WEED MANAGEMENT AND SOIL QUALITY OUTCOMES OF NON-CHEMICAL WEED CONTROL TACTICS

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ABSTRACT

In the Northern Great Plains (NGP), weed management within organic systems remains a challenge. Experiments were conducted at two distinct sites in North Dakota to investigate effects of deep mulch no-till (NT) on soil quality indices, weed densities, and weed seedbank densities. We hypothesized that alfalfa mulch no-till and arbuscular mycorrhizal fungi (AMF) inoculant would be associated with reductions in weed densities and improvements to soil quality and vegetable yield. NT treatments were associated with reductions in weed densities and time required for weeding, with improvements in soil quality, such as increased AMF biomass, and yield for snap pea, onion, beet, and butternut squash compared to tilled treatments. Our findings suggest deep mulch no-till using alfalfa residue may be a viable option for small-scale organic vegetable producers in the NGP. Additional research is required to determine costs associated with sowing, harvesting, baling, and applying alfalfa mulch compared to tilling.

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DEDICATION

For my family, especially my grandparents, who without I would not be who I am today. I am extremely grateful for their love, support, and demonstrable qualities of kindness. I also dedicate this work to Haema Nilakanta, for her endless support and encouragement. Thank you.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

Until the advent of synthetic fertilizers and pesticides, all agricultural production was essentially 'organic;' the U.S. National Organic Standards have existed only since 2002 (USDA-ERS 2016). American organic farming originated from the humus farming movement, which spread throughout Europe and the United States in the 1920s and into the 1950s with the explicit goal to build soil humus (organic matter). The movement continued to grow as some producers viewed the use of synthetic fertilizer and pesticides as cutting corners in the process of fostering biodiversity and soil building (Kuepper, 2010). Organic certification gained popularity throughout the 1970s, involving the roles of producers, consumers, and third party certifying agents – who would affirm that the product was produced in accordance with organic regulations (Coleman 2012).

Organic producers believed that absence of synthetic fertilizer and pesticide was an important part of organic agriculture, which fostered healthier soils, while consumers believed that organic foods were healthier (Howie 2004). Although there is disagreement in peer-reviewed research over nutritional content of organically vs conventionally produced foods (Dangour et al. 2009; Barański et al. 2014), the belief that organic food is healthier or safer continues to drive markets today (Kuepper 2010). As the organic industry grew during the 1980s, different certifiers developed their own standards and certification processes. Discrepancies in standards created barriers for trade, and a consistent set of standards became necessary. In 1990, the U.S. Congress passed the National Organic Program, which became part of the United States Department of Agriculture and the National Organic Standards Board. A set of U.S. standards for organic production, labeling, and marketing was thereby created. In 1995, the National Organic Standards Board defined organic agriculture as "an ecological production management system that promotes and enhances biodiversity, biological cycles, and soil biological activity." In 2002, the National Organic Program redefined organic agriculture as "a production system that responds to site-specific conditions by integrating cultural, biological, and mechanical practices that foster cycling of resources, promote ecological balance, and conserve biodiversity" (USDA Code of Federal Regulations 2016). Organic regulations by the USDA apply to labeling of commodities, planting, soil fertility, weed management, and pest management (Coleman 2012).

Interest in organically certified production is increasing annually and producers wishing to follow organic practices while also conserving natural resources and reduce off-farm inputs may seek research that utilizes science to differentiate belief from site-specific results. Our research was motivated by conversations with a local organic vegetable producer who has employed a deep-mulch no-till system for nearly 30 years. This producer expressed reams of anecdotal evidence supporting the efficacy of this system for weed suppression and soil quality enhancement. However, most producers cannot assess effectiveness of their approaches with detailed and objective measurements of various management outcomes. Therefore, our objective was to measure weed management and soil quality outcomes resulting from a deep-mulch no-till approach employed within a small-scale organic vegetable production system.

LITERATURE REVIEW

Economy of Organic Agriculture

Results from the 2014 USDA Organic Survey showed that U.S. organic producers sold products worth $5.5 billion, a 72% increase from 2008 (USDA-NASS 2016), with fruit and vegetable sales accounting for 43% of total sales (USDA-ERS 2014). In 2015, organic sales further increased, crops totaled $3.5 billion, with overall organic commodity sales in the U.S. increasing to $6.2 billion (USDA-NASS 2016). Historically, agricultural production throughout the Great Plains has been an important component of economic development. In 2008, North Dakota ranked third in the U.S. for total acreage of organically certified cropland (87,642 hectares USDA-ERS 2011), and in 2015, producers sold products worth $21.3 million (USDA-NASS 2015). Because the U.S. organic agriculture industry continues to grow, organic producers require development and testing of management strategies that will improve the environmental and economic sustainability of their operations (Greene 2002).

Agroecological Concepts in Organic Agriculture

The concept of Agroecology is defined as the holistic study of agroecosystems, which encompasses the biological, cultural, and physical aspects of agricultural ecosystems. The principles of agroecology also serve as a framework for the practice of organic agriculture (Altieri and Norgaard, 1987). Agroecology seeks to create synergistic agricultural systems that take advantage of natural processes of a stable ecosystem to replace external inputs. Following this logic, beneficial on-farm interactions and synergies function to reduce off-farm inputs and improve efficiency of farming systems (Altieri and Nicholls, 2012). For example, using hairy vetch (*Vicia villosa*) as a cover crop can improve weed control, increase soil organic matter, and biologically fix nitrogen for subsequent crops. Additionally, improved soil structure and water infiltration reduces surface runoff and potential nutrient leaching (Frye et al., 1988). Another example of a biological synergy would be to use a cover-crop, such as sunn hemp (*Crotolaria juncea* L.) intercropped with zucchini (*Cucurbita pepo* L.) to add biologically fixed nitrogen, increase beneficial insects, and reduce pest insects (Hinds and Hooks, 2013).

Maintaining and increasing yields depends on continued development of improved agronomic and agro-ecological management approaches to control weeds, diseases, insects, and other pests (Godfray et al., 2010). Weed management is a primary challenge for organic producers (Turner et al., 2007), as crops compete with weeds for resources (such as soil nutrients, space, water, and light), which can dramatically reduce crop yield (Clark et al., 1998). As a guiding principle for agroecological weed management, Liebman and Gallandt (1997) coined the idea of "Many Little Hammers", which advocates the combined use of numerous additive or synergistic ecological tactics to achieve effective weed management, while also reducing reliance upon synthetic chemical inputs. The following section will introduce the main approaches used by organic producers to protect crop yields from losses due to weeds.

Non-Chemical Weed Tactics

A major concern of certified organic farmers and those shifting to organic production is managing weeds in a cost-effective manner (Turner et al., 2007). Without effective weed management, weeds cause substantial crop yield losses. For example, in Canada, an estimated $984 million in annual commodity losses are due to competition with weeds (Swanton et al., 1993). In the United States, corn (*Zea mays* L.) and soybean (*Glycine max* L.) yield losses due to competition with weeds are estimated collectively at $43 billion annually (Soltani et al., 2017, 2016). In an experiment conducted in central Alberta, Canada, Harker (2001) observed differences in crop response between hand weeded and non-weeded treatments. Competition resulted in an average yield loss for pea (*Pisum sativum* L.) at 46% and barley (*Hordeum vulgare* L.) at 29%. Anwar et al. (2013) observed a 62% reduction in aerobic rice (*Oryza sativa* L.) production when no weed control was employed.

Producers with organic certifications face substantial weed management challenges, because use of synthetic herbicides is not allowed under organic production (Scialabba and Müller-Lindenlauf, 2010). Integrating cultural practices to optimize the whole cropping system, rather than focusing solely on weed management outcomes is another great challenge organic farmers face (Bàrberi P, 2002). Before the advent of synthetic herbicides, tillage provided a dependable method for post-emergent weed management (Lal et al., 2004; Triplett and Dick, 2008). Because tillage has often been the primary means of weed management used by organic farmers, understanding tillage and no-till effects on weed communities is important.

Use of tillage in annual cropping systems after weed seed germination imposes a filter that negatively affects establishment, growth, and fecundity of weed species (Booth and Swanton, 2002).

Weed species whose traits are vulnerable to a specific filter are therefore less likely to be present after imposition of that filter (Smith, 2006). Frequent soil disturbance may help to provide a degree of predictability for community and seedbank responses to management practices (Légère et al., 2005; Ryan et al., 2010). For example, Brainard et al. (2008) observed that tillage employed during the spring in continuous corn systems effectively prevented overwintered annuals from seed production, whereas winter annuals were able to produce seeds in winter wheat systems that employed spring tillage. Smith (2006) found that spring tillage inhibited establishment of later-emerging forbs, winter annuals, C_3 grasses and species with biennial and perennial life cycles, while fall tillage prevented establishment of early-emerging spring annual forbs and C_4 grasses.

No-till systems impose a filter characterized by a reduction in the frequency of disturbance; however, concerns exist surrounding weed community shifts to perceptually more challenging weed species, in particular, wind-borne, grass, and perennial species (Froud-Williams et al., 1983). Community composition shifts in no-till tend to produce increases in perennial weed species, as life cycle traits associated with less frequent disturbances are favored (Booth and Swanton, 2002). Weed species diversity may increase in response to integrated weed management approaches that include no-till; interactions between individual species may then increase concomitantly (Clements et al., 1994). For instance, Murphy et al. (2006) observed increases in weed species diversity when one dominant species decreased in abundance. Seedbank diversity and realized species richness increased while seedbank density decreased over time in no-till systems that incorporated a corn-soybean-winter wheat (*Triticum aestivum* L.) rotation. Clements et al. (1996) also observed after a seven year corn and soybean rotation that no tillage was associated with a lower seedbank density than chisel and moldboard-plow systems.

Timing of management practice can be considered as another filter for species composition, in which weed species with life cycle traits that reproduce annually are often more abundant in annual cropping systems and are therefore more vulnerable to soil disturbance after seedling emergence during tillage application (Booth and Swanton, 2002; Brainard et al., 2008; Ryan et al., 2010; Smith, 2006). Tillage exposes buried weed seeds to light, triggering germination for many weed species, which tend to germinate in response to light, and are small-seeded (Buhler, 1997; Dyer, 1995; Pons, 1991), furthering seedbank density reductions

(Melander and Rasmussen, 2000). A technique called the “false seedbed” or “stale seedbed” is employed by organic producers and is useful in reducing weed seedbank densities (Rasmussen, 2004). Stale seedbed techniques reduce weed seedbank densities through preparing the seedbed before crop planting, stimulating weed seed germination, and subsequently terminating via flaming or cultivation (Rasmussen, 2004).

No-till by definition leaves soil undisturbed from harvest to seeding and vice versa, employing only light surface cultivation sufficient to sow crop seeds (Doran, 1980; Uri, 2000). Since stale seedbed or false seedbed techniques cannot be employed, seed rain and seedbank management should be important? in no-till systems (Légère et al., 2011). When seed rain is managed with few “deposits” to the seedbank, no-till tends to be associated with decreases in the density of the seedbank. No-till may reduce seedbank densities through reducing successful establishment by limiting a seedling radicle’s surface penetration in soil profiles not loosened by tillage (Liebman et al., 2001). No-till may also reduce seedbank densities by promoting desiccation of newly germinated weed seedlings by limiting access to water (Murphy et al., 2006). Moreover, no-till systems preserve surface crop residues that act as physical growth barriers at soil surfaces, intercept light, and potentially release allelopathic compounds, thereby reducing seed germination and through attrition, consequently reducing seed bank density (Nichols et al., 2015). Tillage results in mixing and redistributing seeds vertically within the soil profile, whereas in the absence of tillage seeds remain concentrated in the top 5 cm of soil (Cardina et al., 1991; Dyer, 1995), in which some weed species are more adapted to germinating and growing (Moyer et al., 1994). No-till management systems can produce increases in weed seedbank density as there are proportionally more weed seeds found at or near the soil surface in no-till (Mohler et al., 2006); however, seeds are exposed to weather and predation while also restricted in light availability, increasing mortality potential (Nichols et al., 2015).

No-till can also potentially reduce seedbank density through increased herbivory and pathogenic infection of seeds; seeds remaining on the soil surface are more susceptible to predation by fauna such as rodents (Harrison et al., 2003) and insects (Cromar et al., 1999; Menalled et al., 2001; Westerman et al., 2006). Furthermore, mulching may add shelter and nesting habitat for arthropods and lead to greater weed seed foraging (Quinn et al., 2016). Effects of tillage and mulch residue on weed seed predation are variable. For example, Cromar et al. (1999) observed rates of seed predation of barnyardgrass (*Echninochloa crus-galli* (L.) P. Beauv) and common lambsquarters (*Chenopodium album*) in no-till systems and moldboard plow systems to be similar, with both treatments resulting in greater granivory than in chisel plow systems. Enhanced predator mobility coupled with food scarcity in the area surrounding seed trays may have contributed to distorted measurements within moldboard plow treatments. Similarly, van der Laat et al. (2015) observed in a 15 year continuous treatment experiment that weed seed predation was greater in conventional and reduced tillage treatments compared to no-till treatments, although no differences in seed predating carabid beetle densities were observed between treatments. Conversely, a 10 year continuous tillage experiment observed seed removal of fall panicum (*Panicum dichotomiforum*) and common lambsquarters to be greater in no-till compared with tillage systems (conventional tillage with herbicide and organic with tillage;(Menalled et al., 2007). While carabid beetle population densities did not differ between tillage treatments; diversity of carabid beetles was found to be two times greater in no-till and organic treatments compared to conventionally tilled with herbicide treatments (Menalled et al., 2007). Some literature suggests that no-tillage systems may limit seed predation due to reduced mobility, as well as greater distribution of seeds on the surface adjacent to pitfall traps, which could lead to a reduction in scouting larger areas(Quinn et al., 2016; Thomas et al., 2006).

To increase efficacy, no-till practices are often used in conjunction with other management tactics that disrupt population dynamics of annual weeds, such as crop rotations and seasonal crop sequencing, which can decrease weed seedling establishment by preventing weed seed production and attenuating weed densities in following crops (Anderson, 2008). For example, a thirteen-fold increase in weed densities wasdensitieswas found in a no-till two-crop rotation when compared to a no-till or till? four-crop rotation (Anderson, 2004). Growing warm and cool season sequences of crops alters weed densities. Planting two cool-season crops followed by two warm-season crops leads to a lower density of weeds when compared to a two- or three-crop rotation of any given sequence (Anderson, 2008). With three-crop rotations, trends of weed communities tend to reflect crop composition, such that weed communities consist of primarily warm-season species when rotations consist of two warm-season crops followed by one cool-season crop (Anderson, 2008). Weeds common in cool-season crops (winter annuals and early summer annuals) are more easily controlled in the warm season, whereas weeds that are problematic in warm season crops (later emerging summer annuals) are more easily controlled in the cool season (Anderson, 2010). For instance, alternating perennial, spring, and winter crops can disrupt life cycles of certain weed species indirectly through timing and frequency of tillage and weed control (Légère et al., 2011). Therefore, diverse crop rotation sequences that address localized weed communities are important considerations, as understanding crop and weed life cycles can reduce overall weed densities, especially in organic production systems (Anderson, 2010; Ball, 1992).

Cover cropping is another effective weed management approach employed by many organic producers. Cover crops can suppress weeds in a number of ways, including disrupting weed life cycles, direct competition, allelopathy, and blocking light stimuli for weed seed germination (Mondal et al., 2015; Teasdale et al., 1991). Cover crops suppress weeds through direct competition for space, light, nutrients, and moisture [53]. Some cover crop species have allelopathic properties that inhibit weed growth by the release of secondary plant compounds, such as barley, cereal rye (*Secale cereale* L.), sunflower (*Helianthus annuus* L.), hairy vetch (*Vicia villosa* Roth), and cowpea (*Vigna unguiculata*) (Dhima et al., 2006; Hill et al., 2007). Allelopathic compounds may act on one specific weed species due to sensitivity of specific glucosinolate hydrolysis products (Norsworthy et al., 2007); therefore, a mixture of many species may be more effective at suppressing a broad range of weed species (Wortman et al., 2013). Furthermore, cover crop mixtures with dense canopies provide competition in the interception of light, establishing a low red to far-red light ratio, which inhibits germination in some weed seeds (Benech-Arnold et al., 2000; Teasdale and Daughtry, 1993). Moreover, cover crop residues can assist in the suppression of weed seedling emergence and growth. For example, Kumar et al. (2009) found that buckwheat (*Fagopyrum esculentum*) residue mediated changes in soil nitrogen dynamics and accounted for suppression of weed growth of three weed species, Powell amaranth (*Amaranthus powellii*), shepherd's purse (*Capsella bursa-pastoris*), and corn chamomile (*Anthemis arvensis*).

Organic no-till management is limited in use of herbicides and tillage, which are considered strong filters that greatly impact community assemblages (Carr et al., 2013). Organic no-till systems utilizing cover crops are challenging as the restriction of herbicide use then relies upon tools other than herbicide or tillage for weed management (Triplett and Dick, 2008).

Terminating cover crops within no-till systems preclude minimal soil disturbance, while targeting conservation of surface residues that act as weed-suppressive mulches, and can include winter kill, as well as roller-crimping (Triplett and Dick, 2008).

There are challenges associated with the adoption of winter annual cover crops in no-till production within the Northern Great Plains. Timing termination with species phenology can be critical in effective mechanical kill from roller-crimping (Ashford and Reeves, 2003; Kornecki et al., 2009; Wayman et al., 2015). Delays in cover crop maturity can further delays in marketable crop seeding, germination, and growth, which are particularly problematic within cool regions with short growing seasons (Carr et al., 2013; Delate et al., 2012; Hoyt, 1999; Leavitt et al., 2011). For example, Leavitt et al. (2011) observed no-till hairy vetch, winter rye, and hairy vetch with rye mixtures to reduce marketable yields of tomato (*Solanum lycopersicum*), L.) , zucchini, and bell pepper (*Capsicum annuum* Group) by 89%, 77%, and 92%, respectively, during 2008 and 65%, 41%, and 79%, respectively, in 2009 compared to no-cover controls in Minnesota. Yield loss was considered to be influenced by delays in soil planting as well as potential allelopathy. Delate et al. (2012) found yield reductions in soybean and corn in no-till systems using roller-crimped wheat/winter pea or rye/hairy vetch mixtures compared with conventional tilled with no cover treatments. However; however, they also found similar yields of tomato between systems. One reason tomato yields differed between Delate et al. (2012) and Leavitt et al. (2011) may be due to the side dressing of tomato crops with swine manure, thus overcoming potentially immobilized N from rye residue. Snapp et al. (2005) provides advantages and disadvantages of different crop species available to producers in different plant hardiness zones, noting that rye is the most promising for winter niches. Winter annual crops can be used as scavengers for nitrogen throughout the fall, effectively capturing nitrogen that could be lost via leaching (Jewett and Thelen, 2007). Residues with high carbon to nitrogen ratios (C:N) have been observed to cause immobilization of soil nitrogen (Burgess et al., 2002; Wells et al., 2013), potentiating yield losses (Leavitt et al., 2011). While nitrogen immobilization with high C:N ratios may have value as a weed management strategy, efficacy may be realized only? in conjunction with legume cash crops (Wells et al., 2013).

Cover crop services, such as weed suppression, depend upon large biomass production and proportionally increase as biomass increases (Mirsky et al., 2017). Services provided are largely dependent on species and variety, seeding rate and date, phenologically determined termination, and perhaps most importantly, climate (Parr et al., 2011; Teasdale et al., 2004; Wilke and Snapp, 2008). The cereal rye biomass needed to sufficiently inhibit annual weed germination has been reported to range regionally between 8000 kg ha^{-1} (>75%) in Maryland and Pennsylvania (Mirsky et al., 2012), and 9000 kg ha^{-1} (>90%) in North-East and North-Central NC (Smith et al., 2011). Legume cover crops have been observed to reduce weed densities with residues of 6500 to 8000 kg ha^{-1}; but to achieve this amount requires supplemental biomass (Mohler and Asdale, 1993).

As an alternative to cover crops, mulching can provide soil coverage adequate to suppress weeds in vegetable production systems (Schonbeck, 1999); thereby providing greater yields (Ibarra et al., 2001), as well as beneficial insects (Johnson et al., 2004; Schonbeck, 1999). Materials typically used as mulches include polyethylene, paper, and straw. Sustainability issues related to use of plastic have encouraged the development and use of biodegradable materials (Anzalone et al., 2010). As with cover crops, tradeoffs are associated with mulching and include: delayed soil warming in spring (Unger, 1978), high carbon to nitrogen ratios potentially immobilizing soil nitrogen (Neilsen et al., 2007), and the potential to attract pest insects

(Andersen et al., 2012). Mulch up to a 5 cm depth has been reported to create a barrier to root oviposition by *Acalymma vittatum*, as the adult female beetle has limited acces to soil around the plant when mulch is present (Necibi et al., 1992). Although the use of alfalfa (*Medicago sativa*) as a green mulch soil amendment has been shown to add NO_3^-N to soil (Molina et al., 2014), when used as a dried mulch alfalfa has been shown to increase microbivore nematodes and protozoa, microbial activity, and mineralization of nutrients. Use of alfalfa within pastures as a grazing crop has been found to effectively manage weeds (Blackshaw et al., 2010), including Canada thistle (*Cirsium arvense*) in the Northern Great Plains (Entz et al., 2002, 1995).

Finally, as organic commodities continue to gain market share, transitioning and newly starting producers will rely upon non-chemical weed management approaches. However, non-chemical weed management is not solely relevant to organic production systems, but may also benefit conventional production systems, especially because of mounting challenges posed by continued evolution of herbicide resistance. The International Survey of Herbicide-Resistant Weeds documented 388 cases involving 210 species of weeds evolving resistance to various herbicide sites of action. These cases report resistance to 21 of 25 known sites of action, which encompass 152 different herbicides (Heap, 2014). Use of herbicides will need to be supplemented through other strategies when confronting resistant weeds, as use of herbicide will be less than effective considering trends in gained resistance, and especially without developing novel mechanisms of action (Owen, 2016).

