil nitrate content of 16 kg ha^{-1} (Figure 22). Red clover and white clover plots both had greater nitrate contents than weedy and weed-free control plots. Both the perennial ryegrass and the weed-free control plots contained approximately equivalent nitrate levels at the end of the 2019 growing season, 17 kg ha^{-1}. Soil nitrate content also varied between locations, with Absaraka soil containing greater levels than Fargo soil at the end of 2019 (Figure 23).

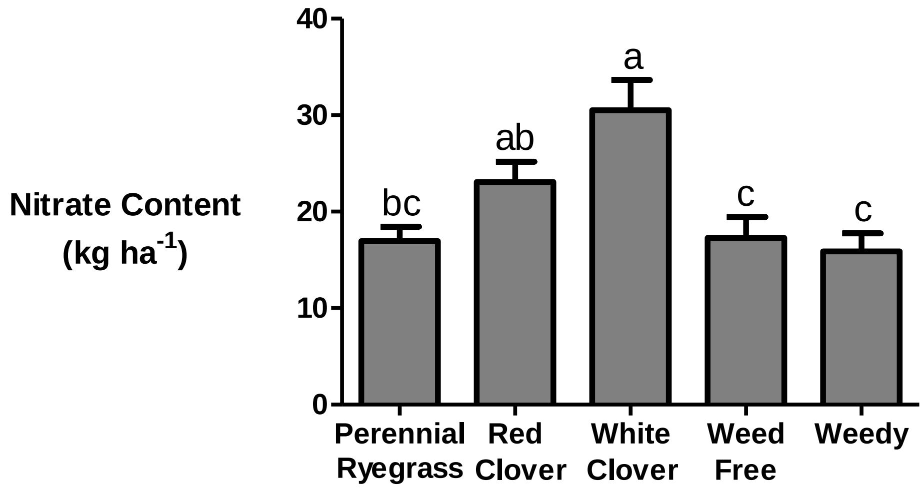

Figure 22. Soil nitrate content among living mulch treatments after carrot harvest in 2019 in Absaraka ND and Fargo ND. Bars with the same letters do not differ according to Tukey's HSD (α=0.05).

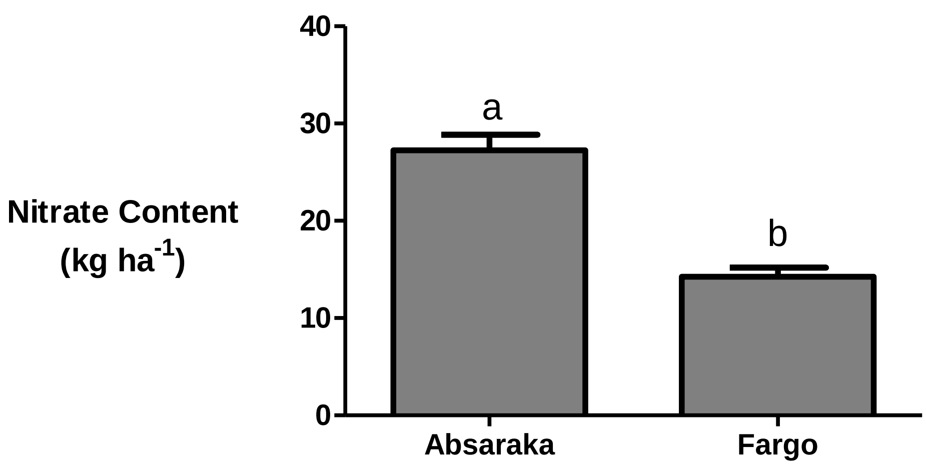

Figure 23. Soil nitrate content after carrot harvest in 2019. Bars with the same letters do not differ according to Tukey's HSD (α=0.05).

Discussion

Higher soil nitrate content in clover treatments was expected and the observed increase of 14 kg NO3-N falls within a reasonable range of expected (Carlsson and Huss-Danell, 2003). Finding that white clover treatments produced greater soil nitrate content than red clover treatments in Absaraka differs from a previous report that nitrogen fixation tends to yield 23$\pm$24 kg more nitrogen in red clover than white clover Higher soil nitrate content in clover treatments was expected and the observed increase of 14 kg NO3-N was a reasonable range (Carlsson and Huss-Danell, 2003).. The variability in this difference, however, is indicative of the many other factors that can affect total nitrogen fixation, such as sowing date, number of years of production, variety type, soil fertility and biomass production. Despite previous research indicating that red clover tends to fix more nitrogen that white clover, the results herein are not surprising because white clover treatments in this experiment appeared healthier and more productive throughout both growing seasons compared with the red clover treatments. One reason red clover treatments may not have appeared as healthy was due to a tall growth stature that may have reduced their resilience to mowing (Ross et al., 2001). When living mulch treatments were mowed for the first time in 2019, red clover treatments were approximately 70 cm high and white clover was approximately 20 cm high. After the initial mowing, red clover treatments did not grow back as vigorously as white clover and stand density in red clover plots appeared lower than in white clover plots. This may have been the result of leaving the cut red clover clippings on the red clover treatments after mowing. This is an example of one management decision that may explain season-long observations from both sites that the red clover treatments appeared less productive and vigorous than the white clover treatments, and these differences in aboveground productivity may explain differences in the soil nitrate content observed at the end of the 2019 growing season.

Whether differences in nitrate would be detectable at the end of the 2019 growing season was unknown. Abnormally heavy rainfall resulted in standing water at both sites for multiple days of the growing season both in July and September. Although living mulch growth appeared more vigorous in 2019 compared to 2018, prolonged periods of soil-water saturation may have reduced nitrogen fixation in the clover treatments. Legume-rhizobial symbioses are typically negatively impacted by saturated soils due to anerobic conditions which reduce the activity of nitrogenase in the nodules (James and Crawford, 1998). White clover, however, has been found to increase its nitrogen fixation under long periods of saturated soil conditions (Pugh et al. 1995). We were uncertain whether the duration of saturation in 2019 at both sites was similar enough to the Pugh et al. (1995) study to expect a similar response. We were further uncertain whether red clover was similar to white clover in its ability to enhance nitrogen fixation during prolonged periods of flooding, or whether it was similar to other legumes and its nitrogen fixation was negatively impacted.