Tillage Effects on Soil Quality

Although tillage is a useful weed management tool, organic producers have also been interested in reducing tillage due to its numerous negative impacts on soil quality, such as increasing soil erosion, nutrient leaching, and nutrient runoff (Uri et al., 1999). Soil quality is defined as the capacity of a soil to maintain environmental quality, while promoting plant and animal health (Doran and Parkin, 1994). Although defining soil quality can be challenging, useful indicators should be sensitive to variations in management, correlated with beneficial soil functions, related to ecosystem processes, useful to land managers, and readily measurable (Doran and Zeiss, 2000). Gregorich et al. (1994) defines soil quality as "the degree of fitness of a soil for a specific use" and considers soil quality to address the capacity of a soil to act as an environmental filter or buffer in the retention, dispersal, and transformation of chemical and biological materials. Examples of common soil quality indices include soil organic matter (SOM), active carbon and microbial biomass, wet aggregate stability, volumetric water content, respiration, phospholipid fatty acids, cation exchange capacity, and general soil-test parameters (pH, P, K, Ca, Mg, Total-N, Total-C, and NO_3-N;(Daigh, 2011; Karlen et al., 1994). SOM is widely accepted as an indicator of soil quality within the scientific literature (Gregorich et al., 1994). While SOM has no definite composition, as such, one primary elemental component of SOM is soil organic carbon (SOC), which is most commonly reported (Weil et al., 2003).

Measuring changes in SOC can be quite difficult as SOC is often characterized by large pools in recalcitrant or stabilized forms that require years to observe measurable changes due to natural variation across landscapes, soil types, and climactic zones (Weil et al., 2003). Characterizing changes in SOM over shorter periods of time requires measured properties to be sensitive to changes in soil management, disturbances, and inputs (Gregorich et al., 1994). Although small (< 20% of the total; (Culman et al., 2013), labile pools considered to be active are sensitive, as well as central to rapid nutrient cycling, aggregation of soils, and carbon sequestration (Schmidt et al., 2011; Wander and Drinkwater, 2000). Measures of labile pools of carbon have been proposed subjected as an early indicator of responses of to land management

(Weil et al., 2003). Physical properties considered as soil quality indicators, such as aggregate stability, also can be detected early in transitions in land use, in particular, no-till (Mochizuki et al., 2008).

Tillage practices affect soil physical, chemical, and biological properties, all of which constitute aspects of soil quality (Dam, 2003); long-term studies assessing soil biological, chemical, and physical characteristics have found no-till improves many soil quality indicators compared to conventional tillage (Karlen et al., 1994). Tillage has been shown to expose soil to wind and water erosion (Wander and Drinkwater, 2000), and to reduce bulk density, microbial activity, and soil active carbon (Jokela and Nair, 2016; Karlen et al., 1994). Conventional tillage has been found to reduce aggregate stability (Beare et al., 1994; Six et al., 2004), which along with soil compaction, reduces water infiltration (Jemai et al., 2013) and accelerates the rate of soil erosion (Lal, 2007).

Production practices that result in little to no biomass residue as ground cover accelerate erosion by allowing wind or water to detach soil particles (Miller et al., 1982). Consequently, no-till practices have been explored as a means to mitigate these negative impacts of tillage. No-till practices are associated with reductions in soil erosion through increased organic matter accumulation (Bescansa et al., 2006; Hernanz et al., 2002), which promotes soil aggregation (Grandy et al., 2006; Lal et al., 2004; Teasdale et al., 2007) along with undisturbed soil pore structures that contribute to greater hydraulic conductivity and infiltration rates (Azooz and Arshad, 1996). No-till is also associated with increases in surface residues, which reduce runoff velocity and decrease detached soil particle transport capacity of the runoff (Cogo et al., 1983).

In the long term, no-till practices have been associated with greater or no different plant available water than conventional tilled soil, with trends of greater macroporosity in the soil surface within conventionally tilled soils (Francis and Knight, 1993; Hill et al., 1985). Bhattacharyya et al. (2006) observed greater water retention within the top 7.5 cm despite greater observed bulk density, as well as greater unsaturated and saturated hydraulic conductivity in no-till treatments when compared with conventional and minimum tillage. Denton and Wagger (1992) found that no-till treatments had higher soil water content than conventionally tilled soils, and similarly, Jemai et al. (2013) observed soil moisture content exceeding the permanent wilting point throughout the growing season in no-till treatments. Greater retention of soil moisture assists in buffering yield loss through crop stress under drought (O'Rourke and Petersen, 2016).

Besides affecting soil physical properties, long-term tillage causes several deleterious effects on soil chemical properties, such as loss of organic matter and nutrient depletion (Lal, 1993). Therefore, some organic producers are experimenting with reducing or eliminating tillage, in an effort to reduce erosion (Trewavas 2004) and improve soil organic matter retention (Arshad et al., 1990). Changes in organic carbon and organic matter influenced by tillage can affect soil cation-exchange capacity (CEC), which assist in the maintaining of soil fertility (Hussain et al., 1999). Long-term research on tillage and CEC has yielded mixed results when comparing conventional tillage (moldboard plow), chisel disking, and no-till. For example, a study with 28 years of no-tillage management found greater CEC associated with no-till (Mahboubi et al., 1993), while a 12 year study found no differences in CEC with tillage system (Karlen et al., 1994). No-till soils are also typically more acidic in surface layers and less acidic deeper in the soil profile than conventionally tilled soils (Logan et al., 1991). No-till practices have been shown to promote reductions in NO_3^-N leaching compared to conventional tillage (Celik et al., 2017) and conversely, shown to promote denitrification of soil NO_3^-N (Doran, 1980).

Along with influencing soil physical and chemical properties, tillage can affect soil biology, including microbiological communities that critically affect plant function and growth (Sessitsch et al., 2001; Smit et al., 2001). Essential microbial functions in soils include processing, recovery, and cycling of key plant nutrients and soil organic matter (Caldwell, 2005), as well as interactions with soil pathogens that can mediate plant disease incidence (Marschner et al., 2003). Soil bacterial abundance, diversity, and community stability are sensitive to management practices such as tillage and additions of manure fertilizer, and are considered a measurement of soil quality (Hartmann et al., 2006; Johnson et al., 2003; Lupwayi et al., 1998; O'Donnell et al., 2001; Yin et al., 2010). No-till management systems have been shown to promote greater microbiological biomass, species diversity, and activity compared to conventionally tilled soils (Doran, 1980; Drijber et al., 2000; Feng et al., 2003; Helgason et al., 2009; Lupwayi et al., 1998). Doran (1980) suggested soils under no-till have greater anaerobic activity, along with higher populations of anaerobic microbes within the soil. Soil respiration is quantified as CO_2 fluxes originating from autotrophic root respiration and heterotrophic microbial respiration within the rhizosphere and bulk soil (Buchmann, 2000) and may act as an indicator of ecological metabolism (Ryan and Law, 2005).

Research to quantify the impact of no-till practices on soil respiration rates has produced mixed results. For instance, no-till practices have been shown to lower soil respiration rates in a maize crop under semi-arid conditions (Lamptey et al., 2017), increase soil respiration rates in a maize crop under hot-humid continental conditions (Karlen et al., 1994), or not affect soil respiration rates compared to conventional tillage in a maize, soybean, sunflower, and small grains crop under semi-arid continental conditions (Carpenter-Boggs et al., 2003). This is likely due to site-specific attributes, such as soil texture, available soil water and nitrogen, as well as the ratio of carbon to nitrogen of crops grown.

Particular types of microorganisms have especially important effects on soil quality and plant growth. Arbuscular mycorrhizal fungi (AMF) are soil fungi that form symbioses with plant roots, thereby providing benefits to plants in the form of greater tolerance to water stress and root pathogens, as well as potential to improve mineral nutrition of crops (Boddington and Dodd, 2000; Bücking and Kafle, 2015; Gosling et al., 2006). AMF also have the potential to provide saline tolerance within inoculated vegetable crops (Hirrel and Gerdemann, 1980), as well as the potential to colonize non-mycorrhizal plant such as many weeds (Francis and Read, 1995; Hirrel et al., 1978; Johnson N. C. et al., 2008; Ocampo et al., 1980). Moreover, AMF provide soil stability by producing a glycoprotein known as ‘glomalin’, a binding agent that leads to micro- and macro- aggregate production (Boddington and Dodd, 2000). Tillage alters and disturbs AMF in the soil (Helgason et al., 1998), which may be a disadvantage to a plant’s early uptake of phosphorus (McGonigle and Miller, 1996). Therefore, inoculating disturbed soils may promote crop growth through increasing AMF abundance and altering AMF community composition (Gosling et al., 2006).

A growing number of organic producers are interested in adopting reduced-tillage systems that integrate soil conservation and labor savings of conventional no-tillage systems with soil building practices used in organic production (Mirsky et al., 2012). These practices not only improve the overall agroecosystem quality but also can be economically viable. For example, a study conducted in Pennsylvania and Maryland showed that a no-till organic 3-year rotation including cover crops led to a 25% decrease in diesel fuel use, and a 33% decrease in labor compared with a standard tillage-based organic management system (Mirsky et al., 2012; Ryan, 2010). Most of the previous research about tillage system impacts on weed species community and dynamics has focused on annual grain cropping systems. Menalled et al. (2001) observed annual grasses such as *Digitaria sanguinalis* (large crabgrass) and *Panicum dichotomiforum* (fall panicum) to be the most prevalent weeds present within the no-till system with corn-soybean-wheat sequences. Conservation tillage practices and technology are less developed for horticultural crops than for agronomic crops (Hoyt et al., 1994) and further research in this area is needed. Furthermore, because of the challenges associated with implementing cover crop-based no-till approaches at northern latitudes, research is needed to develop alternative approaches to achieving tillage reduction.

In conclusion, growth of the organic market posits a need for research which focuses on region-specific ecological weed management and allows small organic producers to make educated decisions regarding soil and weed management and use on-site resources to effectively reduce inputs. As certified organic producers rely on non-chemical weed management, use of on-site resources can provide multi-functional components to aid in managing soil quality, reducing competition from weeds, and maintaining yield.

Upon meeting a North Dakota producer who has used a deep mulch no-till system to grow vegetables organically for over 30 years, we wanted to scientifically validate the producer's claim that no inputs were needed besides the alfalfa mulch. Within a four crop (snap pea, onion (*Allium cepa*), beet (*Beta vulgaris*), and winter squash) (*Cucurbita moshata*) rotation, our objectives were to measure and assess the effects of no-till (alfalfa hay mulch), conventional tillage, and AMF inoculant on 1) weed seed bank density and species diversity; 2) realized weed density and diversity; 3) crop leaf nutritional status, crop leaf chlorophyll, crop leaf stomatal conductance, and crop yield, ; 4)soil quality indices including PLFA (general microbial community composition), soil respiration, aggregate stability, active carbon, soil macro- and micro- nutrients, and soil organic matter; and 5) crop root colonization by AMF and non-AMF fungi (likely plant pathogens).

We hypothesized that 1) no-till would be associated with greater crop yield, reduced weed pressure, reduced weeding time, and greater AMF abundance within crop roots.; 2) no-till to be associated with positive changes in soil quality indices; and 3) AMF inoculant would be associated with greater AMF abundance in crop roots, and enhanced crop yield.

MATERIALS AND METHODS

Description of Sites

From 2015-2017, field experiments were conducted to assess weed management, crop nutrition and yield, soil quality impacts of tillage (no-till with alfalfa hay mulch vs. tilled with no mulch), and AMF inoculant efficacy. These experiments were conducted at two distinct sites with differing soil types and climate in North Dakota on certified organic land. The first site was located near Absaraka (46°59’16.61”N, 97°21’06.39” W), and the second site near Dickinson (46°53’35.67” N, 102°49’12.07” W; Table 1). Precipitation varied between Absaraka (Table 2) and Dickinson (Table 3) for each year.

History of Fields

The Absaraka site was left fallow during 2013, and then sown to forage oat (*Avena sativa* L.) in the spring of 2014. Once harvested for grain, the oat stubble was incorporated into the soil in the fall of 2014 via disk tillage. Prior to experimental plot establishment, this site was disked again during May of 2015 to terminate numerous winter annual weeds. Subsequently, the tilled blocks were tilled during the spring prior to planting and after harvest using a rotary tiller mounted on a BCS tractor (BCS America, Portland, OR). The Absaraka site was certified organic in July 2015.

The history of the Dickinson site was similar in that it was left fallow during 2013, then sown to spring wheat (*Triticum aestivum*) as a cover crop in 2014. Following harvest, the field was disked in the fall of 2014 and tillage treatment plots were established in the spring of 2015 by disking, followed with rototilling. The Dickinson site was certified organic during 2012.

Table 1. Soil series, taxonomy, and slope of Absaraka, Cass County, ND, and Dickinson, Stark County, ND, in 2015 and 2016.

Location	Year	Soil Series†	Soil Texture†	Soil Taxonomy‡	Slope
					%
Absaraka	2015-17	Warsing loam	Sandy Loam	Fine-loamy, mixed, superactive, frigid Oxyaquid Hapludoll	0-3
Dickinson	2015-17	Arnegard loam	Silty Clay Loam	Fine-loamy, mixed, superactive, frigid Pachic Haplustoll	0-2

† Soil data obtained from Web Soil Survey (USDA-NRCS, 2018).
‡ Soil taxonomy listed on individual lines based on hyphenated soil series name.

Table 2. Absaraka summary of recorded monthly total rainfall surplus or deficit as reported by NDAWN as departure from normal total rainfall for 2015 to 2017 growing seasons.

	2015	2016	2017
Month	Total rainfall (as deviation from normal)†		
	--------------------------------mm----------------------------		
May	+71.2	+4.6	-60.7
June	+9.4	-62.7	-12.4
July	+0.5	+0.1	-37.8
August	-30.2	-40.1	-13.9
September	-43.7	-5.0	+86.2
Cumulative	+7.3	-103.2	-38.7

†Data retrieved from the North Dakota Agricultural Weather Network (NDAWN, Fargo, ND, 2018).

Table 3. Dickinson summary of recorded monthly total rainfall surplus or deficit as reported by NDAWN as departure from normal total rainfall for 2015 to 2017 growing seasons.

Month	2015	2016	2017
	Total rainfall (as deviation from normal)†		
	--------------------------------mm----------------------------		
May	-15.0	-26.9	-27.5
June	1.8	-58.3	-70.0
July	-8.0	20.5	-45.4
August	-15.5	-26.9	+16.2
September	-18.5	49.0	+37.9
Cumulative	-55.2	-42.5	+28.0

†Data retrieved from the North Dakota Agricultural Weather Network (NDAWN, Fargo, ND, 2018).

Experimental Design and Treatments

Field Design and Treatments

The experiment consisted of 64 7.44-m^2 plots, with 1.2 m alleys, repeated during 2015, 2016, and 2017. Due to logistics associated with planting and tillage equipment, experimental design at each site varied slightly. The experimental design at the Absaraka site was a randomized complete block design with a split-plot arrangement. The main plot was tillage treatment (no-till with alfalfa hay mulch vs conventional tillage with no mulch) and the subplot treatment was factorial combinations of crop × AMF inoculation (4 crops (sequence phase) × 2 levels of AMF). The experimental design at Dickinson was a randomized complete block design with a factorial arrangement (tillage (no-till with alfalfa hay mulch vs. conventional tillage with no mulch) × crop (sequence phase) × 2 levels AMF). Plots were not re-randomized each year so that we could assess the cumulative impact of tilling vs mulching over a three-year period. In May 2015, the site at Absaraka received composted poultry manure at a rate of 67 kg N ha^{-1}

(Rosen and Eliason, 2005). At Dickinson, composted beef cattle manure was applied at a rate of 39 kg N ha^{-1} during 2013.

At Absaraka, alfalfa hay mulch was locally-sourced, grown without synthetic pesticides, and free from germinable weed seed. Hay bales at both sites were approximately 0.28 m^3 and slabs from the bale were placed to cover the entire plot surface, except where crop rows were located. Slabs were moved aside during planting and moved back post crop emergence. Each plot receiving approximately 28 slabs of hay and each slab weighed an average of 650 g. At Dickinson, hay mulch was locally sourced, grown without synthetic pesticides, and consisted of crested wheatgrass (*Agropyron cristatum* L.). Hay mulch was left in place for the duration of the study and was replenished in the spring and fall as needed to maintain even mulch thickness. At each site, the 32 no-till plots received approximately 18 kg of mulch each, at a depth of 12 cm, for an approximate total of 24,000 kg ha^{-1}. Mulch was opened at both sites during sowing to allow for soil warming and filled back after crop emergence.

Crops were grown in a rotation designed to optimize crop N requirements and were sown in the following rotation order: (1) snap pea (‘Sugar Ann’), (2) onion (‘Dakota Tears’), (3) table beet (‘Sweet Dakota Bliss’), and (4) butternut squash (*Cucurbita moschata* ‘Burpee’s Butternut’) (Table 4.). All four crops were grown in rotation in each year but the crop sequence differed by year (Table 4). Rows were located in the center of the plot, 122 cm from the edge. All plant rows were placed 30 cm in from the length of the plot border and 61 cm from the width of the plot border to minimize edge effects. Drip irrigation was used at Absaraka only during 2017, whereas Dickinson was irrigated throughout the study.

Table 4. Sequence of crops in each year.

Year	Entry 1	Entry 2	Entry 3	Entry 4
2015	Pea	Onion	Beet	Squash
2016	Onion	Beet	Squash	Pea
2017	Beet	Squash	Pea	Onion

Snap peas were direct seeded during 2015 after the last frost date (May 10th) using a Jang JP-1 seeder (Mechanical Transplanter Company LLC, 1150 Central Ave, Holland, MI) and hand sown during 2016 and 2017, in single rows 2.54 cm deep with 3.8 cm spacing and between-row spacing of 61 cm. Stand counts were taken at 6 and 9 weeks after sowing. Harvests from the middle (or data rows) included the number of marketable pods and total fresh weight. Due to the labor-intensive nature of pea harvests and the variable stages of pea pod development, an optimal market size (between 10 and 13.5 mm width and 7.5 cm long) subset of 10 per plot were selected from each harvest and weighed (Fernando and Dimsey, 2007). The total number of pods harvested was multiplied by the average weight per pea pod to estimate the potential total weight of the harvest, if all pods had been picked at an ideal size. Because pea stands were variable, pea yield was expressed as yield per plant.

Onions planted at both sites were hand sown 1.27 cm deep in 6-pack cells measuring 3 cm by 3.5 cm x 5 cm in a greenhouse located at NDSU during mid-March of each year, using either Sunshine Mix #4 or Black Gold (Sun Gro Horticulture, 770 Silver Street, Agawam, MA) and fertilized once a week with a 5-1-1 emulsified fish fertilizer (Alaska Fish Fertilizer, Lilly Miller Brands, 2300 Powers Ferry Road Suite 370, Atlanta, GA) at 0.18g N plant^{-1} for approximately 9 weeks. Onions were then transplanted into the field from plug trays approximately 63 days after planting. Total row length was 190.5 cm, with in-row spacing of 7.6 cm totaling 25 onions per row for approximately 13.5 onions per m^2 and between-row spacing of

61 cm. Transplants were hand watered immediately following planting in order to assist in establishment. Onions were harvested from data rows when tops fell over or at ~90% senescence in order to avoid regrowth. Onions were cured for 3 to 4 weeks in a greenhouse kept at a constant 24 °C with ambient humidity until full leaf senescence and were weighed separately. Because onion stands were variable, onion yield was expressed as yield per plant.

Table beets were sown during 2015 using a Jang JP-1 seeder (Mechanical Transplanter Company LLC, 1150 Central Ave, Holland, MI) and hand sown during 2016 and 2017, in single rows with 4 cm in-row spacing at a depth of 1.27 cm, with between-row spacing of 61 cm at the beginning of June; beets were thinned to 8 cm spacing at 28 days after planting, and harvested at maturity (when 90% of roots attained 8 cm diameter). Data collected included root maximum and minimum diameter, total row count, and fresh weight. Because beet stands were variable, beet yield was expressed as yield per plant.

Winter squash were hand sown in a single bed row, in four mounds of 3 seeds each spaced 5 cm apart. In-row plant spacing was 90 cm, and plants were thinned 25 days after sowing, to achieve four plants per plot. Squash was harvested at maturity and yield data were expressed as total fruit weight per plant.

Commercially available organically certified AMF inoculant, which was stated by the manufacturer to contain four species (*Glomus intraradices, G. mosseae, G. aggregatum,* and *G. etunicatum*; Mycogrow for Vegetables, Fungi Perfecti LLC. P.O. Box 7634. Olympia, WA), was applied directly to each crop after transplanting or sowing during each year of the study at the recommended rate of 3.8 g m^{-2}, by mixing 1 oz of dry product into 3.8 L of water and applied evenly over each row.

Data Collection

Realized Weed Community and Time Required for Weeding

To determine tillage treatment effectiveness on weed management and labor inputs, emergence of weed species was quantified three times throughout the season (at 4, 7, and 12 weeks after planting). Realized weed community was quantified by using four -0.0625-m^2 quadrats across each plot 30 cm in from plot border to minimize edge effects, followed by identifying and quantifying number of species present. At Absaraka, quadrats were uniformly and systematically oriented from north-east to south-west and equally spaced along the plot’s hypotenuse. At Dickinson, quadrats were uniformly and systematically oriented from north-west to south-east and were equally spaced along the plot’s hypotenuse. Weeds were removed after quantifying via hand pulling or hoeing throughout the growing season. Time required for weeding each treatment plot was recorded using stop watches for evaluating labor inputs between tillage treatments. Because weeds were removed in a timely manner, differences in crop response variables between tilled and no-till treatments are likely due to other factors besides weed competition. At both sites, only baseline weed community assessments were conducted during 2015 and these data were not included in the analysis of treatment impacts on weed community density, because when we collected these baseline data, the treatments had not yet been imposed.