Determining whether Fargo or Absaraka would have been under anaerobic conditions was also difficult. The soil textures are very different. In Absaraka where the soil is sandier, water is able to enter and drain more easily. Consequently, Absaraka soil became saturated faster after excessive rain and when standing water was observed on the soil surface, this was indicative that the soil throughout the rooting depth was likely also saturated. In Fargo where the soil texture is more clayey, standing water may have occurred and yet anaerobic conditions may not have been occurring throughout the root zone. The clayey texture of the Fargo soil confers a tortuosity that can trap air bubbles in the rooting zone even when standing water is present on the soil surface. The clover treatments at Fargo may have had adequate soil oxygen supply longer than at Absaraka despite similar durations of standing water on the soil surface. It is difficult to know definitively. Greater nitrate differences among treatments may have existed during the 2019 growing season, but heavy rainfall in September could have transported nitrate out of the soil sampling depth before cores were taken for nitrate measurements (Stein and Klotz, 2016)(Stein and Klotz, 2016)(Stein and Klotz, 2016)(Stein and Klotz, 2016)(Stein and Klotz, 2016)(Stein and Klotz, 2016).

The ability of soil microbial communities to convert organic forms of nitrogen to nitrate could also have been impacted by the wet conditions in 2019. Anerobic conditions reduce mineralization of organic nitrogen to ammonium. Anerobic conditions also reduce nitrification rates. Lastly, denitrification rates increase in anerobic conditions (Stein and Klotz, 2016). As a result, the organic soil nitrogen additions from the legume species may have been greater than detected in the nitrate soil analysis because the conversion of the organic N to ammonium (mineralization) and then ammonium to nitrate (nitrification) would have been slower in prolonged wet soil conditions. Furthermore, some of the nitrate that was converted from the organic nitrogen would also likely be denitrified at higher rates than typical due to the wet conditions.

Conclusion

The utility of combining the surface mulches and living mulches examined in this study depended on their ability to provide beneficial outcomes while minimizing undesirable outcomes. For weed control, living mulches and surface mulches significantly reduced weed density and biomass when applied properly. Surface mulches were associated with greater carrot yields; however, these improvements were minimal compared to the reductions in carrot yield associated with living mulches. Both clover living mulches were associated with lower rates of yield reduction and greater soil nitrate content compared with the perennial ryegrass living mulch.

Both surface mulches examined in this study provided sufficient increases in weed control and crop productivity to warrant future investigation and development. Yield reduction associated with living mulches remains a significant barrier to their adoption in vegetable systems. Further competition management strategies (i.e., wider strip till zones, ridge planting) may be required for simultaneous living mulch and vegetable crop production without unacceptable yield reduction.

While mulches are a highly desirable tool in vegetable production, research rarely targets direct seeded crops resulting in a lack of tools and tactics for crops such as carrot. Utilizing hydromulches directly after thinning an overseeded crop or planting directly into a compost blanket could allow direct seeded vegetable producers to access the benefits provided by mulches and diversify weed control programs.

We attempted to develop these tactics for small scale vegetable production in the Red River valley of North Dakota, though there are likely applications beyond this environment.

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CHAPTER 3: CHARACTERIZING HYDROMULCH AND COMPOST BLANKET MULCHES FOR STRENGTH AND WEED CONTROL

Abstract

Paper hydromulches and compost blankets are biodegradable mulches that may allow growers to control weeds without the use of plastic mulches. Recommended application rates do not exist for these mulches. Weed emergence was determined for eight annual weed species at multiple application rates. No differences were detected in total weed emergence between rates of 6.4 and 12.7 L m^{-2} for the hydromulch. Mulch strength was also characterized at different application rates. Hydromulch strength increased by 0.15 MPa for every 1 L m^{-2} increase in application rate. The characterization of mulches by their properties is critical to further understanding their mechanisms for weed control.

Introduction

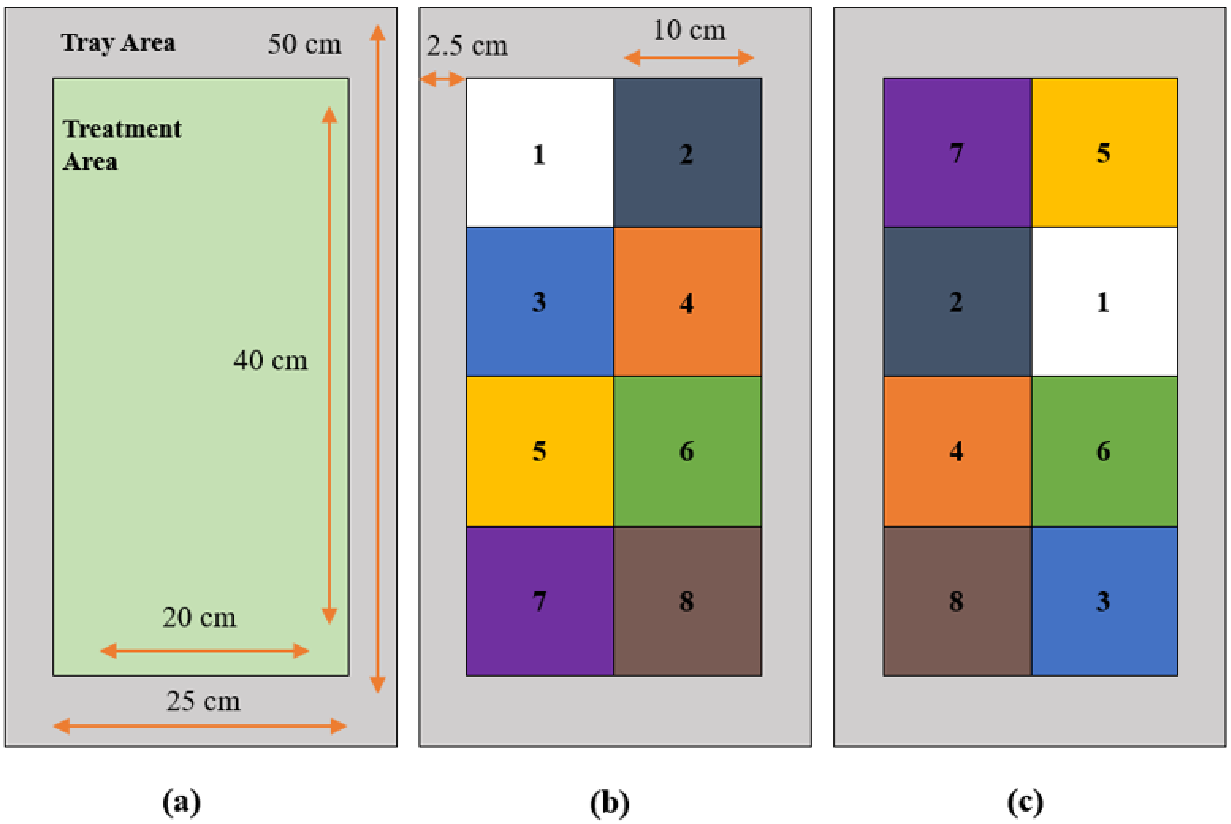
Vegetable producers in the United States apply more than 143,000 tons of plastic mulches annually for weed control (Shogren and Hochmuth, 2004). The removal costs associated with plastic mulches are considerable (\$250 ha^{-1}), and the need for biodegradable alternatives have been discussed (Shogren and Hochmuth, 2004; Goldberger et al., 2015; Chen et al., 2018). Paper mulches are an alternative to plastic mulches that are capable of similar levels of weed control (Cirujeda et al., 2012). Paper mulches can be applied in liquid suspensions called Hydromulches and may be a preferable method for mulch application. Rates of hydromulch application can vary significantly among the limited hydromulch studies available (0.5 to 14 L m^{-2}), complicating an assessment on what hydromulch rates are necessary for acceptable weed control(Warnick et al., 2006; Claramunt et al., 2020). No study has yet investigated the role of application rate on weed control despite previous identification of this knowledge gap (Warnick et al., 2006).