Seedbank Density

To assess changes in the weed seedbank over time and in response to treatment factors, weed seedbank soil samples were collected in the spring before weed emergence occurred in both 2015 and 2017. Soil samples were collected 30 cm in from the plot border to minimize edge effects. Twenty soil samples, each 10 cm (length) x 6 cm (diameter), were extracted with a bulb planter in randomly selected locations within each plot. The soil cores were mixed in a bucket to homogenize samples, for a total volume of 5.65 L per plot. Soil from cores collected were then spread in 54.6 × 28.2 by 5.1 cm plastic trays on top of a layer of potting soil covered by a layer of porous poly mesh fabric. A volume of 2850 cm^3 (1.85 cm depth) of field soil was placed on top of approximately 5000 cm^3 potting soil media (to assist with moisture retention and drainage) at a depth of 3.25 cm. To monitor and control for possible contamination of potting media, eight control trays were used containing only potting soil. Trays were maintained at even moisture in greenhouse with natural daylight, supplemented with mercury vapor lights on a timer for 12 hours, and day/night temperatures of approximately 25/15 °C. As seedlings emerged, they were identified to species, counted, and removed. Any species that was not easily identified was transplanted into pots and allowed to grow until positive identification was possible. Once emergence ceased, the trays were dried and stored in the greenhouse for approximately 4 weeks, soil was mixed and redistributed, then rewetted to stimulate germination of dormant seeds. Trays were randomized on the greenhouse bench and re-randomized after each quantification event to account for microclimate variance within the greenhouse.

Soil Quality Indices

Impacts of tillage treatments and AMF treatment on soil quality variables were assessed via soil samples collected in 2015, 2016, and 2017. All soil samples were collected during July of each year using soil probes with 2 cm outside diameter and 1.8 cm inside diameter (Regular Step Soil Probe, AMS, Inc. 105 Harrison St. American Falls, ID), and were collected in a "W" pattern across plots to account for spatial variability. All samples were air dried in the lab by rolling open double bagged paper bags and hand stirred every two days for 1 week before being shipped for the respective analysis, except for samples for PLFA, which were frozen and shipped frozen. Samples were kept out of direct sunlight after sampling and during transport to lab facilities prior to processing. Approximately 25 soil cores per plot were collected at 0-15 cm depths for Cornell Nutrient Analysis Laboratory (G01 Bradfield Hall, Cornell University, Ithaca, NY), which provided analysis for wet aggregate stability, active carbon, and soil respiration.

Wet aggregate stability methodology includes placement of soil sample on stacked sieves of 2.0 mm and 0.25 mm onto a catch pan. Soil is shaken for 15 seconds on a Tyler Coarse Sieve Shaker to separate aggregates of 0.25-2.0 mm. A single layer of aggregates within this range are then spread onto a 0.25 mm sieve. Sieves are placed 500 mm below a rainfall simulator, which delivers drops of 4.0 mm diameter. This test is ran for 5 minutes, delivering 12.5 mm of water as drops to each sieve, totaling 0.74 J of energy impacting each sieve over the 5 minutes, which is equivalent to a heavy thunderstorm. Material remain on the sieve is then collected, dried, and weighed. This fraction is considered to stable, and WSA (weight of stable aggregates) = Wstable/Wtotal.

Active carbon methodology includes sieving air dried soil to 2 mm, collecting 2.5 g of this sample and placing it into a 50 ml centrifuge tube. The centrifuge tube is then filled with 20 ml of 0.02 M potassium permanganate ($KMnO_4$) solution. Soil and $KMnO_4$ are then shaken for exactly 2 minutes, which oxidizes the active carbon within the sample. The sample tube then settles for 8 minutes, pipetted into another tube, and diluted with distilled water. Absorbance is measured at 550 nm and the absorbance of a standard dilution series of the $KMnO_4$ is also measured to create a standard calibration curve. The loss of color from the KMnO4 is proportional to the amount of oxidizable carbon in the soil sample. The formula (Active C (mg/kg) = [0.02 mol/L - (a + b * absorbance)] * (9000 mg C/mol) * (0.02 L solution/0.0025 kg soil)) is used to convert sample absorbance to active carbon.

Soil respiration methodology includes sieving soil to 8 mm and placing 20 g of dried soil onto aluminum weigh boat (with 9 pin holes through the bottom). Weigh boat is placed on top of two staggered filter papers in the bottom of a standard 1 pint wide-mouth mason jar. A 10 ml glass beaker (secured to a plastic tripod) is filled with 9 ml of 0.5 M KOH (CO_2 trapping solution) and placed inside the jar. Next, 7 ml of distilled, deionized water is pipetted into the jar along the side, where the water is wicked into the soil through filter paper. The jar is then sealed tightly and left undisturbed for 4 days. CO_2 respired is calculated by comparing the conductivity of the trap solution to that of the original trap solution.

Approximately 10 soil cores per plot were collected at 0-15 cm depths for the NDSU Soil Testing Lab (Dept. 7660 P.O. Box 6050, Fargo, ND), which performed routine soil nutrient analysis of NO_3^- N, P, K and organic matter content using water extraction, the Olson procedure, 1N ammonium acetate, and loss on ignition methods, respectively. To assess the microbial community, 15 cores per plot at 0-20 cm depths were collected for analysis of phospholipid fatty acid (PLFA) which was performed by Ward Laboratories (4007 Cherry Ave., P.O. Box 788, Kearney, NE) using methods described by Wu et al. (2009). Soil probes were rinsed with a 10% bleach solution in between samples to avoid cross-treatment contamination. Samples were kept in a cooler with ice packs in the field and stored at -4 °C.

Root samples were collected for scoring of root length colonized (RLC) by AMF from treatment plot guard rows at 90% anthesis or near maturity/harvest. Fine roots ($\leq$ 1 mm) were collected by excavating at a 15 cm depth and distance from the center of crop rows. For all crops except squash, guard row crops were used for these destructive root harvests, so that the center crop row, which was harvested for yield, would not be impacted by this disturbance. Squash crop roots were collected without destructive harvest (individual plants were not uprooted) with minimal disturbance from peripheral fine roots (≤ 1 mm). Roots were stored in 1% KOH and refrigerated at 1.7 C until processed according to Brundrett (1984). Using methods described by Phillips and Hayman (1970) and modified by Koske and Gemma (1989), root samples were cleared in 10% KOH at 90 C in microcassettes (Fisherbrand SURE-TEK 2 Biopsy Cassettes) for approximately 3 min, rinsed with distilled water, acidified in 2% HCl for 20 min, and20 minutes, stained with 0.05% aniline blue dye in lactoglycerol (1:1:1 lactic acid, glycerol and distilled H_2O) for 2 hours. Roots were rinsed again using a slightly acidified water bath (2% HCL and water) to remove excess dye but retain root coloration. Root samples were then placed on glass microscope slides with approximately 26 cm of root sample per slide and mounted using PLVA (poly-vinyl-alcohol-lactic acid-glycerol). Scoring for RLC of AMF included presence of arbuscules, vesicles, and intracellular aseptate hyphae as evidence of colonization (Day et al., 1987). Scoring was performed with 100 observations per slide at 200× magnification in 2 mm increments using the grid line intersect method (McGonigle et al., 1990) and a Zeiss Axio Lab.A1 with phototube and Axiocam 105 color camera. Categories for scoring included AMF present, no AMF present, pathogen/other fungi present, or AMF + pathogen/other fungi present.

Crop Nutritional Status, Yield, and Quality

Crop nutritional status was quantified using leaf tissue samples collected from crop middle (data) rows during peak growing season or at flowering. For each crop, 25 fully-emerged leaves were collected in 2015 and 2016 (Kelling et al. 2002). Tissue samples were analyzed at UW-Wisconsin Madison Soil Testing Laboratories (8452 Mineral Point Rd. Verona, WI) using micro Kjeldahl for total N (Sáez-Plaza et al., 2013) and nitric acid/peroxide digest by inductively coupled plasma spectrometry for P and K (Zarcinas et al., 1987). Stomatal conductance and leaf chlorophyll content were assessed at the onset of flowering using a Decagon Leaf Porometer SC-1 and Opti-Sciences CCM-300, respectively.

Statistical Analysis

Analysis of variance tests (at $\alpha = 0.05$) were conducted using the PROC MIXED procedure in SAS version 9.3 (SAS Institute, Inc. Cary, NC) to test fixed effects of year, tillage, entry point (a proxy for crop species), and use of AMF inoculum on realized weed density, weed seedbank density, weed removal time, soil aggregate stability, soil N, P, K, organic matter, active carbon, soil respiration, microbial biomass and diversity, AMF biomass, AMF colonization, crop leaf chlorophyll, crop leaf stomatal conductance, crop leaf nutrients (N, P, and K), and crop yield.

Replication was treated as a random effect for all analyses. Sites were analyzed separately because the experimental designs differed between sites (RCBD with split-plot arrangement vs. RCBD with no split plots for Absaraka vs Dickinson, respectively) and because preliminary combined analyses typically revealed numerous interactions involving site. When multiple years of data were analyzed, year was considered a repeated measure and appropriate covariance structures were chosen to minimize the goodness of fit criterion, AIC. Prior to ANOVA, data were assessed for conformation to assumptions of ANOVA (Levene's test for heteroscedasticity, Shapiro-Wilk test and Q-Q plot for normality). Data were transformed to meet assumptions, if necessary. Post-hoc multiple comparisons were made using Tukey's Honest Significant Difference adjustments for multiple comparisons. Tests of simple effects ('slice' option in PROC MIXED lsmeans) were used to assess treatment effects in the event of higher-order interactions, using a Bonferroni adjustment for multiple comparisons.

RESULTS AND DISCUSSION

Realized Weed Community

Table 5. Treatment Effects on Weed Densities at Absaraka.

Effect	P
Year	0.8313
Tillage	<0.0001
Year * Tillage	0.0129
AMF	0.8436
Year * AMF	0.6202
Tillage * AMF	0.7142
Year * Tillage * AMF	0.5811
Entry	<0.0001
Year * Entry	0.0782
Tillage * Entry	0.0006
Year * Tillage * Entry	0.1746
AMF * Entry	0.5774
Year * AMF * Entry	0.8543
Tillage * AMF * Entry	0.7897

Interactions between year by tillage and tillage by entry were observed for weed density (Table 5) (p = 0.0129 and p = 0.0006, respectively), but slicing this interaction demonstrated consistent reductions in weed density associated with no-till mulched plots compared to tilled plots during 2016 and 2017 (98 vs. 512 and 37 vs. 564 plants m^{-2} respectively, p = <0.0001) (Fig. 1). No differences were observed between 2016 and 2017 within tilled treatments (p = 0.0964) or within mulched no-till treatments (p = 0.0574) (Figure 1).

An interaction between tillage and entry point (Table 5) (p = 0.0006) occurred as weed densities differed among entry points in tilled plots (p < 0.0001). Entry 2 and 4 did not differ (p = 0.7226), but, entry 2 and entry 4 were both less than entry 1 (429 vs. 575 and 445 vs. 575 weed plants m^{-2}, respectively) (p = 0.0016 and p = 0.0045, respectively) and entry 3 (429 vs. 704 and

445 vs. 704 weed plants m^{-2}, respectively) ($p < 0.0001$ and $p < 0.0001$) , respectively) (Figure 2), but not in mulched no-till plots ($p = 0.8722$) (data not shown). However, no clear pattern was seen that might explain the weed density differences among the various entry points. For instance, entry point 3 had the greatest weed density even though this entry point lacks onion, which is probably the least competitive crop against weeds. Entries 2 and 4 had the lowest weed densities, even though both these entries included onion. In addition, within the tilled plots, these patterns were the same though the differences were not significant. Weed densities were not affected by AMF inoculation ($p = 0.8436$).

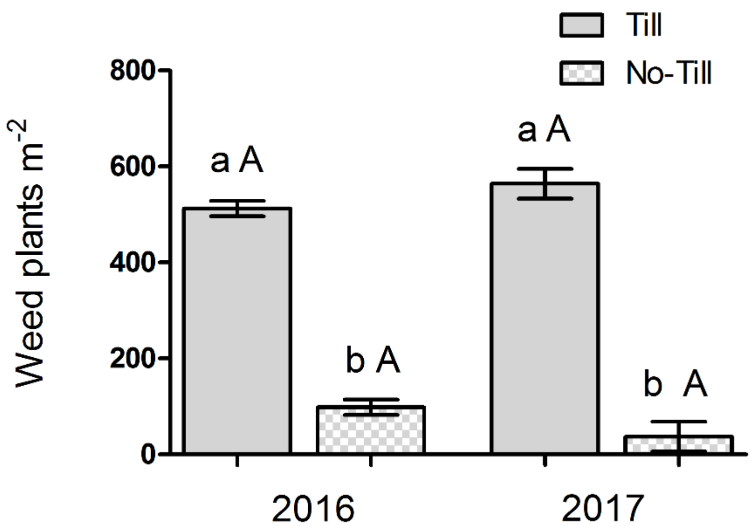

Figure 1. Absaraka mean weed density ± SE for tillage treatments during 2016 and 2017. Bars labeled with different lowercase letters differ between tillage within year ($P \leq 0.05$) according to Tukey's HSD. Bars labeled with different uppercase letters differ between year within tillage ($P \leq 0.05$) according to Tukey's HSD.

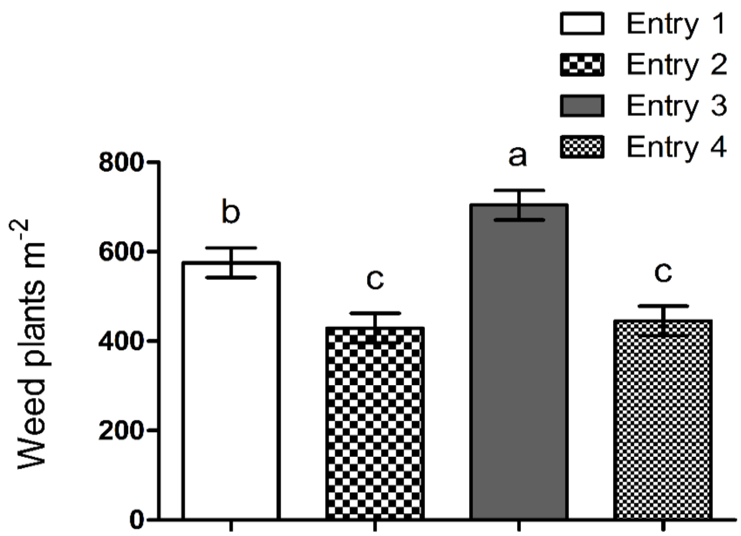

Figure 2. Absaraka mean weed density (± S.E.) for entry points within tilled treatments. Values with different lowercase letters differ (at α = 0.05) by Tukey's HSD.

Table 6. Treatment Effects on Weed Densities at Dickinson.

Effect	P
Year	0.7218
Tillage	<0.0001
Year * Tillage	0.0101
AMF	0.2131
Year * AMF	0.9414
Tillage * AMF	0.5709
Year * Tillage * AMF	0.8079
Entry	0.0025
Year * Entry	<0.0001
Tillage * Entry	0.0105
Year * Tillage * Entry	<0.0001
AMF * Entry	0.5371

For weed density at Dickinson, an interaction among year, entry point, and tillage was noted (Table 6) (p = <0.0001). Therefore, the slice option was used to understand the simple main effects of tillage within year by entry point and entry point within year by tillage. Regardless of year by entry, mulched no-till plots contained fewer weeds than tilled plots (136 vs. 560 weed plants m^{-2}) (Figure 3). During 2016, within tilled treatments, entry 3 was associated with a lower weed density than entries 1, 2, or 4 (262 vs. 569, 643, and 664 weed plants m^{-2}, respectively) (Figure 4). During 2017, within tilled treatments, entry 2 was associated with lower weed density compared to entries 1, 3, and 4 (313 vs. 739, 731, and 560 weed plants m^{-2}, respectively) (Figure 5). During 2016, mulched no-till treatments observed a similar pattern as tilled treatments in 2016, with entry 3 having lower weed densities than entry 1, 2, or 4 (75 vs. 171, 255, and 145 weed plants m^{-2}, respectively) (Figure 6). During 2017, mulched no-till treatments observed a similar pattern, although there was no significance among entries, entry 2 and 3 had the lowest weed densities (Figure 7). Weed densities were not affected by AMF inoculation (Table 6) (p = 0.2131).

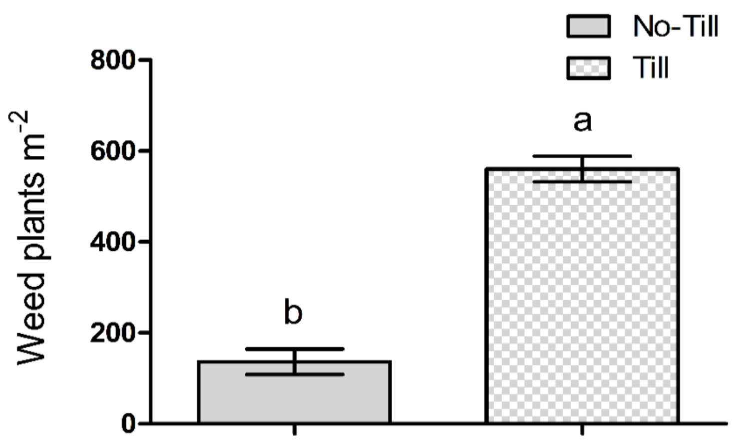

Figure 3. Dickinson mean (±S.E.) total weed density (plants m^{-2}) for tilled and mulched no-till treatments, pooled over year, entry point, and AMF treatments. Tillage effect is shown by bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD.

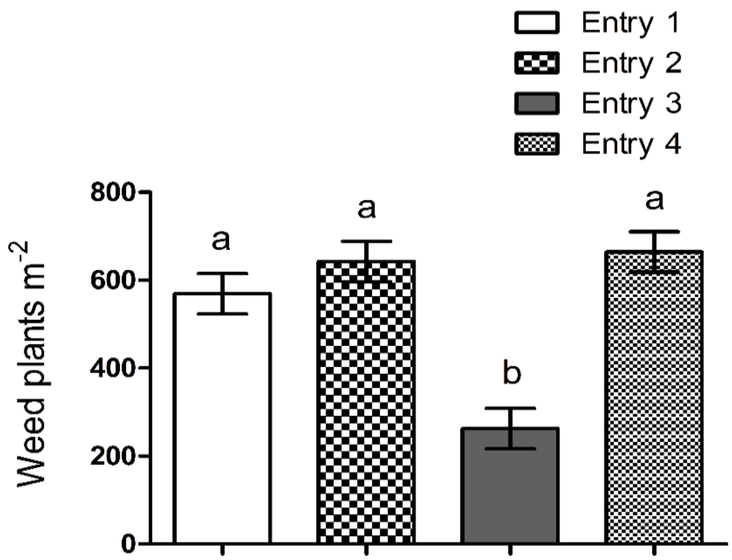

Figure 4. Dickinson mean (±S.E.) total weed density (plants m^{-2}) for entry points during 2016 in tilled treatments. Entry effect within tillage is shown by bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD.

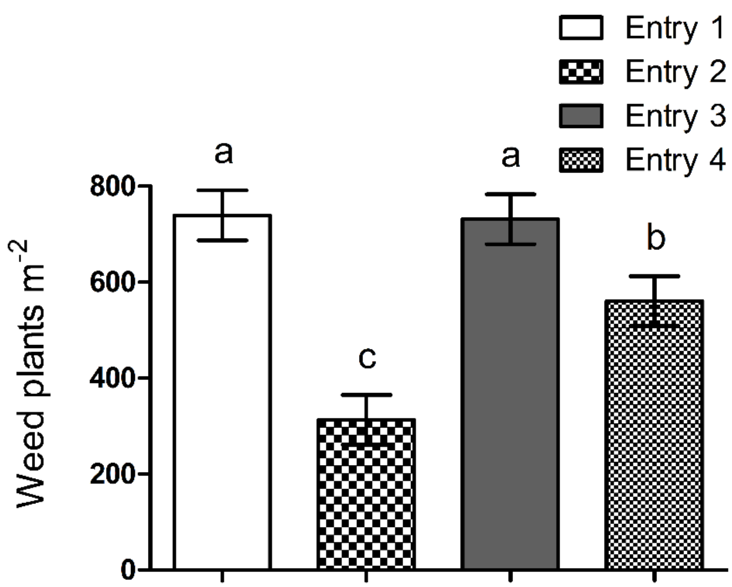

Figure 5. Dickinson mean (±S.E.) total weed density (plants m^{-2}) for entry points during 2017 in tilled treatments. Entry effect within tillage is shown by bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD.

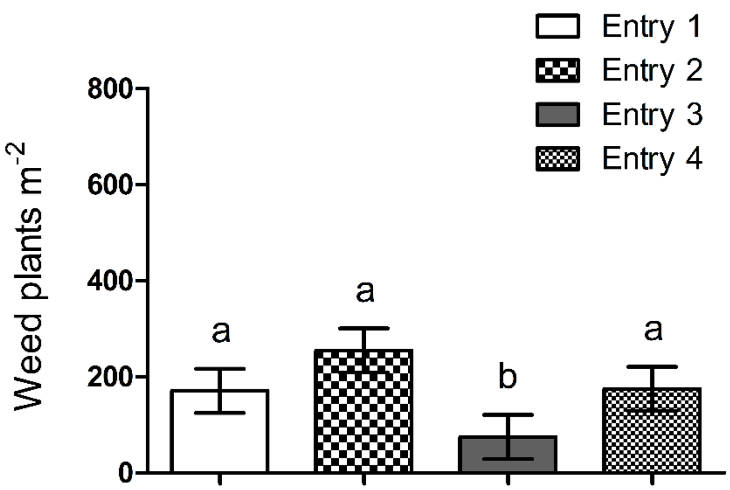

Figure 6. Dickinson mean (±S.E.) total weed density (plants m^{-2}) for entry points during 2016 in mulched no-till treatments. Entry effect within tillage is shown by bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD.