The primary objective of this study was to determine how weed response differs among multiple mulch rates in order to optimize application rates. The design of this study was conceptualized from a previous field experiment that used a newspaper hydromulch and a compost blanket mulch (unpublished, chapter 2). We hypothesized that (i) weed emergence would be similar between hydromulch and compost blanket treatments (ii) weed emergence would increase as application rates were reduced and (iii) weed emergence would be greater for grass species than for broadleaf species. The secondary objective of this study was to determine the relationship between mulch strength and application rates. Previous research indicated that mulch strength determined weed control efficacy (Claramunt et al., 2020). We hypothesized that increases in application rate would result in increases in both mulch strength and weed control. Characterizing mulch strength and weed response to different application rates of hydromulch and compost blankets are likely necessary steps for the development of these mulches as alternatives to plastic mulches.

Materials and Methods

Three experimental runs were conducted in greenhouses at North Dakota State University in 2019. Environmental conditions in the greenhouse were managed to achieve temperature ranges typical for North Dakota in July. Daily temperature range was 20-35 °C and day length was kept at 16 hours using overhead lights.

Five application rates of two surface mulches were arranged in a completely random design containing four replicates. The five application rates (0X, 0.25X, 0.5X, 1X, 1.5X) were determined from rates used in previous field experiments (unpublished, chapter 2). Hydromulch standard rate, 1X, was 12.7 L m^{-2} of hydromulch at a ratio of 35 L of water per 1 kg of newspaper. Compost blanket standard rate, 1X, was 108 L m^{-2} at a 2:1 ratio by volume of composted cow manure and hemp hurd, respectively. Within each treatment area, 8 plant species were randomly arranged (Figure 24). Plant species were a combination of weeds and surrogate weed species: large seeded broadleaves [sunflower (*Helianthus annuus* L.), pea (*Pisum sativum* L.)], large seeded grasses [oat (*Avena sativa* L.), jointed goatgrass (*Aegilops cylindrica* Host)], small seeded broadleaves [redroot pigweed (*Amaranthus retroflexus* L.), common lambsquarters (*Chenopodium album* L.)], and small seeded grasses [witchgrass (*Panicum capillare* L.), barnyardgrass (*Echinochloa crus-galli* (L.) P. Beauv.)].



Code	Plant Species
1	Sunflower
2	Common bean
3	Oat
4	Jointed goat grass
5	Redroot pigweed
6	Common lambsquarters
7	Witchgrass
8	Green foxtail

Figure 24. Three trays from the greenhouse experiment are represented. Figure (a) demonstrates the dimension of the treatment area within each tray. Figure (b) demonstrates how plant species were arranged within the treatment area. Figure (c) demonstrates how plant species were randomized within a treatment area. For example, Figure (b) could be a hydromulch at 0.25X application rate and Figure (c) could be a compost blanket at a 1X application rate, each with their own respective arrangement of plant species.

Experimental units were shallow plastic trays with dimensions of 25 cm x 50 cm x 6 cm. Each tray received 3 L of potting soil that was then compressed (ProMix potting mix, Quakertown PA). Each split within the tray was 10 cm x 10 cm and was seeded to one of the eight species. Seeding rates were 25 seeds per split. Seeds were placed on the soil surface and lightly covered with an additional layer of potting soil and compressed again. All treatments were watered before mulch application. After mulch application, all trays were watered every 1-2 days as necessary using subsurface irrigation to ensure adequate soil moisture without disturbing the surface mulch. Trays were also rearranged every 1-2 days in order to limit the possible effects of environmental gradients within the greenhouse.

Experimental runs were adjusted in scope based on findings of previous runs. The first run was performed exactly as previously described except the 1.5X application rate for the compost blanket was abandoned due to the movement of the mulch material outside the experimental area when applied at such a high rate. The second and third run did not contain any compost blanket treatments due to cracking that occurred when trays were watered and re-randomized during the greenhouse experiment. The second and third run of the experiment also did not contain sunflower, jointed goatgrass, common lambsquarters, and witchgrass due to the limited information these species provided in the first experimental run (Figure A6, A7). A 0.75X mulch application rate was also added for the second and third run of the experiment. The dates for the runs were March 11, July 17 and July 19, respectively.

Data Collection

In the first experimental run, trays were assessed daily for weed emergence. Emergence was defined as any visible plant tissue above the mulch surface. For the second and third runs, weed counts were only taken at the end of the experiment after all weeds had emerged (2 weeks after planting).

Weed counts at the end of the experiment were computed into a cumulative emergence from the initial seeding rate [1].

$$Total\ emergence = \frac{Total\ number\ of\ emerged\ plants}{Number\ of\ seeds\ planted} * 100 \qquad (1)$$

Two weeks after the mulch application, mulch strength was measured using a force gauge (FG-5000, Extech instruments, Waltham MA). The hydromulch was removed from the tray and placed in a deeper bin filled with potting soil to ensure the instruments would not immediately hit the base of the tray after penetrating the hydromulch. Mulch strength was measured as the peak resistance of the mulch which was recorded in grams of force and converted to grams cm^{-2} by calculating the surface area of the cone at the end of the force gauge [2]. Cone diameter was 6.4 mm, cone height was 6 mm and cone angle was 60 degrees.

$$Cone\ surface\ area = \pi r\sqrt{r^2 + h^2} \tag{2}$$

Analysis

Cumulative emergence and mulch strength were analyzed using mixed models in JMP (JMP, Cary NC). The fixed effects were a full factorial of application rate and weed species; the random effect was experimental run. Models were examined for goodness of fit using adjusted r-squared values and treatment effects were ultimately separated by weed species due to interactions. Hydromulch and compost blanket were never combined in an analysis. Differences among means for all analyses were determined using Tukey’s HSD (α=0.05).