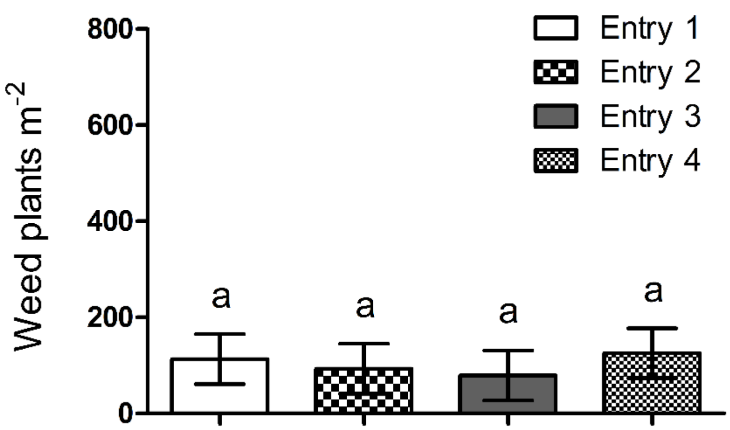

Figure 7. Dickinson mean (±S.E.) total weed density (plants m^{-2}) for entry points during 2017 in mulched no-till treatments. Entry effect within tillage is shown by bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD.

Use of mulch is generally recognized as an approach that reduces weed density(Teasdale and Mohler, 2000). In our study, mulched treatments were also left untilled for the duration of the study, but the treatment effects on weed density are due to the combined effects of physical weed suppression by the mulch and other processes affected by the absence of tillage (such as lack of repeated redistribution of seeds within the vertical soil profile). Similarly, interpreting results from previous studies about the effects of no-till on weed density is challenging, because different approaches to no-till leave different amounts of plant residue on the soil surface and the weed density is affected by both suppression of weed emergence by residue (analogous to mulch) and other processes related to lack of tillage, such as enhanced weed seed predation (Pullaro et al., 2006).

Jokela and Nair (2016) conducted a tillage study focused on vegetable production in Iowa and found that weed densities were lowest between-row regions in no-till vs. conventionally tilled treatments, wherein both included fall seeded cover crops cereal rye and hairy vetch. Conventionally tilled plots had cover crop residue incorporated, whereas no-till plots were roller-crimped, leaving residue on the soil surface, which exceeded the 8000 kg ha^{-1} that Teasdale and Mohler (2000) observed to be sufficient for effective weed suppression.

Wiens et al. (2006) found weed suppression from alfalfa mulch in red spring wheat increased as the amount alfalfa mulch applied increased, with the greatest weed suppression at rates ranging from 3900 to 5200 kg ha^{-1}. Timing of alfalfa mulch application was also found to reduce weed densities, when applied later in the growing season, at the 3-leaf stage as opposed to pre-emergence of red spring wheat. Mulch applied earlier in the season and with less mass may have added more available N to early germinating weeds (Buhler, 1997), especially for leguminous cover crop species, whereas mulch applied later in the season contributed to longer duration of weed suppression. Teasdale and Mohler (2000) observed similar results, whereby mulch masses of 2000 kg ha^{-1} stimulated redroot pigweed (*Amaranthus retroflexus*) emergence whereas mulch rates of 4000 kg ha^{-1} and greater provided exponential decreases in weed emergence. Our treatments received approximately 24,000 kg ha^{-1}, which far exceeds rates applied by Weins et al. (2006) and Teasdale and Mohler (2000). This difference points out an advantage of the deep mulching approach compared to roller crimped cover crops – much greater amounts of residue can be applied via mulching than generated via cover crops, so weed suppression ability is increased with mulches, provided enough material is applied.

A study (Smith et al., 2011) focused on weed suppressive abilities of a fall seeded rye and termination methods of roller-crimped and flail-mowed *in situ* mulch in no-till soybean production. The results of this study indicated no differences between termination treatments in terms of weed suppression, despite ranging medium to high cover crop biomass production (4,450 kg ha^{-1} to 10,854 kg ha^{-1}). Brown and Gallandt (2018) found lower weed biomass in straw and hay mulch treatments when compared to polyethylene mulch treatments with onion and sweet corn systems.

Our Absaraka experiment site demonstrated effective weed suppression, most likely due to the conditions of mulch used. A clean, weed seed-free, alfalfa was used, whereas the Dickinson site utilized a crested wheatgrass mulch contaminated with field bindweed (*Convolvulus arvensis* L.), downy brome (*Bromus tectorum* L.), and Russian thistle (*Salsola tragus* L.). Our site at Dickinson was also managed differently in that rows and borders between plots were sown into a cover crop mixture, whereas our site at Absaraka had rows and borders tilled and weeded after each weed quantification event. Potential tradeoffs exist within alley management practices. With tillage, a producer could decide to till when necessary, whereas with living mulch alleys, depending on species grown, alleys may need to be mowed during flowering stage to retain vegetative vigor and maintain competitive ability against weeds.

When considering entry effects on weed densities, it may be appropriate to also consider one of the most consistent conclusions of crop competitiveness (vigorous growth and morphology that reduces light quantity and quantity below the canopy of the crop) (Buhler, 2002). Entry points beginning with onion having greater weed densities align with the findings of van Heemst (1985), who observed onion to be relatively less competitive than both red table beets and peas. Similarly, entries growing squash within tilled treatments in respective years were observed to have lower weed densities compared to other entry crops. Cucurbits, such as squash, have been traditionally planted along with corn in southeastern Mexico to provide continuous ground cover that outcompetes low-growing or prostrate weed species (Chacón and Gliessman, 1982).

Weed Seedbank Density

Table 7. Treatment Effects on Weed Seedbank Densities at Absaraka.

Effect	*P*
Year	< 0.0001
Tillage	0.2657
Year * Tillage	0.0080
AMF	0.5789
Year * AMF	0.7437
Tillage * AMF	0.5870
Year * Tillage * AMF	0.8376
Entry	0.4520
Year * Entry	0.0223
Tillage * Entry	0.0707
Year * Tillage * Entry	0.4583
AMF * Entry	0.1585
Year * AMF * Entry	0.9532
Tillage * AMF * Entry	0.4715

Weed seed bank densities at Absaraka were influenced by interactions between year x tillage (Table 7.) ($p = 0.0080$) and year x entry (Table 7) ($p = 0.0223$). Therefore, the slice option was used to understand the simple effects of both tillage and entry within year. At Absaraka, weed seedbank density did not differ between tillage treatments in 2015 ($p = 0.1039$) (Figure 8).

During 2017, both tilled and mulch no-till treatments resulted in a decrease in seedbank density compared to the baseline 2015 densities ($p = 0.0063$ and $p < 0.0001$, respectively); however, the reduction was more pronounced for no-till treatments. During 2017, tillage treatments contained a greater seedbank density than no-till treatments (5422 vs. 3209 seeds m^{-2} slice, respectively) ($p = 0.0152$) (Figure 8). During 2015, no differences were observed between entries ($p = 0.7860$) (Figure 9), as soil and seed samples were collected during the spring before treatment applications. During 2017, entries 3 and 4 had the lowest weed seed densities, although only entry 2 differed from entry 4 ($p = 0.0004$), where entry 4 had the least amount of weed seeds and entry 2 had the most (3377 vs. 5230 seeds m^{-2}, respectively) (Figure 10.). During 2017, entries 3 and 4 had contained squash during 2015 and 2016, respectively, whereas entry 2, which had the most weed seeds did not include squash during either 2015 or 2016. Weed seedbank densities were not affected by AMF inoculation ($p = 0.5789$).

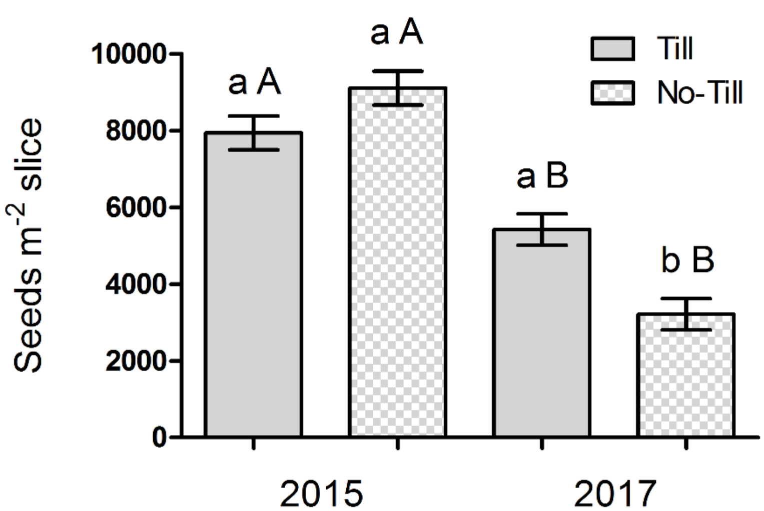

Figure 8. Absaraka mean (±S.E.) total weed seed densities (seeds m^{-2} slice) for tilled and mulched no-till treatments during 2015 and 2017. Tillage effect within year is shown by bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD. The simple effect of year within tillage is shown by bars labeled with different uppercase letters differ ($P \leq 0.05$) according to Tukey's HSD.

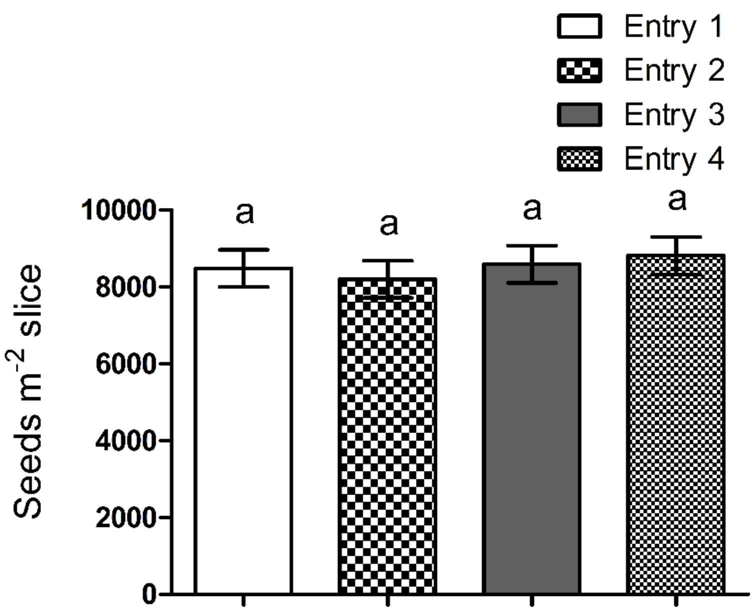

Figure 9. Absaraka mean (±S.E.) total weed seed densities (seeds m^{-2} slice) for entry points during 2015. Entry effect within tillage is shown by bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD.

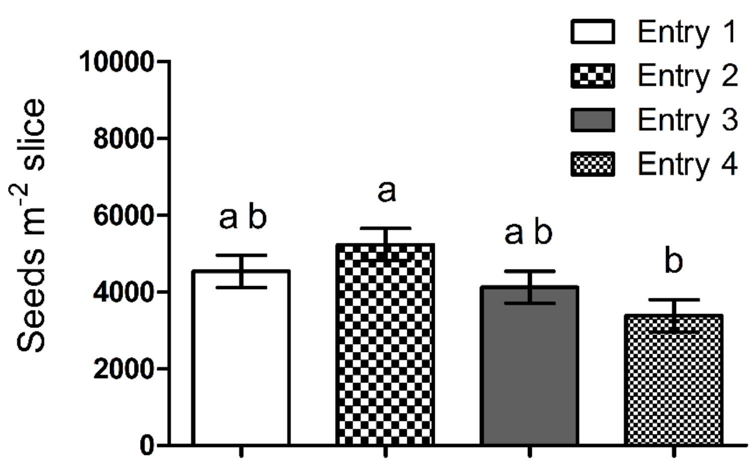

Figure 10. Absaraka mean (±S.E.) total weed seed densities (seeds m^{-2} slice) for entry points during 2017. Bars labeled with different lowercase letters differ between entry ($P \leq 0.05$) according to Tukey's HSD.

Table 8. Treatment Effects on Weed Seedbank Densities at Dickinson.

Effect	*P*
Year	<0.0001
Tillage	<0.0001
Year * Tillage	<0.0001
AMF	0.7179
Year * AMF	0.7605
Tillage * AMF	0.6545
Year * Tillage * AMF	0.4181
Entry	0.0005
Year * Entry	0.1591
Tillage * Entry	0.9284
Year * Tillage * Entry	0.2264
AMF * Entry	0.9847
Year * AMF * Entry	0.1648
Tillage * AMF * Entry	0.6612
Year * Tillage * AMF * Entry	0.9190

Dickinson weed seed bank density was influenced by a year x tillage interaction (Table 8) (p = <0.0001). Using the slice option to understand the simple main effects of tillage within year showed that seedbank density did not differ between tillage treatments in 2015 (p = 0.2212) (Figure 11). During 2017, seedbank density for tilled treatments increased from 2015 (2774 vs. 1070 seeds m^{-2} slice, respectively) ($p < 0.0001$) (Figure 11). While seedbank density for no-till treatments did not differ from 2015 to 2017 (p = 0.7970), no-till treatments had reduced seedbank density compared to tillage treatments in 2017 (1247 vs. 2772 seeds m^{-2} slice, respectively) ($p < 0.0001$) (Figure 11). A simple effect of entry was also shown to influence weed seed bank density at Dickinson (p = 0.0005). Entry 2 had greater weed seed bank density than entries 1 and 3 the (2114 seeds m^{-2} slice vs. 1473 and 1277, respectively) (p = 0.0079 and p = 0.0004), but no differences between entries 2 and 4 or between entries 1 and 3 were observed

(p = 0.0181 and p = 0.7322, respectively) (Figure 12). Weed seedbank densities were not affected by AMF inoculation (p = 0.7179).

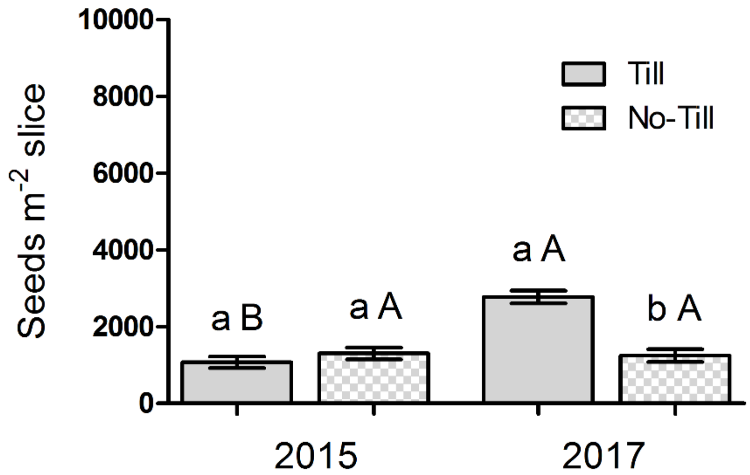

Figure 11. Dickinson mean (±S.E.) Total weed seed density (seeds m^{-2} slice) for tilled and mulched no-till treatments during 2015 and 2017. Tillage effect within year is shown by bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD. The simple effect of year within tillage is shown by bars labeled with different uppercase letters differ ($P \leq 0.05$) according to Tukey's HSD.

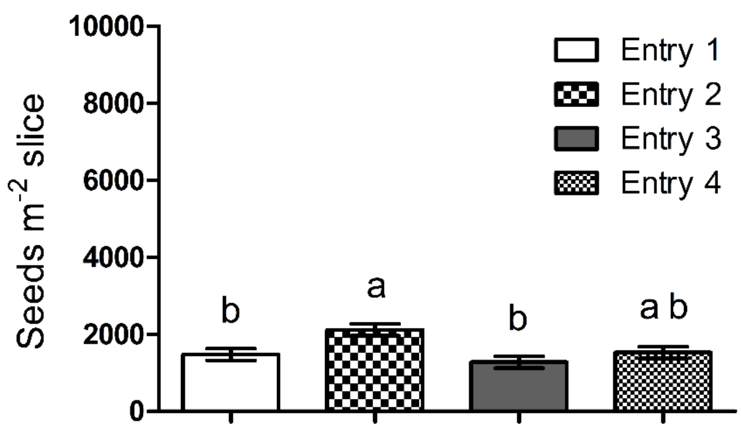

Figure 12. Dickinson mean (±S.E.) Total weed seed density (seeds m^{-2} slice) for entry points across years and tillage treatments. Entry effect within tillage is shown by bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD.

Because the seed bank was sampled before the crops were sown during 2017, only the crops grown during 2015 and 2016 would have impacted the weed seed bank. Entry point 2 contained onion in 2015 and beet in 2016. Onion is a non-competitive crop against weeds (van Heemst, 1985) and the beet stands at Dickinson were poor during 2016. Lack of competitive crop canopies in this particular entry may have caused the weed seed bank increase relative to the other entry points.

Our results agree with previous publications reporting that combining conservation tillage practices with crop residue can reduce weed seedbank densities (Kelton et al., 2011). However, our results also somewhat contradict results from Cardina et al. (2002), who reported that no-till often resulted in greater seedbank densities than chisel plowing and moldboard plowing, despite differences in crops with varying residues (continuous corn, corn-soybean, and corn-oat-hay rotation treatments). Cardina et al. (2002) suggested seed physical and physiological properties (seed size, type of dormancy, germination requirements, and dispersal adaptations) interact with environmental filters to influence seedbank community assemblages, which provide snapshots of past and current management which influence future vegetation.

For Absaraka, that both tillage treatments produced declines in seedbank densities was not surprising, given the aggressive weed management throughout each year (after counting, weeds were always removed). By removing weeds after quantification events, we effectively minimized “deposits” to the seed bank, enacting the concept of “zero seed rain” (Forcella, 2003). The weeding of tilled treatments may have contributed to soil disturbance through the use of hoe tools stimulating germination and further reducing viable seedbank density. Evidence of this is supported by the large quantity of common purslane (*Portulaca oleracea*) we observed emerging post weeding (data not shown).

We observed slightly different results at the Dickinson site, where tillage increased seedbank density over time, and no-till treatment seedbank densities were unchanged. This could be due to surrounding fields and alleyways contributing to the tilled seedbanks through wind dispersion before tillage redistributed seed within the soil profile, burying seeds. At this site, the alleys between plots were planted to a spring wheat cover crop, which was mowed, but became excessively weedy during all three years of the study.

Weeding Time

Table 9. Treatment Effects on Weeding Time at Absaraka.

Effect	P
Year	<0.0001
Tillage	<0.0001
Year * Tillage	<0.0001
AMF	0.5390
Year * AMF	0.5481
Tillage * AMF	0.1613
Year * Tillage * AMF	0.4148
Entry	0.0116
Year * Entry	<0.0001
Tillage * Entry	0.6908
Year * Tillage * Entry	0.1738
AMF * Entry	0.3987
Year * AMF * Entry	0.5812
Tillage * AMF * Entry	0.2991
Year * Tillage * AMF * Entry	0.8574

At Absaraka, weeding times were influenced by a year x entry interaction (Table 9) ($p < 0.0001$). During 2015, no differences between entries with respect to weeding times were observed ($p = 0.6485$). During 2016, weeding times differed among entries ($p < 0.0001$). Differences were observed between entries 1 (onion) and 3 (squash), entries 2 (beet) and 3 (squash), and entries 3 (squash) and 4 (pea) (35 vs. 22 hours, 32 vs. 22, and 22 vs. 32 hours, respectively) ($p < 0.0001$, $p = 0.0002$, and $p = 0.0002$, respectively) (Figure 13). No weeding time differences were observed between entries 1 (onion) and 2 (beet), entries 1 (onion) and 4 (pea), or entries 2 (beet) and 4 (pea) ($p = 0.2523$, $p = 0.2836$, and $p = 0.9408$, respectively) (Figure 13). During 2017, weeding times differed among entry points ($p = 0.0010$). Differences were observed for weeding hours between entries 2 (squash) and 3 (pea) (17 vs. 29 hours) ($p < 0.0001$) (Figure 14) No differences were observed between entries 1 (beet) and 2 (squash), entries 1 (beet) and 3 (pea), entries 1 (beet) and 4 (onion), entries 2 (squash) and 4 (onion), and entries 3 (pea) and 4 (onion) ($p = 0.0279$, $p = 0.0399$, $p = 0.7042$, $p = 0.0110$, and $p = 0.0893$, respectively) (Figure 14).

A year x tillage interaction also influenced weeding times at Absaraka (Table 9) ($p < 0.0001$). Within tilled treatments, differences were observed between 2015 and 2016 and between 2015 and 2017 (24 vs. 33 hours and 24 vs. 31 hours, respectively) ($p < 0.0001$ and $p = 0.0009$, respectively) (Figure 15). No differences were observed between 2016 and 2017 ($p = 0.3992$). Within mulched no-till treatments, differences were observed between 2015 and 2016, between 2015 and 2017, and between 2016 and 2017 (3 vs. 28 hours, 3 vs. 16 hours, and 16 vs. 28 hours, respectively) ($p < 0.0001$, $p < 0.0001$, and $p < 0.0001$, respectively) (Figure 15). During 2015, 2016, and 2017, mulched no-till treatments were associated with less time required for weeding compared to tilled treatments (24 vs. 3 hours, 33 vs. 28 hours, and 31 vs. 16 hours, respectively) ($p < 0.0001$, $p = 0.0251$, and $p < 0.0001$, respectively) (Figure 15). Weeding hours were not affected by AMF inoculation ($p = 0.5390$).

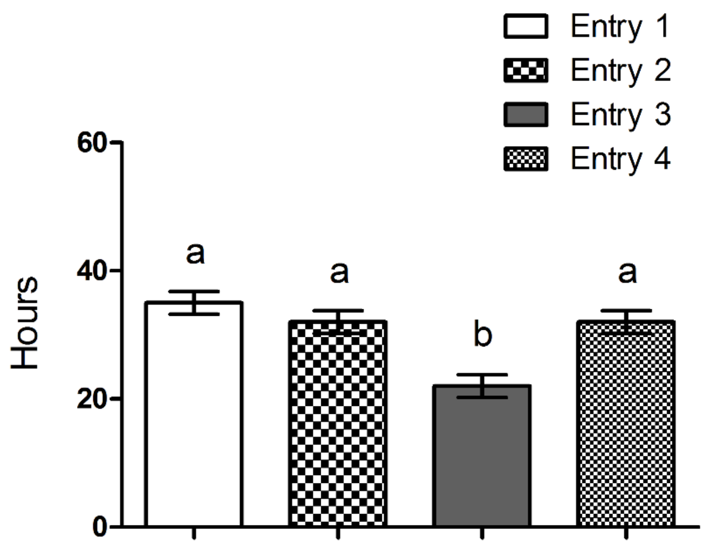

Figure 13. Absaraka mean (±S.E.) weeding time (hours) for entry points during 2016 across AMF and tillage treatments. Entry effect is shown by bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD.

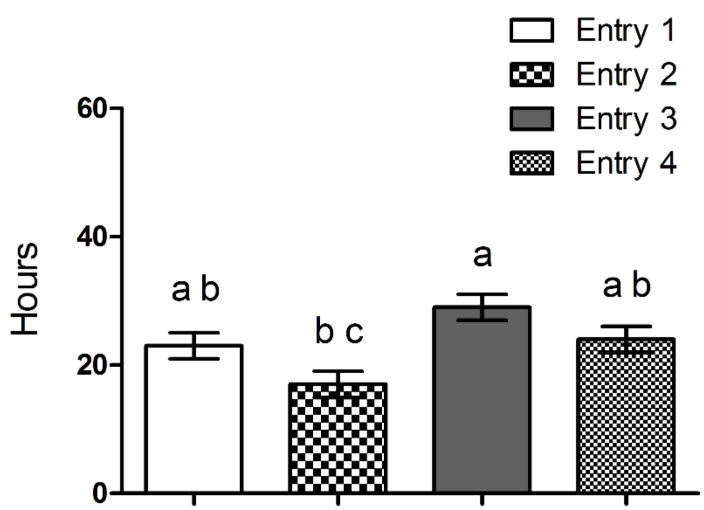

Figure 14. Absaraka mean (±S.E.) weeding time (hours) for entry points during 2017 across AMF and tillage treatments. Entry effect is shown by bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD.

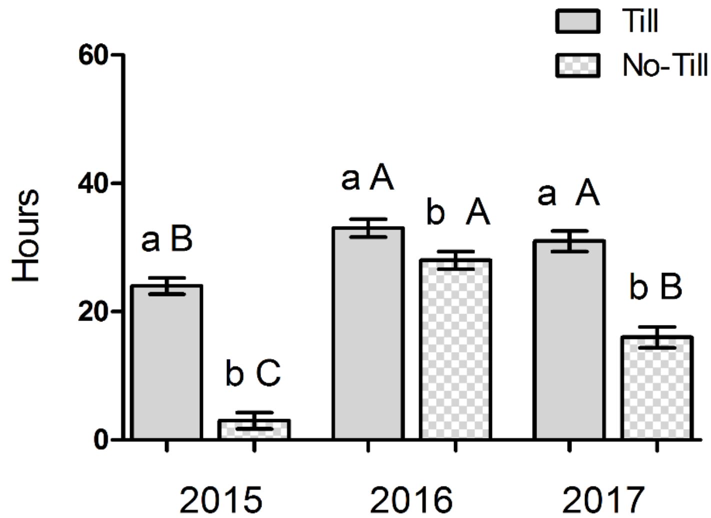

Figure 15. Absaraka mean (±S.E.) weeding time (hours) for tillage treatments between years across AMF treatments. Tillage within year is shown by bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD. Year within tillage is shown by bars labeled with different uppercase letters differ ($P \leq 0.05$) according to Tukey's HSD.

Table 10. Treatment Effects on Weeding Time at Dickinson during 2015 and 2016.

Effect	P
Year	<0.0001
Tillage	0.0117
Year * Tillage	0.5641
AMF	0.4367
Year * AMF	0.6795
Tillage * AMF	0.1301
Year * Tillage * AMF	0.3355
Entry	<0.0001
Year * Entry	<0.0001
Tillage * Entry	0.2529
Year * Tillage * Entry	0.0961
AMF * Entry	0.5638
Year * AMF * Entry	0.8664
Tillage * AMF * Entry	0.8865
Year * Tillage * AMF * Entry	0.8789

For Dickinson weeding time data, 2017 data were analyzed separately from 2015/2016 data because during 2017 two crops failed and were not weeded (beet and pea), which resulted in unbalanced data. For 2015 and 2016 data, a year x entry interaction was observed (Table 10) ($p < 0.0001$). During 2015, differences were observed for weeding times between entries 1 (pea) and 2 (beet), entries 1 (pea) and 3 (onion), entries 1 (pea) and 4 (squash), entries 2 (beet) and 4 (squash), and entries 3 (onion) and 4 (squash) (16 vs. 10 hours, 16 vs. 10 hours, 16 vs. 5 hours, 10 vs. 5 hours, and 10 vs. 5 hours, respectively) ($p < 0.0001$ for all comparisons) (Figure 16).

During 2016, differences were observed for weeding times between entries 1 (onion) and 2 (beet), entries 1 (onion) and 3 (squash), entries 2 (beet) and 3 (squash), entries 2 (beet) and 4 (pea), and entries 3 (squash) and 4 (pea) (36 vs. 50 hours, 36 vs. 20 hours, 50 vs. 20 hours, 50 vs. 37 and 20 vs. 37 hours, respectively) ($p = 0.0020$, $p = 0.0006$, $p < 0.0001$, $p = 0.0031$, and $p = 0.0004$, respectively) (Figure 17).

Across 2015 and 2016, a tillage effect on weeding time was observed (Table 10) ($p = 0.0117$). Mulched no-till treatments were associated with fewer weeding hours required compared to tilled treatments (21 vs. 25 hours, respectively) (Figure 18). Weeding hours were not affected by AMF inoculation ($p = 0.4367$).

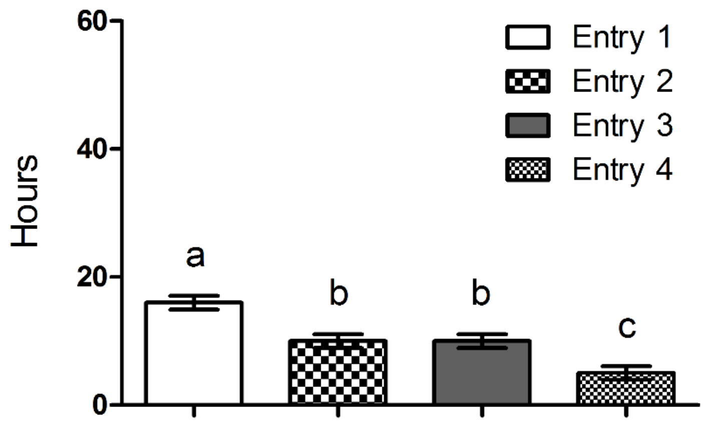

Figure 16. Dickinson mean (±S.E.) weeding time (hours) for entry points during 2015 across AMF and tillage treatments. Entry effect is shown by bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD.

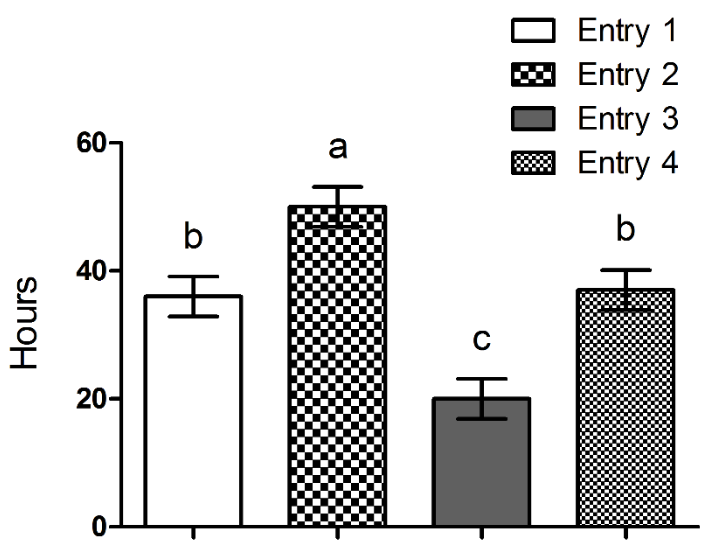

Figure 17. Dickinson mean (±S.E.) weeding time (hours) for entry points during 2016 across AMF and tillage treatments. Entry effect is shown by bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD.

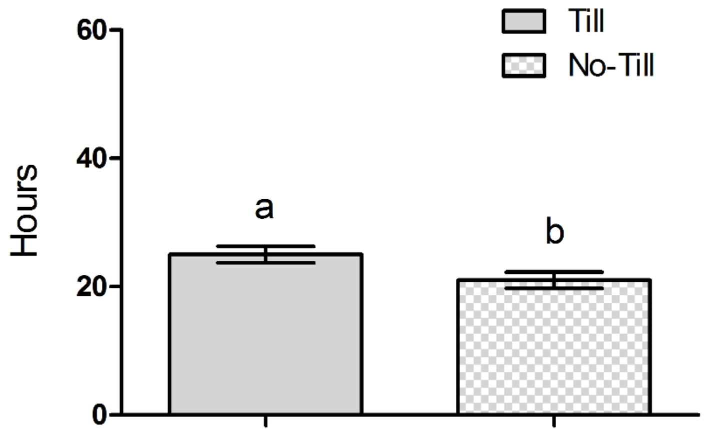

Figure 18. Dickinson mean (±S.E.) weeding time (hours) for tillage treatments across 2015 and 2016, AMF and entry treatments. Entry effect is shown by bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD.

Table 11. Treatment Effects on Weeding Time at Dickinson during 2017.

Effect	P
Tillage	0.4420
AMF	0.8824
Tillage * AMF	0.3305
Entry	<0.0001
Tillage * Entry	0.6602
AMF * Entry	0.5972
Tillage * AMF * Entry	0.3385

At Dickinson, a crop failure in 2017 resulted in a separate analysis for crop entries 2 and 4 only. During 2017, an entry effect was present for weeding times (Table 11) ($p < 0.0001$). Entry 2 (squash) required less weeding time than entry 4 (onion) (10 vs. 35 hours, respectively) (Table 11) ($p < 0.0001$) (Figure 19). Weeding hours were not affected by tillage or AMF treatment ($p = 0.4420$ and $p = 0.8824$, respectively).

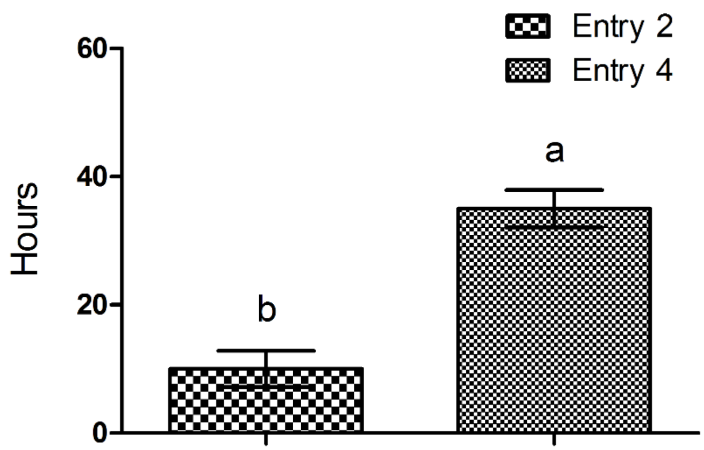

Figure 19. Dickinson mean (±S.E.) weeding time (hours) for entry points during 2017 across AMF and tillage treatments. Entry effect is shown by bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD.

Overall, fewer hours were required to hand weed mulched no-till treatments compared to tilled treatments at both Absaraka and Dickinson (Figure 15 and Figure 18). During 2016 at Absaraka, squash crop (crop entry 3) required less weeding time compared to any other crop entry (Figure 13). During 2017 at Absaraka, squash (crop entry 2) required less weeding time compared to pea (crop entry 3) (Figure 14). During 2015 and 2016 at Dickinson, squash (crop entry 4 and 3, respectively) consistently required less weeding time compared to any other crop (Figure 16 and 17). During 2017 at Dickinson, crop failure resulted in comparison of only two crops, where squash (entry 2) required less weeding time than onion (entry 4) (Figure 19). Similarly, in an experiment comparing stale seedbed to rolled-crimped rye mulch, Forcella et al. (2015) observed hand weeding time to be greatly reduced within rye mulched treatments for cucumber, pumpkin (*Cucurbita maxima*), and watermelon (*Citrullus lanatus*) crops compared to stale seedbed (tilled) treatments (11 ± 6.2 h ha^{-1} vs. 82 ± 3.8 h ha^{-1}, 5 ± 2.8 h ha^{-1} vs. 85 ± 5.9 h ha^{-1}, and 18 ± 7.6 h ha^{-1} vs. 84 ± 6.7 h ha^{-1}, respectively).

Soil Quality Indices

Physical

<u>Aggregate Stability</u>

Table 12. Treatment Effects on Aggregate Stability at Absaraka.

Effect	P
Year	0.0006
Tillage	<0.0001
Year * Tillage	<0.0001
AMF	0.4432
Year * AMF	0.8906
Tillage * AMF	0.9117
Year * Tillage * AMF	0.8230
Entry	0.0441
Year * Entry	0.8073
Tillage * Entry	0.0085
Year * Tillage * Entry	0.0703
AMF * Entry	0.8219
Year * AMF * Entry	0.9554
Tillage * AMF * Entry	0.8336
Year * Tillage * AMF * Entry	0.9238

At Absaraka, a tillage x entry interaction was observed (Table 12) (p = 0.0085). Entry 1 was associated with greater aggregate stability than entry 4 within mulched no-till treatments (11 vs. 7.5 % aggregates 30g soil^{-1}, respectively) (p = 0.0013) (Figure 20). No differences were observed for aggregate stability between entry points within tilled treatments (Figure 21). Regarding the tillage effect within entry point, mulched no-till treatments were associated with greater aggregate stability compared to tilled treatments within entry point 1 (11 vs. 9 % aggregates 30g soil^{-1}, respectively) (p <0.0001) and entry 3 (8 vs. 5 % aggregates 30g soil^{-1}) (p = 0.0076) (Figure 22). Within entries 2 and 4, aggregate stability did not differ between mulched no-till and tilled plots (p = 0.1955 and p = 0.7543, respectively) (Figure 22).

A year x tillage interaction was also observed to influence aggregate stability (Table 12) ($p < 0.0001$). Aggregate stability in tilled treatments decreased from 2015 to 2017 (9 vs. 5 % aggregates 30 g soil^{-1}, respectively) ($p < 0.0001$), whereas within mulched plots, aggregate stability did not change over time ($p = 0.4690$) (Figure 23). No differences in aggregate stability were observed between tillage treatments in 2015 ($p = 0.7660$); however, during 2017 mulched no-till plots were associated with greater aggregate stability compared to tilled plots ($p < 0.0001$) (Figure 23). Aggregate stability was not influenced by AMF inoculation ($p = 0.4432$).

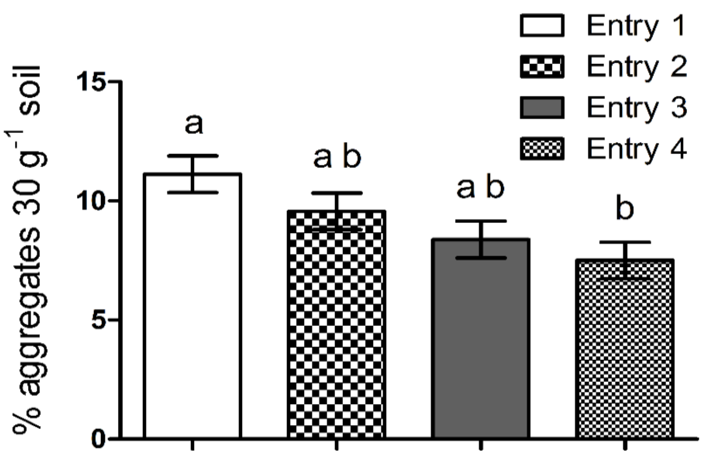

Figure 20. Absaraka mean (±S.E.) % aggregate stability (% 0.25-2.0 mm aggregates 30 g^{-1} soil) for entry within mulched no-till treatments across year. Entry effect within tillage is shown by bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD.

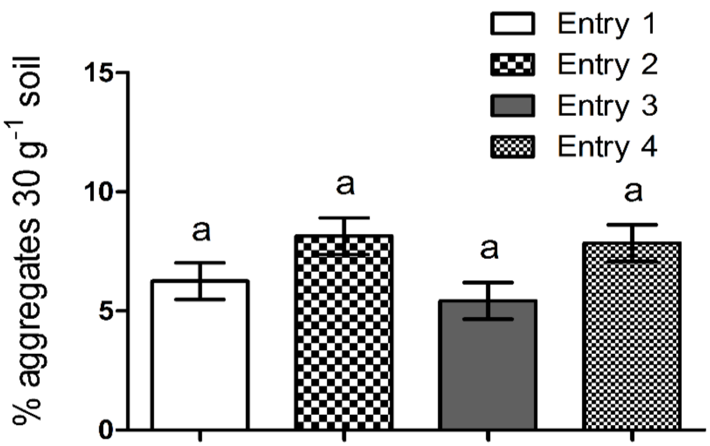

Figure 21. Absaraka mean (±S.E.) % aggregate stability (% 0.25-2.0 mm aggregates 30 g^{-1} soil) for entry within tilled treatments across year. Entry effect within tillage is shown by bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD.

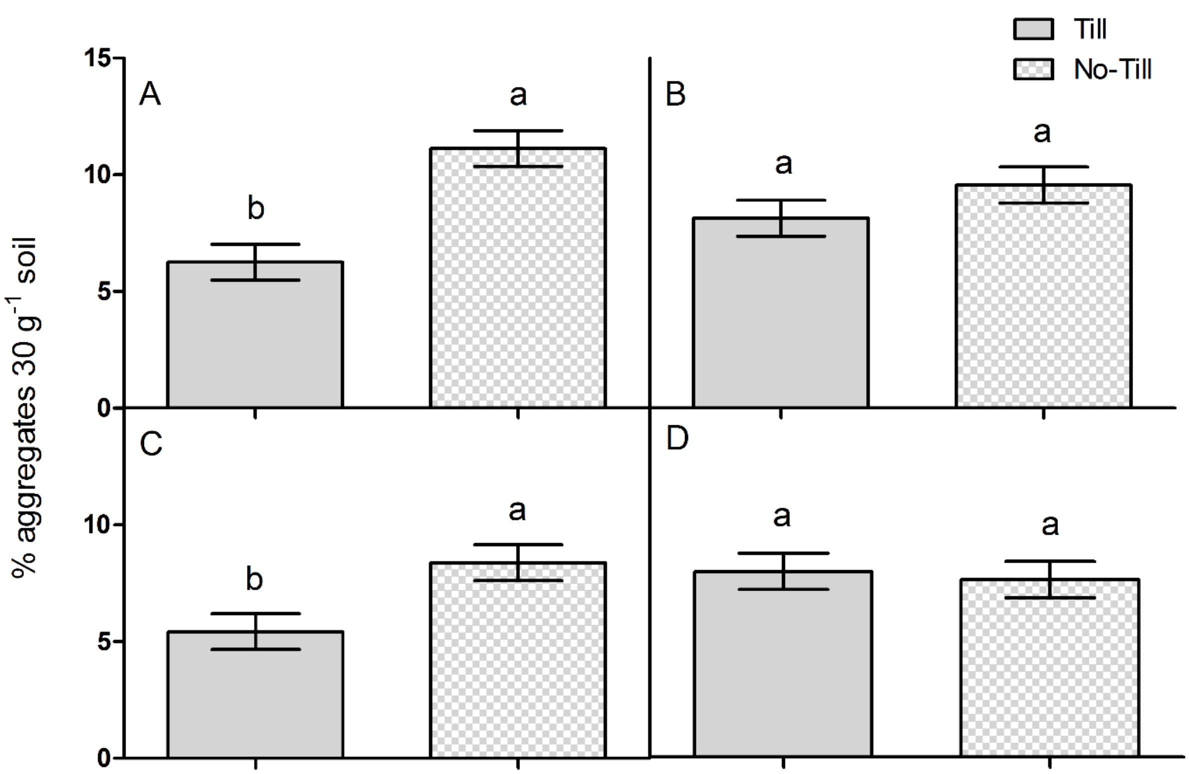

Figure 22. Absaraka mean (±S.E.) % aggregate stability (% 0.25-2.0 mm aggregates 30 g^{-1} soil) for entry between tillage interactions. A) Entry 1, B) Entry 2, C), Entry 3, and D) Entry 4. Entry effect within tillage is shown by bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD.