Results and Discussion

Weed Responses

Cumulative emergence differed among hydromulch application rates over all three runs of the experiment (Figure 25). In barnyardgrass, cumulative emergence was greater at the 0.25X rate than the 1X rate, but did not differ at the 0.5X rate (12%, 0.3% and 1.3%, respectively). In oat, cumulative emergence was greater at the 0.25X rate than at the 1X rate, but also did not differ at the 0.5X rate (22%, 2%, 3%, respectively). In pea, cumulative emergence was greater at the 0.25X rate than at the 1X rate, but also did not differ between the 0.5X and 1X rate (17%, 0%, 2%, respectively). Findings from the first experimental run which included the compost blanket and four additional weed species presented similar trends but were not statistically analyzed due to a lack of replication (Figures A6, A7).

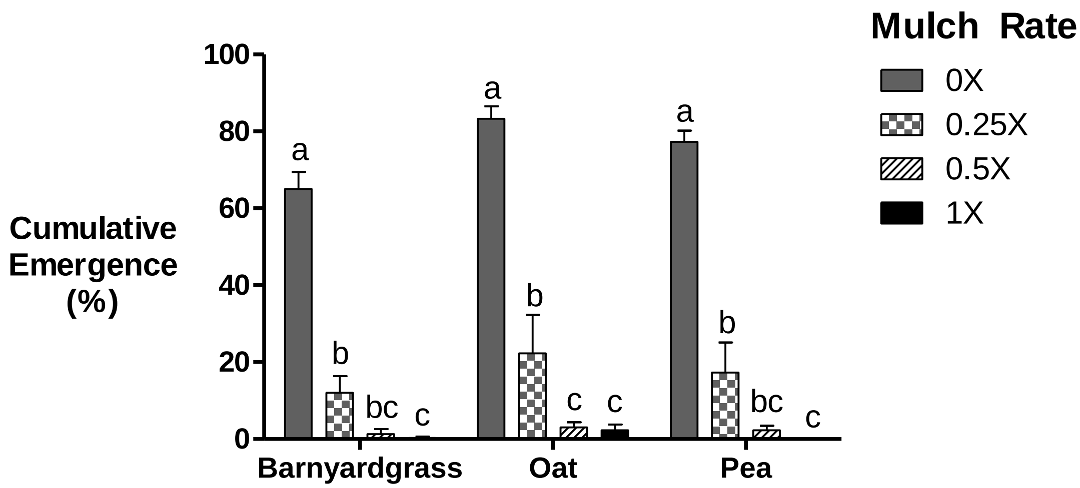


Figure 25. Cumulative emergence of key weed and surrogate weed species at differing rates of hydromulch combined across all three runs of a greenhouse experiment at North Dakota State University. Bars with the same letters do not differ according to Tukey's HSD (α=0.05).

Mulch Strength

In the second and third run of the experiment, increases in mulch strength were detected in the hydromulch as application rate increased (Figure 26). Differences in mulch strength were detected among all hydromulch application rates except between the 0.25X and 0.5X rates (0.36 and 0.57 MPa respectively). Apparent increases in mulch strength were also present in the first run of the experiment (Figure A8).

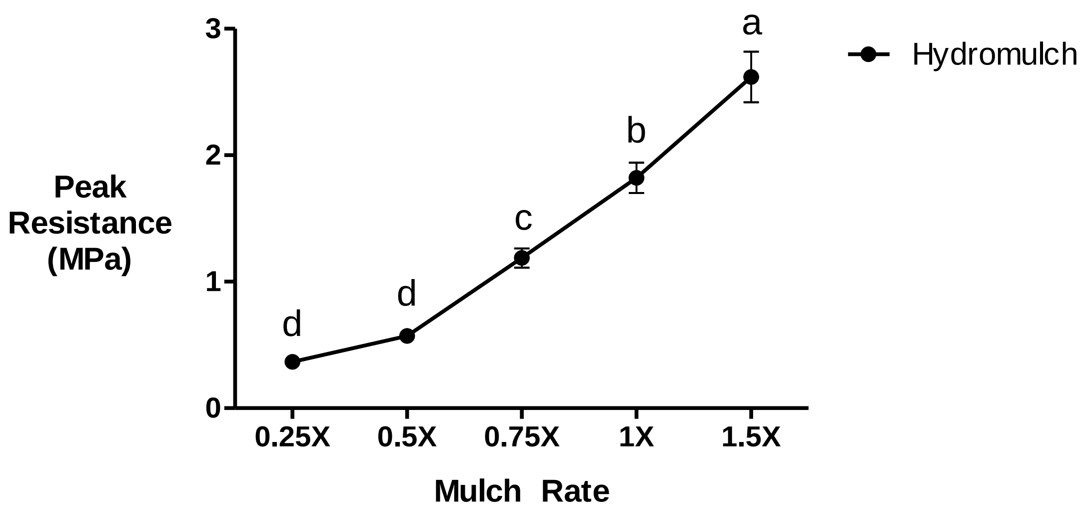


Figure 26. Mulch strength of the hydromulch in the second and third experimental run at North Dakota State University. Data points with the same letters do not differ according to Tukey's HSD (α=0.05).

A linear relationship was fit between hydromulch application rate and mulch strength (Figure 27). Every additional liter of hydromulch per square meter was associated with an increase in mulch strength of 0.15 MPa.

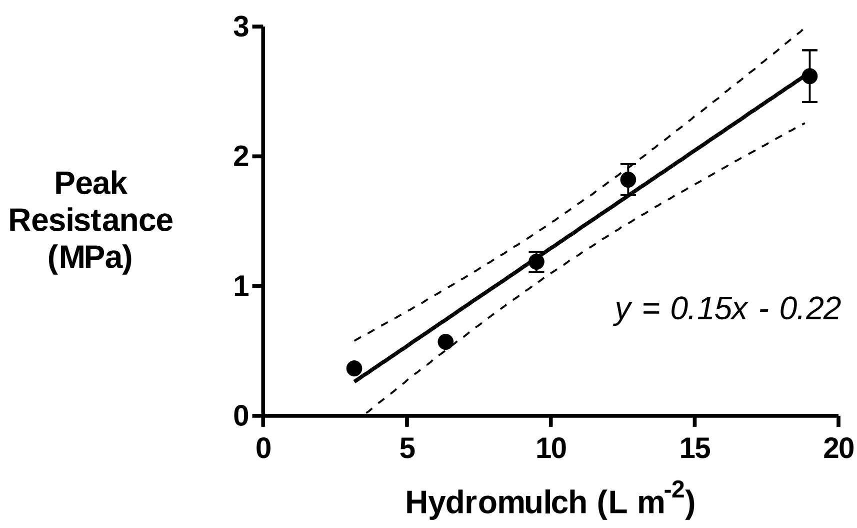


Figure 27. Linear relationship between hydromulch peak resistance application rate from the second and third run of the greenhouse experiment conducted at North Dakota State University. Dotted lines represent 95% confidence intervals. The linear equation has an r^2 value of 0.7 and a root mean square of 4.4.

Discussion

Determining weed emergence differences between hydromulch and compost blanket was not possible due to the lack of multiple experimental runs that included compost blanket. All three experimental runs demonstrated lower weed emergence at increasing application rates of hydromulch. The first experimental run with compost blanket, however, did not contain similar patterns of decreasing weed emergence with increasing mulch application rates (Figure A6, A7). The unexpected observations of large cumulative weed emergence even at high application rates of compost blanket may be explained by the experimental procedure of constantly rearranging the plastic trays which resulted in shifting and cracking of the compost blanket in a way that had not previously been observed in the field experiments. The cracking of the compost blanket may explain why weed emergence did not greatly differ as application rate increased because weeds emerging through cracks in the mulch likely did not receive a treatment effect from the compost blanket mulch. The compost blanket treatments were not included in the subsequent runs of the experiment because we believed they could not be properly applied and maintained in the greenhouse experimental design.

Weed species relevant to carrot production in North Dakota tend to be summer annuals with small seed sizes. Among these species, the hypothesis of grasses or broadleaves being favored in different mulches and at different application rates was not supported. However, the experimental design may not have been sufficient to answer this question and further experimental runs would be required in order to confidently claim that mulch species selectivity was not occurring. Four of the weed species were eliminated from the second and third experimental runs due to poor performance in the first experimental run. While findings do not support the hypothesis that mulches were selecting for broadleaf or grasses, the experiment was ultimately unable to answer this question due to execution adjustments made after the first experimental run.

Results in all three runs of the experiment supported the hypothesis that greater rates of hydromulch would result in reduced weed emergence. Importantly, however, differences between the 0.5X rate and the 1X rate were not observed in the three plant species that were present in all three runs of the experiment. These findings suggest that 0.5X rates may provide similar reductions in weed emergence as the 1X rate used in the field experiment, though their ability to maintain this control over the course of the growing season is not known.

Of the small seeded weed species, overall emergence was lower in part due to lower seed germination. As a result, these species were not present in the second and third run of the experiment despite their response being more relevant for weed control than the response of the large-seeded weed surrogates oat and pea. In the first experimental run, the zero emergence of redroot pigweed and witchgrass in both the 1X and 0.5X treatments suggest these species are incapable of penetrating the hydromulch at the 1X and 0.5X application rates (Figures A6, A7). Smaller-seeded weeds contain lower energy reserves and are generally less capable of exerting high forces during emergence as compared with larger seeded weed surrogates (Teasdale and Mohler, 2000). The lack of differences in cumulative emergence between the 1X and 0.5X rate in oat and pea suggest this response would be similar in small-seeded weeds such as purslane which have even less energy reserves to overcome the mulch strength.

Results support the initial hypothesis that mulch strength increases with greater application rates. The linear relationship between mulch strength and application rate in hydromulch was strong within the application rates investigated and useful for estimating mulch strength at a given application rate. The relationship between hydromulch and application rate is likely more sigmoidal as application rates reach increasingly smaller and larger rates, but these rates were outside the scope of this study. Since no differences in weed emergence were observed between the 1X and 0.5X rate, the strength of the mulch at the 0.5X rate (0.6 MPa) may be sufficient for weed control.

Determining the strength of the hydromulch greatly expanded the relevance and utility of the research findings. Most published research examining mulches did not report the mulch strength. With respect to the limited research on hydromulch, mixtures were often complex and involved multiple materials (i.e., gypsum, wheat straw, cotton cellulose), which complicated direct comparisons among studies. Standardizing mulches on a strength basis allows for more relevant comparisons and may provide more useful targets in determining weed control efficacy because the mechanism for weed control by mulches is believed to primarily be mechanical (Claramunt et al., 2020). In previously discussed studies Warnick et al. (2006) and Masiunas et al. (2003), comparisons between the agronomic responses to the hydromulch mixtures in their studies and this study are confounded by differences in the material composition. The foam mulching system in Masiunas et al (2003), for example, contained more than 100 separate ingredients. The three hydromulch mixtures used in Warnick et al. (2006) are similarly unlikely to be replicated by other researchers and therefore their relevance was limited. In Claramunt et al. (2020), however, the 24 unique hydromulch mixtures were accompanied with corresponding mulch strength values. As a result, the newspaper hydromulch used in this experiment can be more easily compared with the paper hydromulch used in Claramunt et al. (2020). Furthermore, the weed control efficacy can be more easily estimated from the strength values using the relationships determined in this experiment.

Mulch strength of the hydromulch was hypothesized to be similar to ranges reported in Claramunt et al. (2020), 0.48-1.45 MPa. At the rate of 11 L m^{-2}, the penetration resistance of the hydromulch in this study was approximately twice as great as in Claramunt et al. (2020) (Table 8). The hydromulch blends with the addition of glue were closer to the strength measured in this hydromulch study (1 and 1.43 MPa respectively). Differences in methods for mulch strength determination could explain part of this discrepancy. The force gauge is far less precise than the instruments used in Claramunt et al. (2020) and improper calibration is possible. However, the source material for the paper differed between our greenhouse study and Claramunt et al. (2020). Claramunt et al. (2020) used recovered paper from paper mills rather than new newsprint. Recovered paper tends to have lower lignin content, more degraded lignin and shorter fiber length, all of which contribute to a reduction in the strength of the material (Richard, 1996). While fiber length characterization of the newspaper hydromulch was beyond the scope of this study, it underscores the variability among paper products and importance of providing estimates of the mulch strength for comparison among studies.