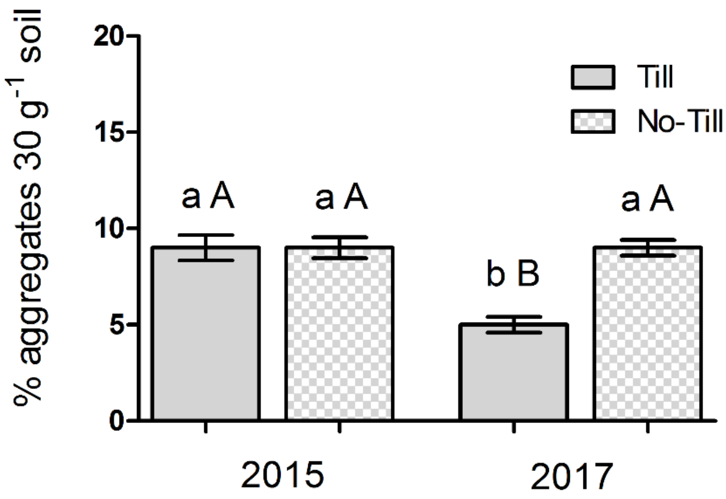

Figure 23. Absaraka mean (±S.E.) % aggregate stability (% 0.25-2.0 mm aggregates 30 g^{-1} soil) for tillage between years. Tillage effect within year is shown by bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD. The simple effect of year within tillage is shown by bars labeled with different uppercase letters differ ($P \leq 0.05$) according to Tukey's HSD.

Table 13. Treatment Effects on Aggregate Stability at Dickinson.

Effect	P
Year	<0.0001
Tillage	0.2426
Year * Tillage	0.0007
AMF	0.9610
Year * AMF	0.4147
Tillage * AMF	0.6258
Year * Tillage * AMF	0.9416
Entry	0.1089
Year * Entry	0.0738
Tillage * Entry	0.0015
Year * Tillage * Entry	0.5083
AMF * Entry	0.7307
Year * AMF * Entry	0.3587
Tillage * AMF * Entry	0.0898
Year * Tillage * AMF * Entry	0.6564

At Dickinson, a tillage x entry interaction was observed to influence aggregate stability (Table 13) (p = 0.0015). Within mulched no-till plots, entry 2 was associated with greater aggregate stability than entry 1 (15 vs. 12 % aggregates 30 g^{-1} soil, respectively) (p = 0.0078), but no differences were observed between entries 1 and 3 (p = 0.1775), entries 1 and 4 (p = 0.8489), entries 2 and 3 (p = 0.1767), entries 2 and 4 (p = 0.0131), or entries 3 and 4 (p = 0.2460) (Figure 24). Within tilled treatments, entry 1 was associated with greater aggregate stability than entry 3 and 4 (17 vs. 13 and 17 vs. 13% aggregates 30 g^{-1} soil, respectively) (p = 0.0019 and p = 0.0031, respectively), but was no different from entry 2 (p = 0.0102) (Figure 25). Entries 3 and 4 were also no different (p = 0.8644) (Figure 25).

Between tillage treatments, entry 1 was associated with greater aggregate stability within tilled treatments than in mulch no-till treatments (17 vs. 12% aggregates 30 g^{-1} soil, respectively) (p = 0.0002) (Figure 26). No differences between tillage treatments were observed for entry 2 (p = 0.1442), entry 3 (p = 0.4903), or entry 4 (p = 0.5197) (Figure 26)

A year x tillage interaction was observed to influence aggregate stability at Dickinson (Table 13) (p = 0.0007). Within tilled plots, aggregate stability increased from 2015 to 2017 (13 vs. 15% aggregates 30g^{-1} soil, respectively) (p = 0.0238) (Figure 27). Similar to tilled treatments, mulched no-till treatments increased in aggregate stability from 2015 to 2017 (10 vs. 17 % aggregates 30g^{-1} soil, respectively) (p < 0.0001) (Figure 27). While aggregate stability increased over time for both tillage treatments, the effect was more pronounced within the mulch no-till treatment, which is the source of the interaction.

Differences between tillage treatments in 2015 were observed between mulched no-till and tilled treatments (13 vs. 10% aggregates 30g^{-1} soil, respectively) (p = 0.0014), but not during

2017 (p = 0.1057) (Figure 27). Aggregate stability was not influenced by AMF inoculation

(Table 13) (p = 0.9610).

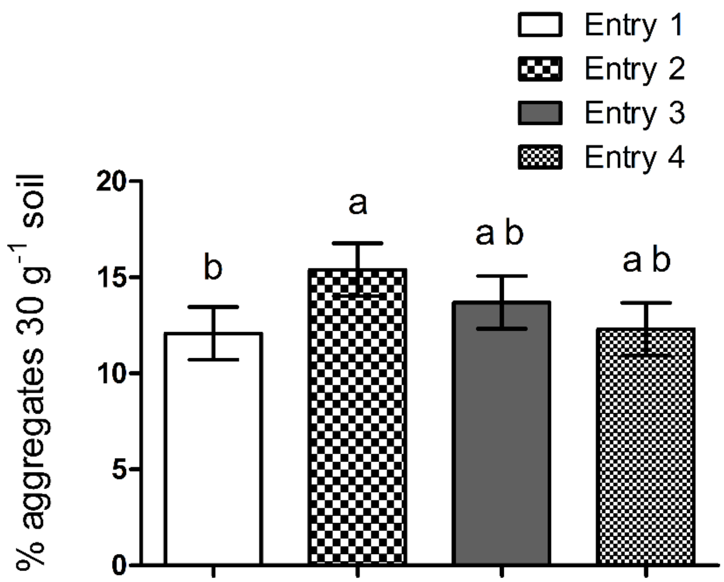

Figure 24. Dickinson mean (±S.E.) % aggregate stability (% 0.25-2.0 mm aggregates 30 g^{-1} soil) for entry within mulched no-till treatments. Entry effect within tillage is shown by bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD.

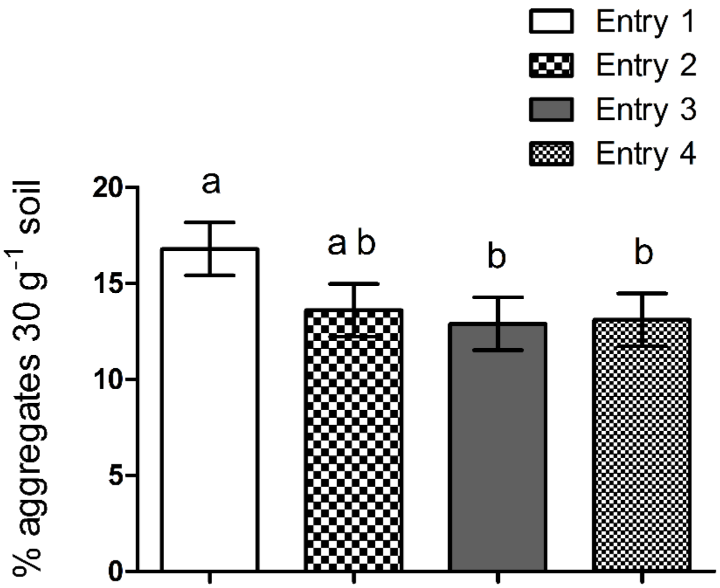

Figure 25. Dickinson mean (±S.E.) % aggregate stability (% 0.25-2.0 mm aggregates 30 g^{-1} soil) for entry within tilled treatments. Entry effect within tillage is shown by bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD.

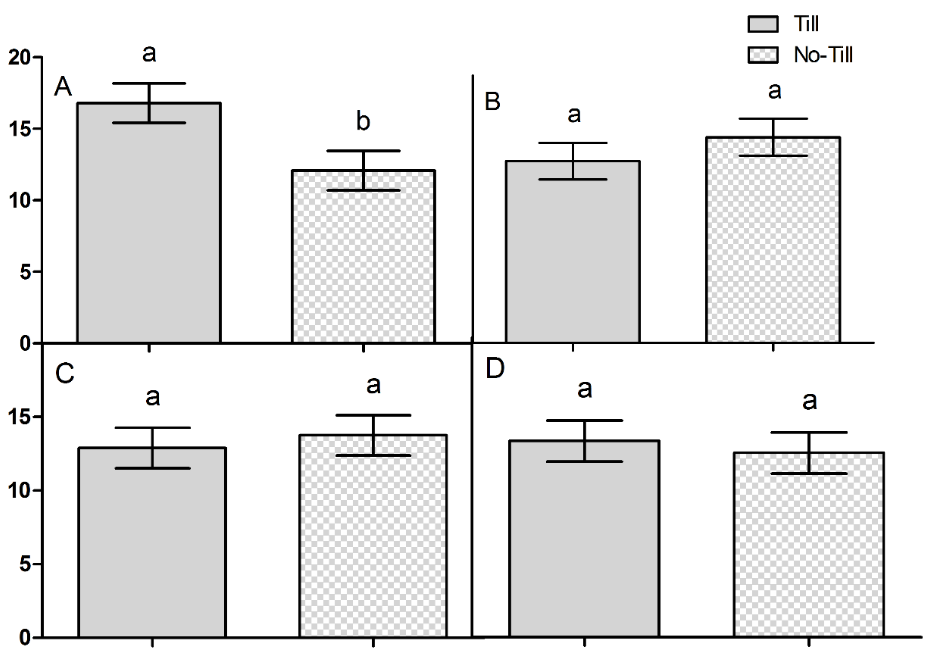

Figure 26. Dickinson mean (±S.E.) % aggregate stability (% 0.25-2.0 mm aggregates 30 g^{-1} soil) for entry between tillage interactions. A) Entry 1, B) Entry 2, C), Entry 3, and D) Entry 4. Entry effect within tillage is shown by bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD.

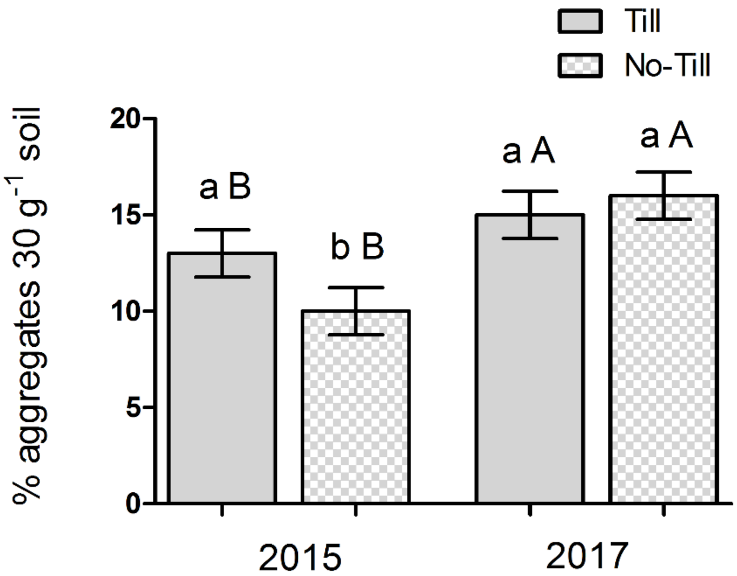

Figure 27. Dickinson mean (±S.E.) % aggregate stability (% 0.25-2.0 mm aggregates 30 g^{-1} soil) for year x tillage interactions. Tillage effect within year is shown by bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD. The simple effect of year within tillage is shown by bars labeled with different uppercase letters differ ($P \leq 0.05$) according to Tukey's HSD.

Our findings are consistent with studies of Martínez et al. (2008), Shukla et al. (2003), Rhoton et al. (2002), and Pieper et al. (2015), with the exception that aggregate stability increased over time regardless of tillage treatment. The depth of sampling may have had an influence on treatment effects. We choose one sampling depth of 0-15.2 cm, whereas Rhoton et al. (2002) sampled at varying depths including: 0-1, 1-3, 3-7.6, and 7.6-15.2 cm. Rhoton et al. (2002) observed no differences between aggregate stability of no-till at soil depths of 3-7.6 and 7.6-15.2 cm vs. tilled treatment depths of 0-1, 1-3, 3-7.6, and 7.6-15.2 cm. Martínez et al. (2008) sampled at depths of 0-2, 2-5, and 5-15 cm and tillage treatments were establish 4 and 7 years before measurements were collected. Shukla et al. (2003) observed aggregate stability to be greater in no-till treatments at depths of 0-10 and 10-20 cm compared to conventionally tilled treatments. Soil disturbances may cause reductions in soil organic matter by reducing aggregate stability and rate of aggregate formation, influencing turn over time of macro-aggregates, and increasing decomposition rates of soil organic matter (Six et al., 1999).

Chemical

<u>Nitrogen</u>

Table 14. Treatment Effects on Soil NO_3-N at Absaraka.

Effect	P
Year	<0.0001
Tillage	<0.0001
Year * Tillage	0.0006
AMF	0.3024
Year * AMF	0.8710
Tillage * AMF	0.1608
Year * Tillage * AMF	0.2505

At Absaraka, an interaction was present between year and tillage (Table 14) ($p = 0.0006$). NO_3-N declined over time for both tillage treatments, but remained greater for no-till treatments than tilled treatments during 2015, 2016, and 2017 (92 vs. 35, 63 vs. 47, and 51 vs. 23 kg ha^{-1}, respectively) ($p < 0.0001$, $p = 0.0141$, and $p = 0.0003$, respectively) (Figure 28). For year within tillage, tilled treatments were marginally no different between 2015 and 2016 (35 vs. 47 kg ha^{-1}) ($p = 0.0620$) or 2015 and 2017 (35 vs. 23 kg ha^{-1}) ($p = 0.0561$), but differences were observed between 2016 and 2017 (47 vs. 23 kg ha^{-1}) ($p = 0.0010$) (Figure 28). For year within tillage, mulched no-till treatments differed between 2015 and 2016 (92 vs. 63kg ha^{-1}, respectively) ($p = 0.0002$) and between 2015 and 2017 (92 vs. 51 kg ha^{-1}, respectively) ($p < 0.0001$), but differences between 2016 and 2017 were marginally insignificant (63 vs. 51 kg ha^{-1}, respectively) ($p = 0.0524$) (Figure 28). Soil NO_3-N was not influenced by AMF inoculation (Table 14) ($p = 0.3024$).

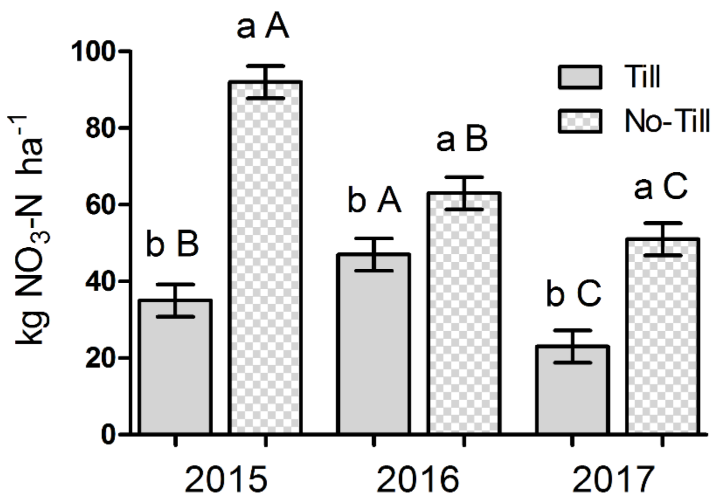

Figure 28. Absaraka mean (±S.E.) NO_3-N (kg ha^{-1}) for tilled and mulched no-till treatments during 2015, 2016, and 2017. Tillage effect within year is shown by bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD. The simple effect of year within tillage is shown by bars labeled with different uppercase letters differ ($P \leq 0.05$) according to Tukey's HSD.

Table 15. Treatment Effects on Soil NO_3-N at Dickinson.

Effect	P
Year	0.0002
Tillage	<0.0001
Year * Tillage	<0.0001
AMF	0.4999
Year * AMF	0.5429
Tillage * AMF	0.5739
Year * Tillage * AMF	0.7947

At Dickinson, a year x tillage interaction was observed (Table 15) ($p < 0.0001$). Soil NO_3-N declined over time within tilled treatments, with 2015 differing between 2016 (37 vs. 22 kg ha^{-1}, respectively) ($p = 0.0034$) and between 2015 and 2017 (37 vs. 16 kg ha^{-1}, respectively) ($p < 0.0001$), but not between 2016 and 2017 ($p = 0.2432$) (Figure 29). Soil NO_3-N decreased within mulched no-till treatments between 2015 and 2016 (49 vs. 35 kg ha^{-1}, respectively) ($p = 0.0047$) then increased between 2016 and 2017 (35 vs. 63 kg ha^{-1}, respectively) ($p < 0.0001$)

(Figure 29). Soil NO_3-N levels also differed between 2015 and 2017 (49 vs. 63 kg ha^{-1}, respectively) (p = 0.0086) (Figure 29).

For tillage within year, mulched no-till plots contained more soil NO_3-N than tilled treatments during 2015, 2016, and 2017 (49 vs. 37 kg ha^{-1}, 35 vs. 22 kg ha^{-1}, and 63 vs. 16 kg ha^{-1}, respectively) (p = 0.0145, p = 0.0107, and p < 0.0001, respectively) (Figure 29). Within tilled treatments, NO_3-N decreased each year, whereas within no-till treatments, NO_3-N decreased between the first and second year (2015 to 2016), then increased between the second and third year (2016 to 2017). Soil NO_3-N was not influenced by AMF inoculation (Table 15) (p = 0.4999).

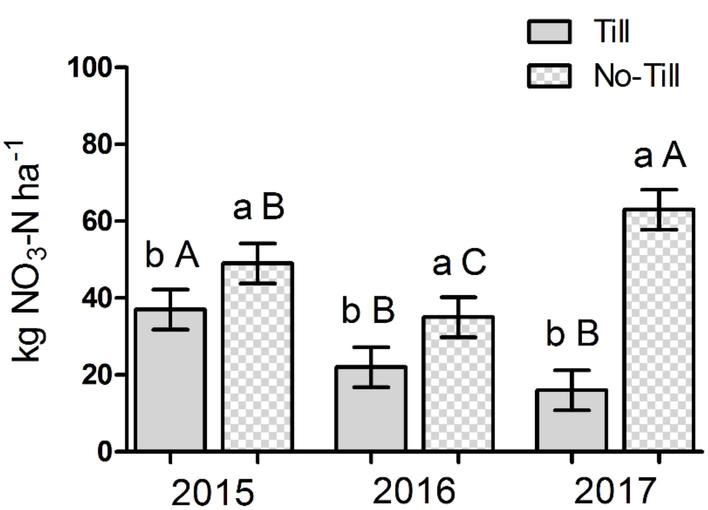

Figure 29. Dickinson mean (±S.E.) NO_3-N (kg ha^{-1}) for tilled and mulched no-till treatments during 2015, 2016, and 2017. Tillage effect within year is shown by bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD. The simple effect of year within tillage is shown by bars labeled with different uppercase letters differ ($P \leq 0.05$) according to Tukey's HSD.

These results are similar to that of Wang et al. (2011), in which a 15 year treatment tillage and input study found that both no-till with conventional inputs and no-till with organic inputs were associated with increased soil organic N compared to tilled with conventional inputs and tilled with organic inputs by an average of 85.5% and 26%, respectively. Rasse et al. (1999)

observed two years of applied alfalfa shoot mulch to contribute 590 kg N ha^{-1} (NH_4-N and NO_3-N) when applied at rates of 16,400 kg ha^{-1}. Efficiencies of plant uptake of soil N are attributed to the volatile nature of N (Crews and Peoples, 2005). A high C:N ratio associated with plant mulch or crop residue can cause the immobilization of nitrogen, and a low C:N can more easily provide nitrogen to a system. Mature alfalfa hay contains a carbon to nitrogen ratio (C:N) of approximately 25:1, which is an ideal ratio for soil microorganisms and results in a temporary surplus of mineralized nitrogen (USDA-NRCS, 2011).

Phosphorus

Table 16. Treatment Effects on Soil Phosphorus at Absaraka.

Effect	P
Year	<0.0001
Tillage	<0.0001
Year * Tillage	<0.0001
AMF	0.8885
Year * AMF	0.6026
Tillage * AMF	0.1297
Year * Tillage * AMF	0.7446

At Absaraka, a year x tillage interaction was observed (Table 16) ($p < 0.0001$). Soil phosphorus (P) did not differ between mulched no-till and tilled treatments during 2015 (p = 0.6490), but did differ during 2016 (17 vs. 7 mg kg^{-1} soil, respectively) ($p < 0.0001$) and 2017 (23 vs. 6 mg kg^{-1} soil, respectively) ($p < 0.0001$) (Figure 30). Tilled treatments did not differ between 2015 and 2016, 2015 and 2017, or 2016 and 2017 ($p = 0.4794$, $p = 0.2313$, and $p = 0.6091$, respectively) (Figure 30). Mulched no-till treatments increased in soil P between 2015 and 2016, 2015 and 2017, and 2016 and 2017 (8 vs. 17 mg kg^{-1} soil, 8 vs. 23 mg kg^{-1} soil, and 17 vs. 23 mg kg^{-1} soil, respectively) ($p = 0.0001$, $p < 0.0001$, and $p < 0.0001$, respectively) (Figure 30). Soil P was not influenced by AMF inoculation (Table 16) ($p = 0.8885$).

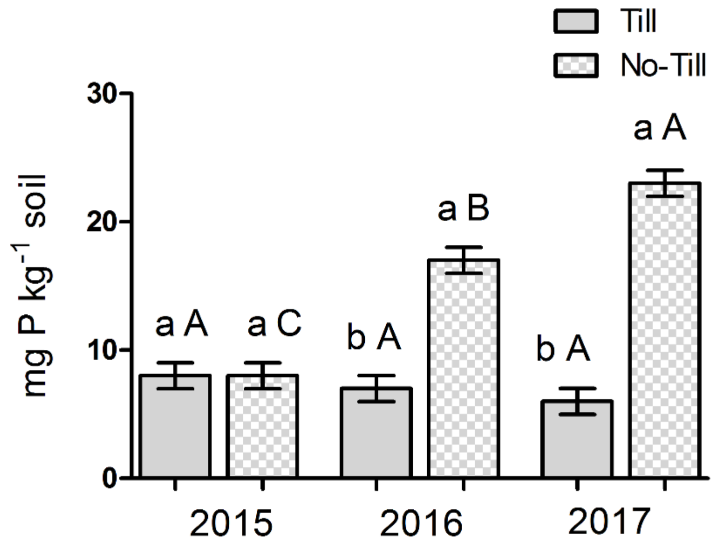

Figure 30. Absaraka mean (±S.E.) phosphorus (mg kg^{-1}) for tilled and mulched no-till treatments during 2015, 2016, and 2017. Tillage effect within year is shown by bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD. The simple effect of year within tillage is shown by bars labeled with different uppercase letters differ ($P \leq 0.05$) according to Tukey's HSD.