Table 8. Peak resistance at a hydromulch rate of 11 L m^{-2} compared between Claramunt et al. (2020) and estimates from three greenhouse experimental runs at North Dakota State University.

Glue rate	Claramunt et al.	Greenhouse trials
–mL L^{-1}–	————MPa————	
0	0.68	1.43
2.5	0.85	--
5	0.88	--
20	1.00	--

Lastly, the findings of Claramunt et al. (2020) also suggested that the addition of 20 mL L^{-1} of glue to a recovered paper hydromulch was associated with a strength increase of 0.32 MPa. A strength increase of 0.32 MPa can also be achieved by the addition of 2.1 L m^{-2} of new newsprint according to this study. The relationship between the application rate of any mulch material and the corresponding change to mulch strength can have applications in tailoring mulches to achieve certain levels of strength that are required for a control of certain weed species. Future research should further characterize mulch strength and weed response to improve the utility of these tools for weed management decisions.

Conclusion

Three runs of a greenhouse experiments were conducted to clarify the effect of mulch application rate on weed emergence and mulch strength. No difference was identified in weed emergence between a hydromulch application rate of 12.7 L m^{-2} and 6.4 L m^{-2}. A positive linear relationship was observed between hydromulch application rate and mulch strength where 1 L m^{-2} of hydromulch was associated with a 0.15 MPa increase in strength. Findings suggested that weed emergence did not differ in mulches with a strength greater than 0.6 MPa; however, these findings are preliminary and limited by the short duration and environment conditions of the study.

Characterizing mulches by their strength is critically needed to improve the relevance of studies that report weed response to mulches. Although surface applied mulches control weeds through multiple mechanisms, one primary ‘mode of action’ is the strength of the physical barrier. By extension, identification of mulch strength required for control of weed species will help in determining optimal mulch rates for weed management objectives.

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APPENDIX. SUPPLEMENTAL FIGURES

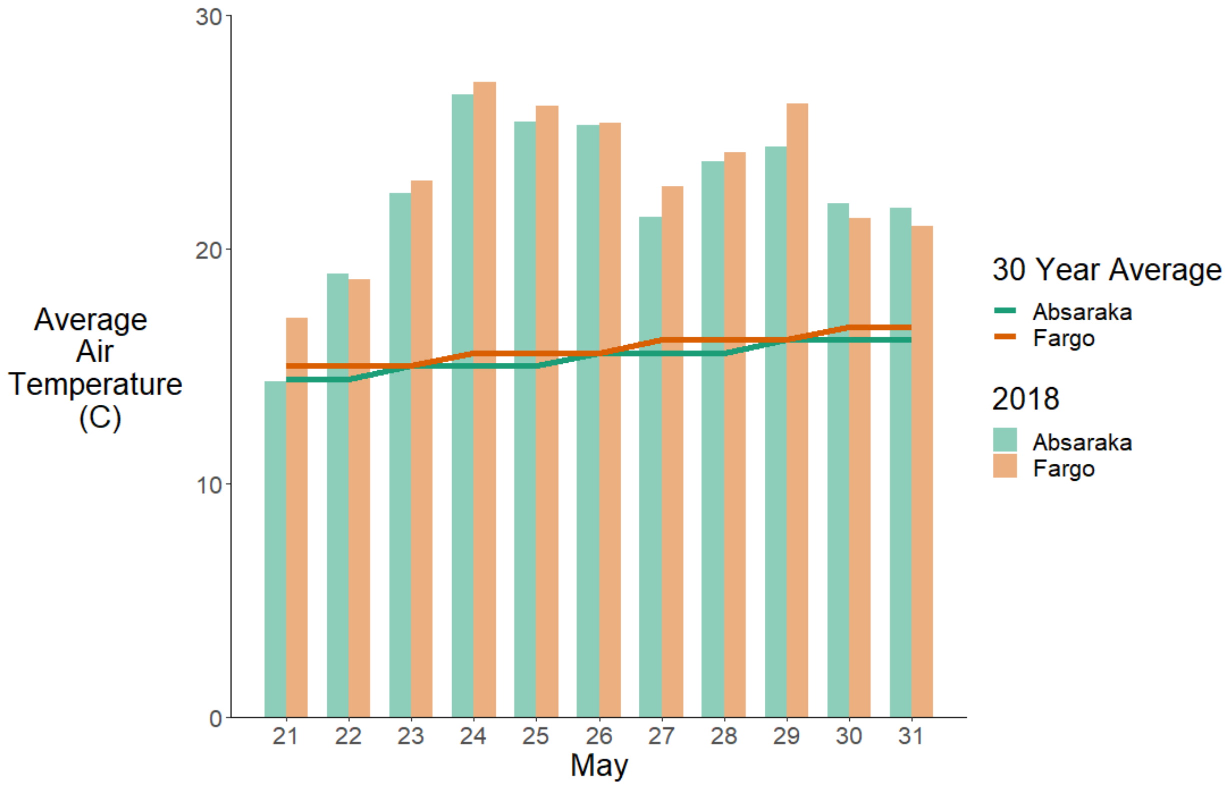

Figure A1. Daily average air temperatures compared with the 30-year average at Absaraka ND and Fargo ND during living mulch establishment in 2018.

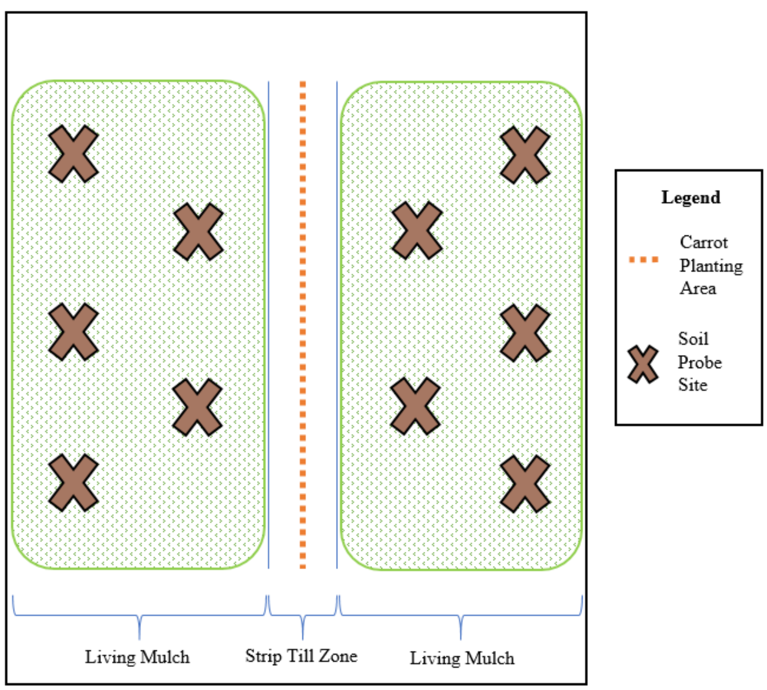

Figure A2. Soil sampling pattern used for every plot in Absaraka ND and Fargo ND during 2018 and 2019.