Table 17. Treatment Effects on Soil Phosphorus at Dickinson.

Effect	P
Year	0.2881
Tillage	0.9512
Year * Tillage	0.1324
AMF	0.3773
Year * A.MF	0.2797
Tillage * AMF	0.1734
Year * Tillage * AMF	0.3287

At Dickinson, soil phosphorus did not differ by year (Table 17) ($p = 0.2881$) or AMF ($p = 0.3773$) (Figure 31). Soil P levels did not differ between tillage treatments (21 vs. 21 mg kg^{-1} soil, respectively) ($p = 0.9512$) (Figure 31). The simple main effect of AMF did not impact soil P (Table 17) ($p = 0.3773$).

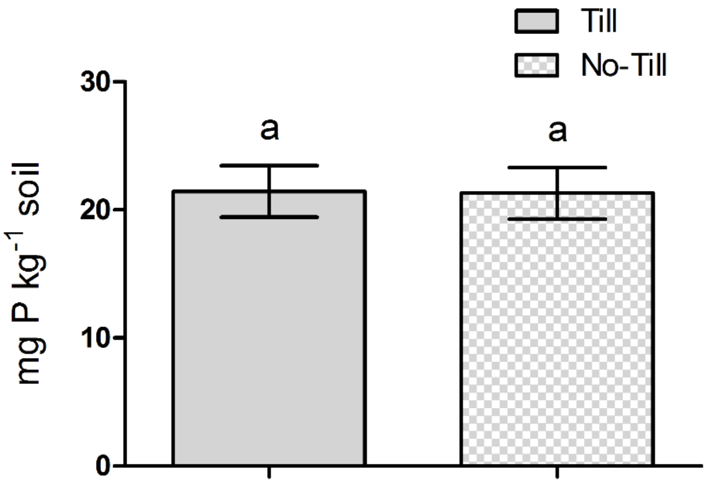

Figure 31. Dickinson mean (±S.E.) phosphorus (mg kg^{-1}) for tilled and mulched no-till treatments across years, entry, and AMF. Tillage effect is shown by bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD.

Similar to our observations at Absaraka, Duiker and Beegle (2006) found after 25 years of continuous treatments of no-till, moldboard plow/disking, and chisel plow/disking, extractable soil phosphorus was greater at shallow depths (0-15 cm) for no-till treatments and chisel plow/disking compared to moldboard plowing/disking. At Dickinson, soil P levels were considered very high for snap peas (21+ mg kg^{-1} soil) and medium-high for beets, squash, and onion (21-30 mg kg^{-1} soil).

Our results at Absaraka show increases in available P over time, cautioning that long term no-till practices have been found to increase dissolved phosphorus loss via surface runoff (as more soil phosphorus accumulates in shallow depths along with saturated sorption of soil P) as well as through subsurface leaching (Jarvie et al., 2017). Loss of soil P under no-till practices is further compounded by macropore development from conservation tillage and tile drainage (Jarvie et al., 2017). Phosphorus loading of surface water contributes to eutrophication, causing water quality declines that negatively affect coastal, lacustrine, and riverine communities, and potentiate toxic algal blooms that can influence human health (Kleinman et al., 2011). Therefore, considerations should be made choosing management practices to conserve soil P as well as sourcing and timing application of fertilizer (Kleinman et al., 2009).

Potassium

Table 18. Treatment Effects on Soil Potassium at Absaraka.

Effect	P
Year	0.0003
Tillage	<0.0001
Year * Tillage	<0.0001
AMF	0.9633
Year * AMF	0.9701
Tillage * AMF	0.1650
Year * Tillage * AMF	0.3495

At Absaraka, a year x tillage interaction was observed (Table 18) ($p < 0.0001$). Soil potassium (K) differed between mulched no-till and tilled treatments, where mulched no-till treatments were associated with greater soil K than tilled treatments during 2015, 2016, and 2017 (174 vs. 127 mg kg^{-1} soil, 289 vs. 92 mg kg^{-1} soil and 351 vs. 99 mg kg^{-1} soil, respectively) (p = 0.0263, $p < 0.0001$, and $p < 0.0001$, respectively) (Figure 32). Soil potassium did not differ between years for tilled treatments ($p = 0.1981$). Differences were observed for mulched no-till treatments ($p < 0.0001$), where soil K differed between 2015 and 2016 (174 vs. 289 mg kg^{-1} soil, respectively ($p < 0.0001$), 2015 and 2017 (174 vs. 351 mg kg^{-1} soil, respectively) ($p < 0.0001$) (Figure 32). Soil K levels between 2016 and 2017 were marginally insignificant (p = 0.0054) (Figure 32). The simple main effect of AMF did not impact soil K (Table 18) ($p = 0.9633$).

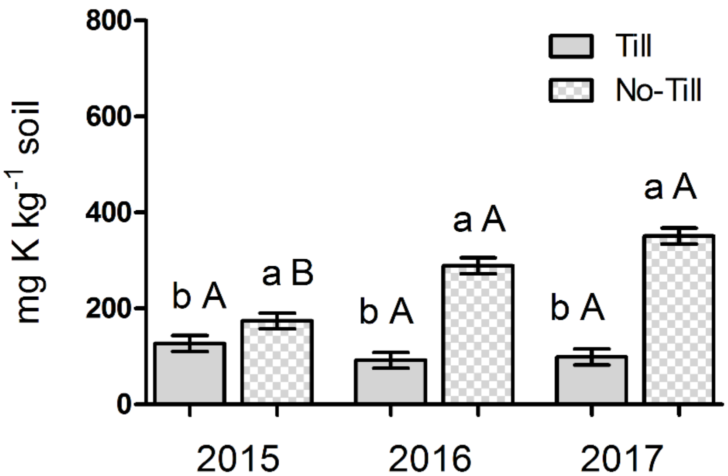

Figure 32. Absaraka mean (±S.E.) Potassium (mg kg^{-1}) for year by tillage treatment interactions. Bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD. Bars Tillage effect within year is shown by bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD. The simple effect of year within tillage is shown by bars labeled with different uppercase letters differ ($P \leq 0.05$) according to Tukey's HSD.

Table 19. Treatment Effects on Soil Potassium at Dickinson.

Effect	P
Year	<0.0001
Tillage	<0.0001
Year * Tillage	<0.0001
AMF	0.9182
Year * AMF	0.8768
Tillage * AMF	0.0935
Year * Tillage * AMF	0.7977

At Dickinson, a year x tillage interaction was observed (Table 19) ($p < 0.0001$). Soil K did not differ between mulched no-till and tilled treatments during 2015 ($p = 0.0848$) (Figure 33). During 2016 and 2017, mulched no-till treatments were associated with greater soil K than tilled treatments (334 vs. 272 mg kg^{-1} soil and 577 vs. 333 mg kg^{-1} soil, respectively) ($p = 0.0058$ and $p < 0.0001$) (Figure 33). Soil K differed between years within tillage, where mulched no-till was different between 2015 and 2016, 2015 and 2017, and 2016 and 2017 (450 vs. 334 mg kg^{-1}

soil, 450 vs. 577 mg kg^{-1} soil, and 334 vs. 577 mg kg^{-1} soil , respectively) ($p < 0.0001$, $p < 0.0001$, and $p < 0.0001$, respectively) (Figure 33). A similar pattern was observed for tilled treatments, where soil K levels differed between 2015 and 2016, 2015 and 2017, and 2016 and 2017 (411 vs. 272 mg kg^{-1} soil, 411 vs. 333 mg kg^{-1} soil, and 272 vs. 411 mg kg^{-1} soil, respectively) ($p < 0.0001$, $p = 0.0005$, and $p = 0.0070$, respectively) (Figure 33). The simple main effect of AMF did not impact soil K (Table 19) ($p = 0.9182$).

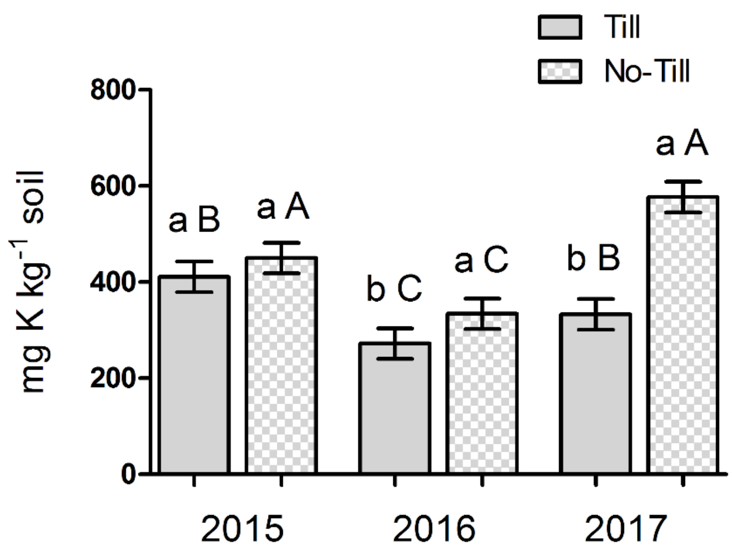

Figure 33. Dickinson mean (±S.E.) potassium (mg kg^{-1}) tilled and mulched no-till treatments during 2015, 2016, and 2017. Tillage effect within year is shown by bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD. The simple effect of year within tillage is shown by bars labeled with different uppercase letters differ ($P \leq 0.05$) according to Tukey's HSD.

Soil potassium levels at the Absaraka site within mulched no-till plots were well above levels considered very high (161+ mg kg^{-1} soil) and tilled treatments were within the medium-high range (81-120 mg kg^{-1} soil) from the University of Minnesota Extension vegetable production guide (Rosen and Eliason, 2005), whereas at Dickinson soil P values were well above recommendations regardless of tillage treatment. An analysis of alfalfa grown in Manitoba, Canada was found to contain an average 223 kg ha^{-1} of potassium per year (Wiens et al., 2006).

Although our experiment site at Dickinson did not receive alfalfa mulch, the initial average within the tilled plots were 411 mg kg^{-1} soil, which is considered very high (161+ mg kg^{-1}) according to the University of Minnesota Nutrient Management for Commercial Fruit and Vegetable Crops in Minnesota Guide (Rosen and Eliason, 2005). Both mulched no-till and tilled treatments were above the very high level during 2017.

Soil Organic Matter

Table 20. Treatment Effects on Soil Organic Matter at Absaraka.

Effect	P
Year	0.0020
Tillage	0.0675
Year * Tillage	0.0541
AMF	0.7776
Year * AMF	0.7510
Tillage * AMF	0.0118
Year * Tillage * AMF	0.0710

At Absaraka, a tillage x AMF interaction was observed (Table 20) ($p = 0.0118$) for soil organic matter. In the absence of AMF inoculant, no-till treatments had greater organic matter than in tilled treatments (2.3 vs. 2.2 % organic matter, respectively) ($p = 0.0043$) (Figure 34.). In the presence of AMF inoculant, no differences were observed in organic matter % between no-till and tilled treatments ($p = 0.8725$) (Figure 34). The year x tillage interaction was marginally insignificant ($p = 0.0541$). The simple main effect of AMF did not impact soil organic matter (Table 20) ($p = 0.7776$).

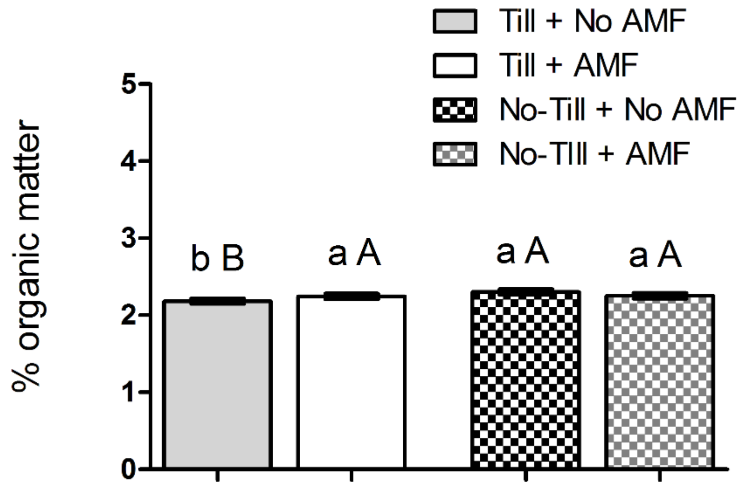

Figure 34. Absaraka mean (±S.E.) % organic matter for each pairwise combination of tillage and AMF treatments. AMF effect within tillage is shown by bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD.

Table 21. Treatment Effects on Soil Organic Matter at Dickinson.

Effect	P
Year	<0.0001
Tillage	0.0379
Year * Tillage	0.1684
AMF	0.6817
Year * AMF	0.7683
Tillage * AMF	0.2641
Year * Tillage * AMF	0.8106

At Dickinson, a tillage effect was observed, in which mulched no-till treatments had slightly greater soil organic matter than tilled treatments (Table 21) (3.8 vs. 3.7%, respectively) ($p = 0.0379$) (Figure 35). The simple main effect of AMF did not impact soil organic matter (Table 21) ($p = 0.6817$).

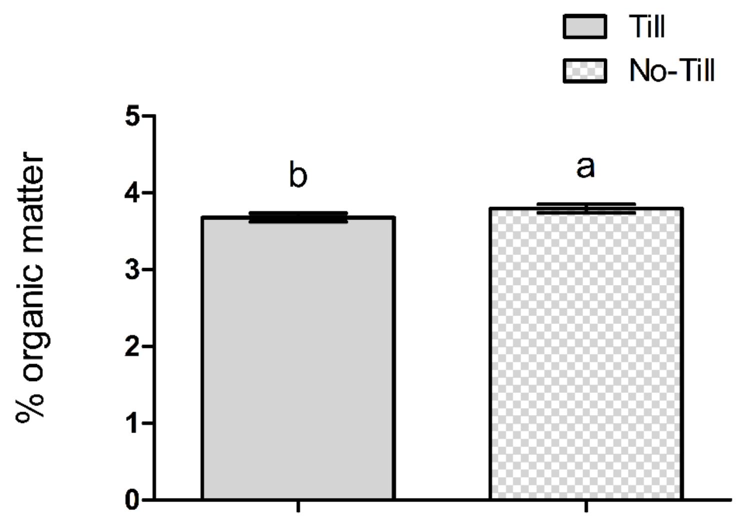

Figure 35. Dickinson mean (±S.E.) % organic matter for tilled and mulched no-till treatments. Bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD.

At Absaraka, tilled treatments without AMF were associated with slightly less soil organic matter than tilled treatments with AMF inoculant. No-till practices that utilize mulch are considered to physically protect the soil and therefore are considered to contribute to the physical protection of soil organic matter, as microaggregate disruption is decreased (Balesdent et al., 2000).

According to Rosen and Eliason (2005), soils with organic matter less than 3.1% are considered low, soils with organic matter between 3.1 and 4.5% are considered medium, and soils with organic matter greater than 4.5% are considered high. Soil organic matter at Absaraka is therefore considered low, regardless of tillage treatment effects, and soil organic matter at Dickinson would be considered medium, regardless of tillage treatment.

One reason why our results were not as pronounced might be the relatively short length of time our treatments were in place coupled with initial soil conditions or soil types. Carter (1992) found that after 3-5 years of no-till drilling, 10-17% increases in organic matter were observed at 0-5 cm depths. Smith (2004) modeled soil organic matter accumulation and observed that detection of differences of 3% would require 5 years and 30% of a carbon input relative to soil carbon levels at initial experiment start. Fungi have been observed to have higher carbon assimilation efficiencies than bacteria (Holland and Coleman, 1987); therefore, compositions of soil biota communities may be important in predicating accumulation and losses of soil organic matter (Beare et al., 1994).

Active Carbon

Table 22. Treatment Effects on Active Carbon at Absaraka.

Effect	P
Year	0.4890
Tillage	0.8247
Year * Tillage	<0.0001
AMF	0.0796
Year * AMF	0.1290
Tillage * AMF	0.1572
Year * Tillage * AMF	0.0404
Entry	0.6560
Year * Entry	0.4805
Tillage * Entry	0.5854
Year * Tillage * Entry	0.8877
AMF * Entry	0.6130
Year * AMF * Entry	0.4046
Tillage * AMF * Entry	0.2265
Year * Tillage * AMF * Entry	0.5759

At Absaraka, a year x tillage x AMF interaction was observed (Table 22) (p = 0.0404). During 2015, active carbon (AC) was greater within tilled treatments with AMF than with no AMF (418 vs. 350 mg carbon kg^{-1} soil, respectively) (p = 0.0128) and tilled treatments overall were greater in AC than in mulched no-till treatments (418 and 350 vs. 303 and 305 mg carbon kg^{-1} soil, respectively) (Figure 36). Conversely in 2017, mulched no-till treatments were associated with greater active carbon with AMF and without AMF treatments compared to tilled treatments with AMF and without AMF (377 vs. 300 and 368 vs. 304 mg carbon kg^{-1} soil, respectively) ($P = 0.0088$ and $p = 0.0217$, respectively) (Figure 37). The simple main effect of entry did not impact AC (Table 22) ($p = 0.6560$).

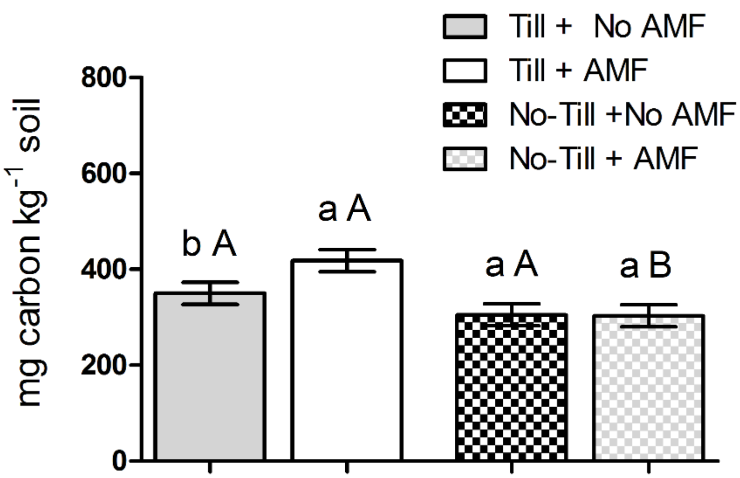

Figure 36. 2015 Absaraka mean (±S.E.) active carbon (mg carbon kg^{-1} soil) for each pairwise combination of tillage and AMF treatments during 2015. Bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD.

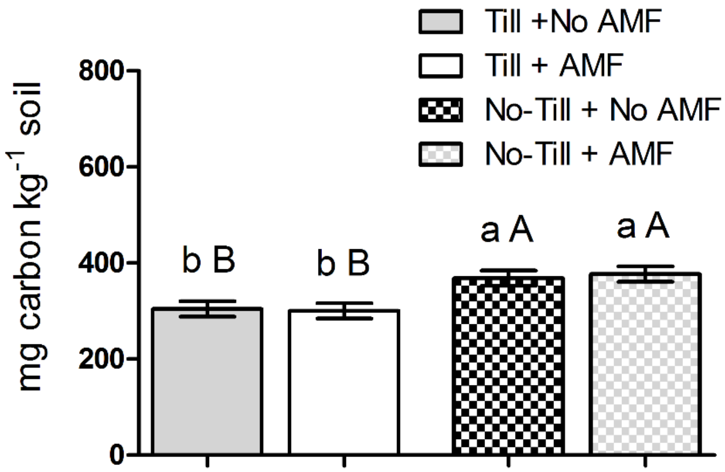

Figure 37. 2017 Absaraka mean (±S.E.) active carbon (mg carbon kg^{-1} soil) for each pairwise combination of tillage and AMF treatments during 2017. Bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD.

Table 23. Treatment Effects on Active Carbon at Dickinson.

Effect	P
Year	<0.0001
Tillage	0.1272
Year * Tillage	0.4461
AMF	0.1017
Year * AMF	0.1302
Tillage * AMF	0.0696
Year * Tillage * AMF	0.1968
Entry	0.7863
Year * Entry	0.6677
Tillage * Entry	0.9485
Year * Tillage * Entry	0.5719
AMF * Entry	0.5910
Year * AMF * Entry	0.7942
Tillage * AMF * Entry	0.6026
Year * Tillage * AMF * Entry	0.7715

At Dickinson, a tillage x AMF interaction was marginally insignificant ($p = 0.0696$) and a year effect was observed ($p < 0.0001$) (Table 23). AC declined over time regardless of tillage or AMF treatments (580 vs. 377 mg carbon kg^{-1} soil) (Figure 38). The simple main effect of entry did not impact AC (Table 23) (p = 0.7863).

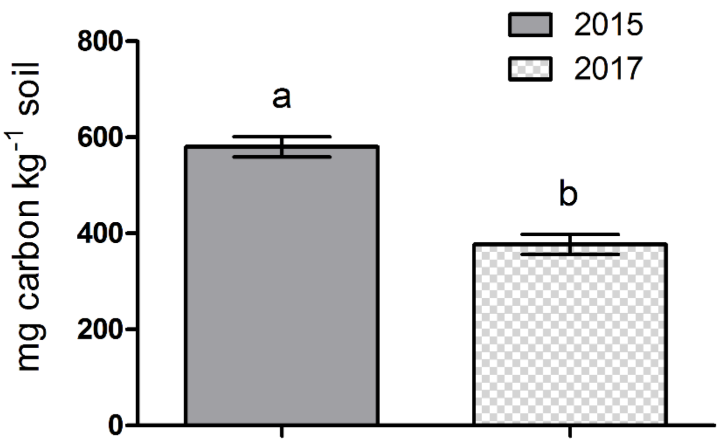

Figure 38. 2017 Dickinson mean (±S.E.) active carbon (mg carbon kg^{-1} soil) by year. Bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD.