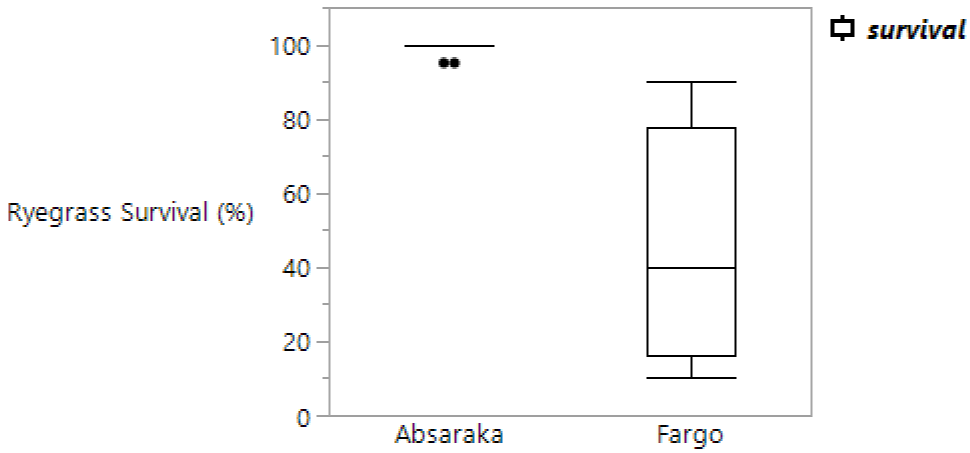

Figure A3. Percent visual assessments of perennial ryegrass survival assessed on June 6, 2019.

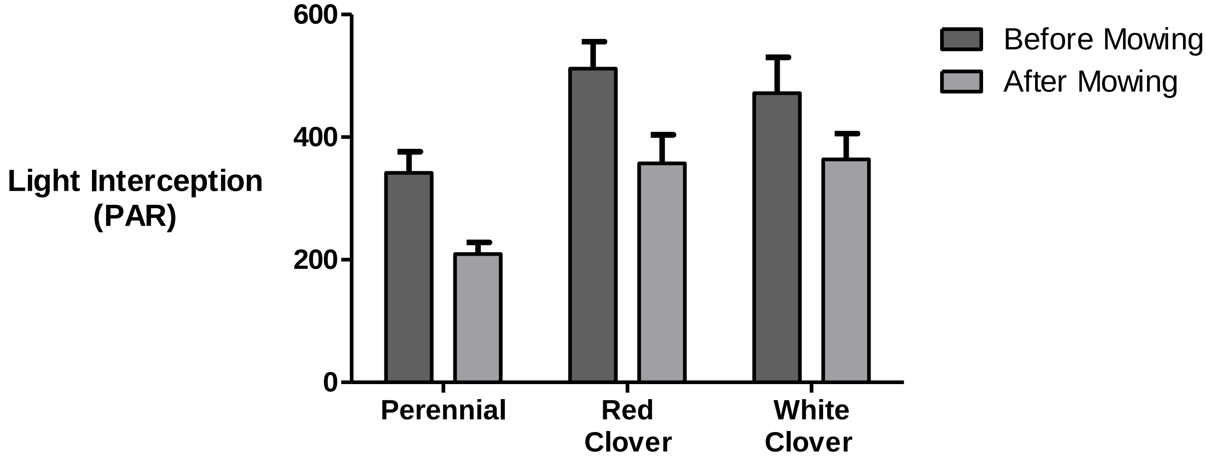

Figure A4. Light interception in the strip till zone before and after mowing in 2019.

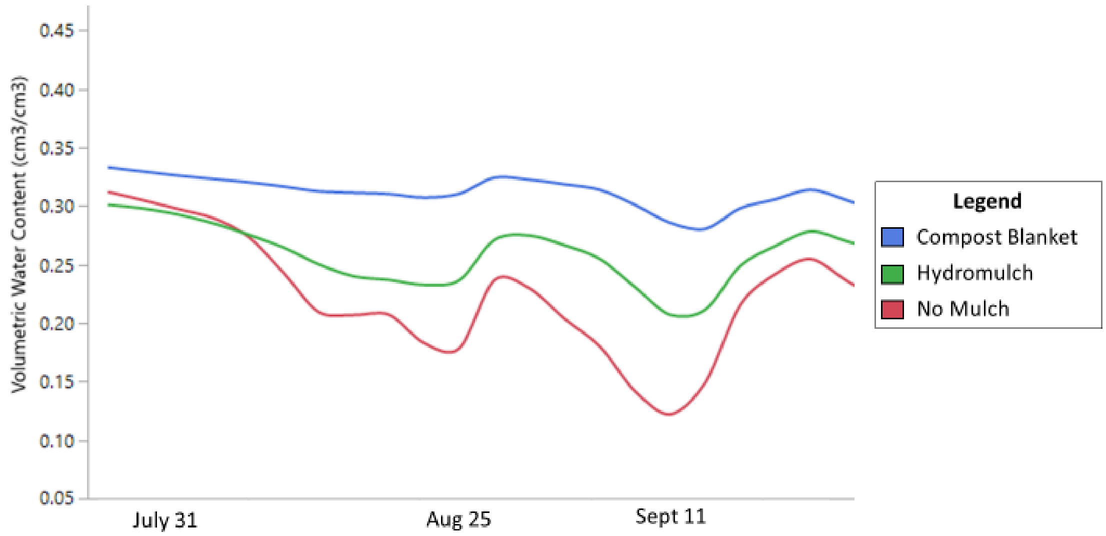

Figure A5. Soil volumetric water content in the strip till zone at a depth of 10 cm in Absaraka ND in 2018; n=1.

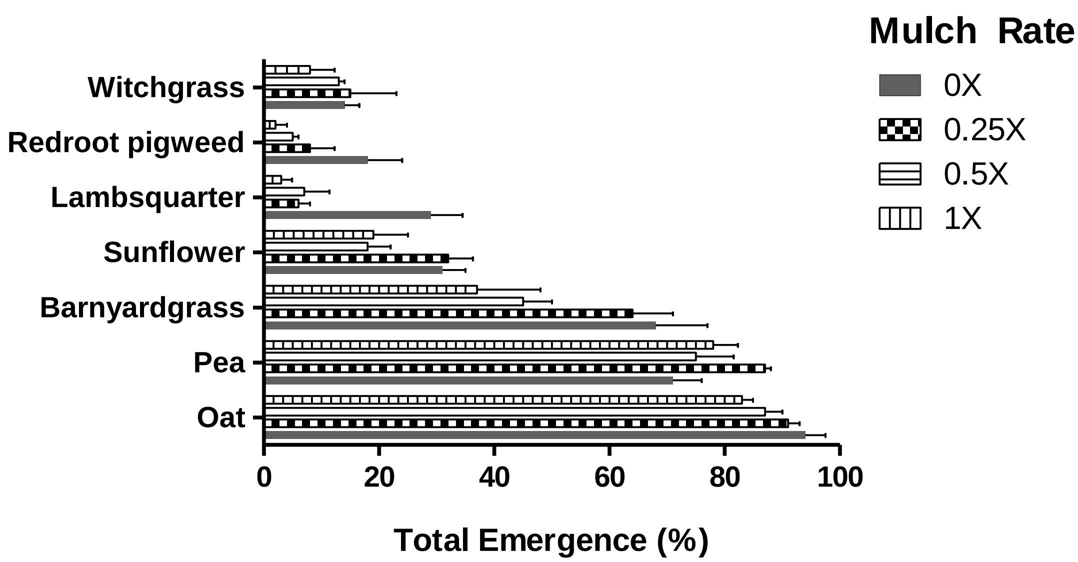

Figure A6. Total emergence of seven species in the compost blanket at the end of the first run of the experiment at North Dakota State University on March 24, 2019.

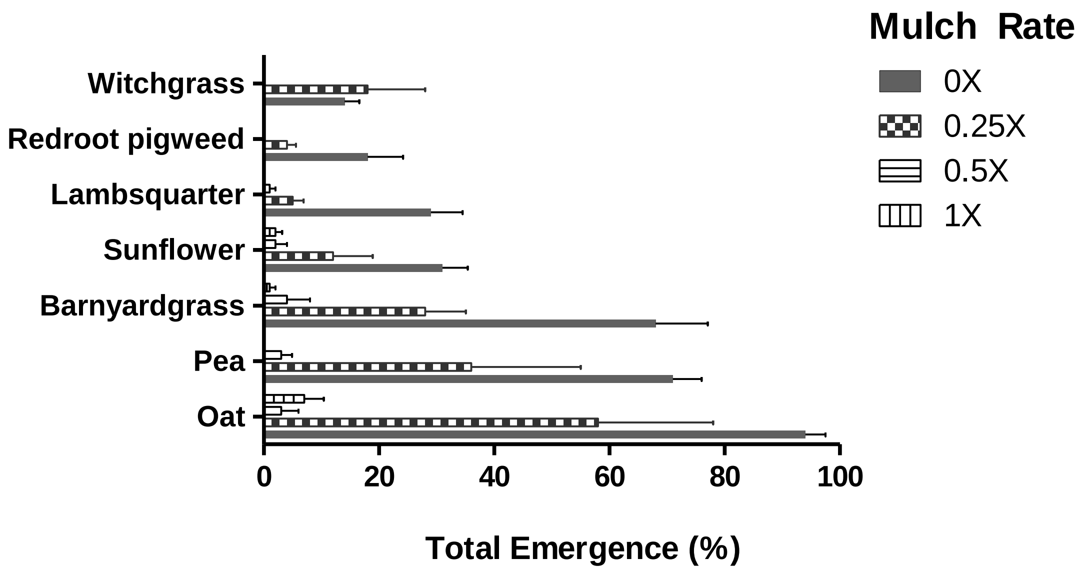

Figure A7. Total emergence of seven weed and weed surrogate species at differing rates of hydromulch at the end of the first run of the experiment at North Dakota State University on March 24, 2019.

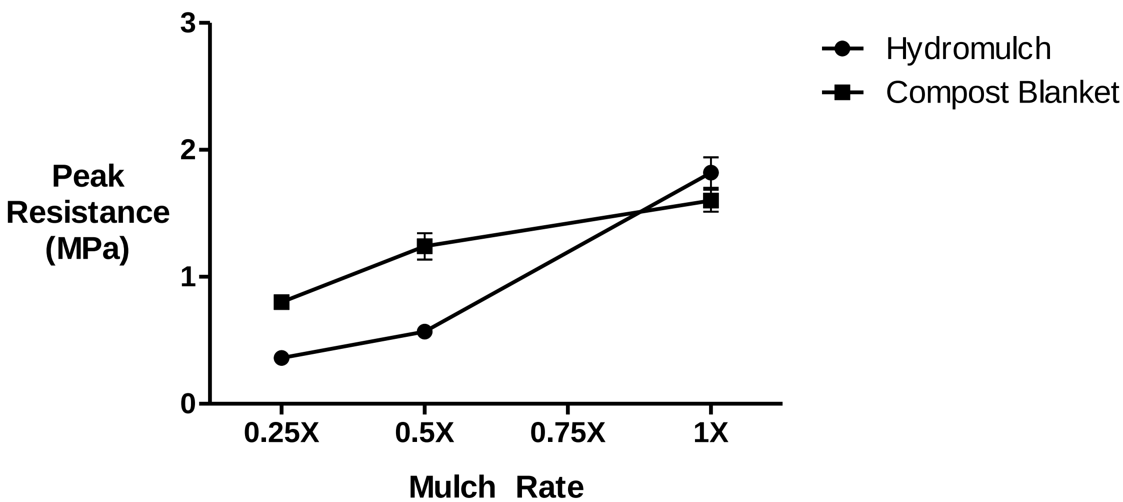

Figure A8. Mulch resistance in compost blanket and hydromulch from the first experimental run at North Dakota State University on March 24, 2019.