Pools of SOM that are the most biologically active and have relatively short turnover times, are defined as 'labile' (McLauchlan and Hobbie, 2004). Labile pools are fractions that influence nutrient cycles from biological activity as sources of microbial energy (Weil et al., 2003). AC is a small fraction within the labile pool, is related to the productivity of ecosystems, and has been proposed as a particularly useful measure of soil quality under arid conditions (Oyonarte et al., 2007). Labile pools, such as AC can indicate changes provoked by soil use, as changes in quantities are more readily observed (Oyonarte et al., 2007). Soil organic carbon is often more uniform in vertical distribution within moldboard plow/disking practices, while no-till systems typically have greater percentages of soil organic carbon within the soil's surface (0-15 cm) (Duiker and Beegle, 2006; Gál et al., 2007). Our results from Absaraka align with findings of Pieper at al. (2015) who found that reduced tillage with the addition of perennial mulch (fall disked, rye planted, mowed and rototilled in spring) and strip tillage (fall disked and rye planted, spring roller-crimped rye) resulted in greater active soil carbon than conventionally tilled (Fall disked and rye planted, moldboard plow followed by disking in Spring) treatments.

Biological

Soil Respiration

Table 24. Treatment Effects on Soil Respiration at Absaraka.

Effect	P
Year	<0.0001
Tillage	<0.0001
Year * Tillage	<0.0001
AMF	0.1303
Year * AMF	0.6039
Tillage * AMF	0.9177
Year * Tillage * AMF	0.2523
Entry	0.3141
Year * Entry	0.0028
Tillage * Entry	0.1546
Year * Tillage * Entry	0.5847
AMF * Entry	0.8722
Year * AMF * Entry	0.6244
Tillage * AMF * Entry	0.6406
Year * Tillage * AMF * Entry	0.8762

At Absaraka, a year x entry interaction was observed (Table 24) (p =0.0028). During 2015, entry 1 differed from entry 4 (0.59 vs. 0.53, respectively) (p = 0.0012) but was no different from entries 2 and 3 (p = 0.3896 and p = 0.0094, respectively) (Figure 39). No differences were observed between entries 2 and 3, entries 2 and 4, or entries 3 and 4 (p = 0.0774, p = 0.0154, and p = 0.4963, respectively) (Figure 39).

During 2017, no significant interactions were observed between entries 1 and 2, entries 1 and 3, entries 1 and 4, entries 2 and 3, entries 2 and 4, or entries 3 and 4 (p = 0.4348, p = 0.8954, p = 0.2032, p = 0.3619, p = 0.0416, and p = 0.2533, respectively) (Figure 40).

A year x tillage interaction was observed ($p < 0.0001$) (Table 24) During 2015, mulched no-till treatments were associated with greater soil respiration compared to tilled treatments (0.57 vs. 0.54 mg CO_2 g^{-1} soil, respectively) ($p = 0.0071$) (Figure 41). During 2017, soil respiration decreased from 2015 within tilled treatment by 55% (0.30 vs. 0.54 mg CO_2 g^{-1} soil, respectively) ($p < 0.0001$) (Figure 41). No between year differences were observed for no-till treatments (p = 0.8917). The simple main effect of AMF did not impact soil respiration (Table 41) ($p = 0.1303$).

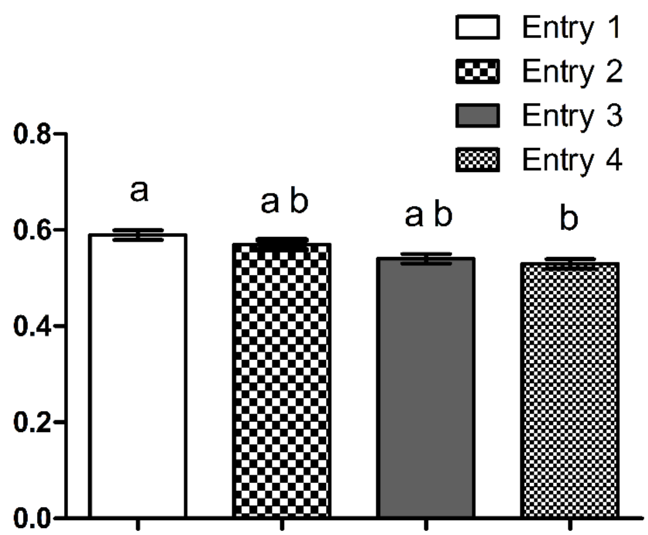

Figure 39. Absaraka mean (±S.E.) soil respiration (mg CO_2 g^{-1} soil) during 2015 by entry. Bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD.

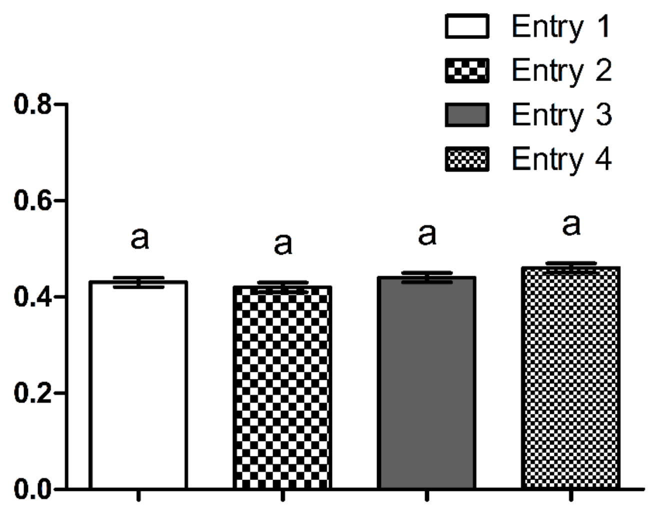

Figure 40. Absaraka mean (±S.E.) soil respiration (mg CO_2 g^{-1} soil) during 2017 by entry. Bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD.

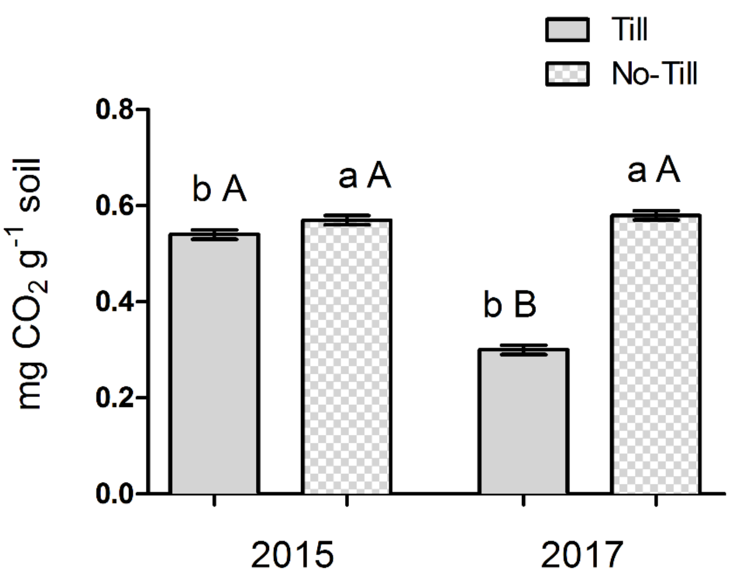

Figure 41. Absaraka mean (±S.E.) soil respiration (mg CO_2 g^{-1} soil) for year by tillage treatment interactions. Bars labeled with different lowercase letters between tillage within year differ (P ≤ 0.05) according to Tukey's HSD. Bars labeled with different uppercase letters between year within tillage differ ($P \leq 0.05$) according to Tukey's HSD.

Table 25. Treatment Effects on Soil Respiration at Dickinson.

Effect	P
Year	<0.0001
Tillage	<0.0001
Year * Tillage	<0.0001
AMF	0.6898
Year * AMF	0.6872
Tillage * AMF	0.1594
Year * Tillage * AMF	0.4848
Entry	0.7432
Year * Entry	0.2191
Tillage * Entry	0.0792
Year * Tillage * Entry	0.2642
AMF * Entry	0.9455
Year * AMF * Entry	0.6560
Tillage * AMF * Entry	0.9567
Year * Tillage * AMF * Entry	0.7123

At Dickinson, a year x tillage interaction was observed (Table 25) ($p < 0.0001$). During 2015, soil respiration did not differ between tillage treatments ($p = 0.7783$) (Figure 42). During 2017, soil respiration was greater in mulched no-till than in tilled treatments plots (0.68 vs. 0.38 mg CO_2 g^{-1} soil, respectively) ($p < 0.0001$) (Figure 42). Soil respiration did not differ between 2015 and 2017 for tilled treatments ($p = 0.6371$), mulched no-till was greater in 2017 than in 2015 (0.68 vs. 0.40 mg CO_2 g^{-1} soil, respectively) ($p < 0.0001$) (Figure 42). The simple main effect of AMF did not impact soil respiration (Table 25) ($p = 0.6898$).

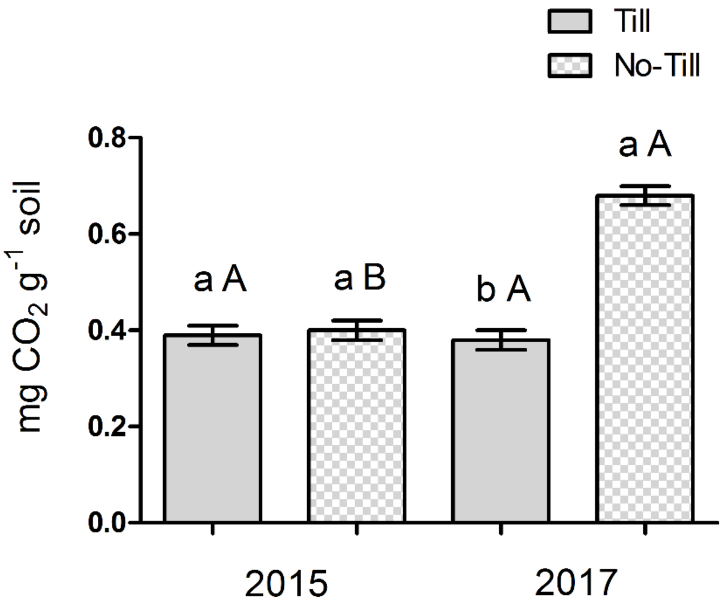

Figure 42. Dickinson mean (±S.E.) soil respiration (mg CO_2 g^{-1} soil) for year by tillage treatment interactions. Bars labeled with different lowercase letters between tillage within year differ ($P \leq 0.05$) according to Tukey's HSD. Bars labeled with different uppercase letters between year within tillage differ ($P \leq 0.05$) according to Tukey's HSD.

According to the Cornell Soil Health Manual Series, a soil respiration measurement of 0.5 mg CO_2 g^{-1} soil has rates 40 on a scale of 0 to100, and thus is on the lower end of average. Rates of respiration at 0.6 mg CO_2 g^{-1} soil is at a rating of 60 of 100, which is considered to be on the higher end of average. Karlen et al. (1994) found similar results within a twelve-year continuous corn system, wherein no-till treatments were observed to have greater rates of soil respiration than a two-year moldboard plot treatment (352 vs. 74 mg CO_2 kg^{-1} soil, respectively).

Potential issues arise from measuring soil respiration in laboratory settings as opposed to field settings. The lack of standardized operating procedures across soil types and the variability within protocols coupled with variability of results calls for discretion when interpreting mineralizable C analyses (Haney et al., 2008; Wade et al., 2018). Sources of variation include sieve sizes, incubation intervals, and direction and volume of water applied in rewetting. Sample collection timing in relation to other field operations is important to note. For example, CO_2

bursts are often observed immediately following tillage (Calderón et al., 2001, 2000; Calderón and Jackson, 2002; Ellert and Janzen, 1999; Glenn et al., 2011). Calderón et al. (2000) and Calderón et al. (2001) attributed short-lived decreases in respiration following soil disturbances such as tillage to stress on microbial communities and changes in soil structure.

In an experiment performed by Glenn et al. (2011), reduced tillage (light, single pass of chisel-plow) resulted in twice the level of soil respiration as an intensive tillage (chisel-plow followed with disk harrow, at a 20 cm depth), and significantly more aboveground and belowground biomass. Campbell et al. (1991) observed during a crop rotation and residue management study that microbial respiration increased (especially at 7.5-15 cm depths) as frequency of crop rotations and inclusion of leguminous green manure and hay (90/10 alfalfa-brome mix) increased. Although respiration was observed to slightly decrease over three years at Absaraka, the noted decrease in soil respiration within tilled treatments may be of more biological significance, as rating in tilled plots went from a lower-range of average to a rating considered poor. Conversely, observations at Dickinson noted an increase in soil respiration over three years of continuous mulch no-till treatments, while no differences were observed within the tilled treatments between years.

Microbial Biomass

Table 26. Treatment Effects on Microbial Biomass at Absaraka.

Effect	P
Year	0.0235
Tillage	0.0008
Year * Tillage	0.0094
AMF	0.7407
Year * AMF	0.4141
Tillage * AMF	0.1541
Year * Tillage * AMF	0.7371
Entry	0.0059
Year * Entry	<0.0001
Tillage * Entry	0.1378
Year * Tillage * Entry	0.9618
AMF * Entry	0.7185
Year * AMF * Entry	0.5506
Tillage * AMF * Entry	0.6403
Year * Tillage * AMF * Entry	0.6115

Table 27. Treatment Effects on Microbial Diversity at Absaraka.

Effect	P
Year	0.5894
Tillage	0.9016
Year * Tillage	0.6044
AMF	0.7721
Year * AMF	0.2410
Tillage * AMF	0.1644
Year * Tillage * AMF	0.8712
Entry	0.1298
Year * Entry	0.4611
Tillage * Entry	0.1767
Year * Tillage * Entry	0.3576
AMF * Entry	0.4300
Year * AMF * Entry	0.2480
Tillage * AMF * Entry	0.3731
Year * Tillage * AMF * Entry	0.2080

Table 28. Treatment Effects on AMF Biomass at Absaraka.

Effect	P
Year	0.1479
Tillage	<0.0001
Year * Tillage	0.0054
AMF	0.5745
Year * AMF	0.8319
Tillage * AMF	0.0608
Year * Tillage * AMF	0.6379
Entry	0.0162
Year * Entry	0.0017
Tillage * Entry	0.1477
Year * Tillage * Entry	0.0934
AMF * Entry	0.3651
Year * AMF * Entry	0.1206
Tillage * AMF * Entry	0.9356
Year * Tillage * AMF * Entry	0.4810

At Absaraka, a year x entry effect was observed for microbial biomass (MB) ($p < 0.0001$) (Table 26). During 2015 and 2017, there was no differences for MB between entry ($p = 0.6792$ and $p = 0.4588$, respectively). During 2016, entry 1 differed from entry 2 (1685 vs. 2659 ng microbial biomass g^{-1} soil, respectively) ($p = 0.0015$), entry 2 differed from entry 3 and entry 4 (2659 vs. 927 ng microbial biomass g^{-1} soil and 927 vs. 1503 ng microbial biomass g^{-1} soil, respectively) ($p < 0.0001$ and $p = 0.0002$, respectively) (Figure 43). No differences were observed between entries 1 and 3, entries 1 and 4, or entries 3 and 4 ($p = 0.0115$, $p = 0.5311$, and $p = 0.0514$, respectively) (Figure 43).

A year x tillage interaction was observed for microbial biomass (Table 26) ($p = 0.0094$). During 2015 and 2016, no differences were observed for microbial biomass between tillage treatments ($p = 0.4474$ and $p =0.3464$, respectively). During 2017, mulched no-till had greater microbial biomass than tilled treatments (2,385 vs. 1,313 MB ng g^{-1} soil, respectively) (*p* <0.0001) (Figure 44).

No differences were observed between years for entry 1, entry 3, or entry 4 ($p = 0.1841$, $p = 0.024$, and $p = 0.0539$). Entry 2 differed between 2015 and 2016 and between 2016 and 2017 (1322 vs. 2659 ng microbial biomass g^{-1} soil and 2659 vs. 1671 ng microbial biomass g^{-1} soil, respectively) ($p < 0.0001$ and $p = 0.0010$, respectively) (Figure 45). The simple main effect of AMF did not impact microbial biomass (Table 26) (p = 0.7407). Simple effects of tillage, AMF, and entry observed no differences on microbial diversity (Table 27) ($p = 0.9016$, $p = 0.7721$, and $p = 0.1298$, respectively).

A year x entry interaction was observed for AMF biomass (Table 28) ($p = 0.0017$). No differences between entry were observed during 2015 or 2017 (p = 0.3582 and $p = 0.5671$, respectively). During 2016, and entry effect was observed for AMF biomass ($p < 0.0001$), in which entry 1 differed from entry 2 (61 vs. 91 ng AMF biomass g^{-1} soil, respectively) ($p = 0.0015$), entry 1 differed from entry 3 (61 vs. 31 91 ng AMF biomass g^{-1} soil, respectively) ($p = 0.0017$), entry 2 differed from entry 3 (91 vs. 31 91 ng AMF biomass g^{-1} soil, respectively) ($p < 0.0001$), and entry 2 differed from entry 4 (91 vs. 48 91 ng AMF biomass g^{-1} soil, respectively) ($p < 0.0001$) (Figure 46). No differences were observed between entries 1 and 4 or entries 3 and 4 during 2016 ($p = 0.1665$ and $p = 0.0600$, respectively) (Figure 46).

No differences were observed between years for entry 1 ($p = 0.2537$), entry 3 ($p = 0.0228$), or entry 4 ($p = 0.0580$). Entry 2 differed between 2015 and 2016 (60 vs. 91 91 ng AMF biomass g^{-1} soil, respectively) ($p = 0.0031$), but no differences were found between 2015 and 2017 or 2016 and 2017 ($p = 0.5601$ and $p = 0.2044$, respectively) (Figure 47).

A year x tillage interaction for AMF biomass was observed (Table 28) ($p = 0.0054$). No differences between tillage treatments were observed during 2015 or 2016 for AMF biomass ($p = 0.5132$ and $p = 0.1139$, respectively) (Figure 48.). During 2017, mulched no-till had greater AMF biomass than tilled treatments (112 vs. 39 ng AMF biomass g^{-1} soil, respectively) ($p < 0.0001$) (Figure 48). Addition of AMF inoculant did not impact AMF biomass (Table 28) ($p = 0.5745$). No differences were observed between years for tilled treatments ($p = 0.2682$), but differences were observed between years for mulched no-till treatments ($p = 0.0025$). For mulched no-till treatments, no differences were found between 2015 and 2016 ($p = 0.9918$), but were observed between 2015 and 2017 and between 2016 and 2017 (65 vs. 112 ng AMF biomass g^{-1} soil and 65 vs. 112 ng AMF biomass g^{-1} soil, respectively) ($p = 0.0005$ and $p = 0.0004$, respectively) (Figure 49).

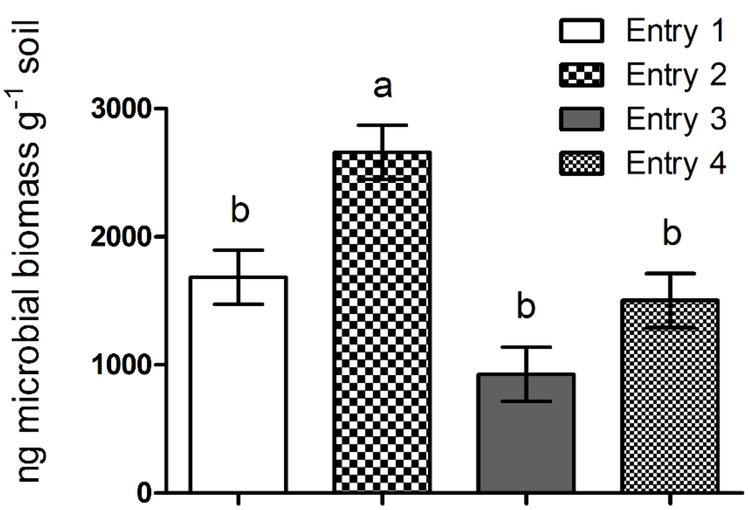

Figure 43. Absaraka mean (±S.E.) total microbial biomass (ng g^{-1} soil) by entry during 2016. Bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD.

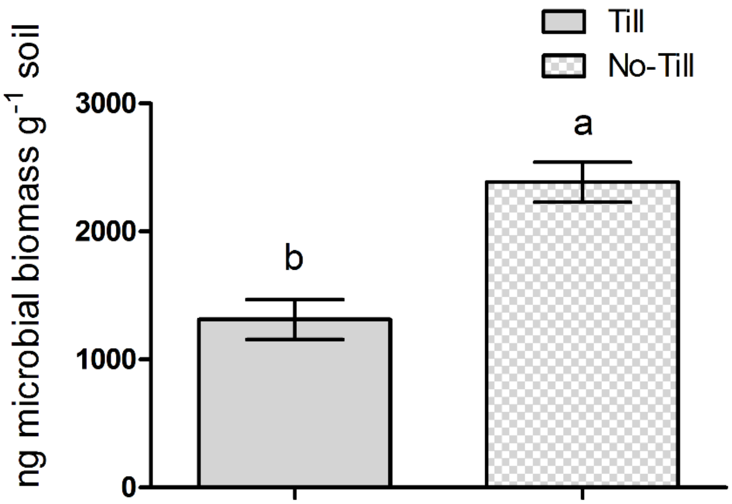

Figure 44. Absaraka mean (±S.E.) total microbial biomass (ng g^{-1} soil) by tillage treatment during 2017. Bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD.

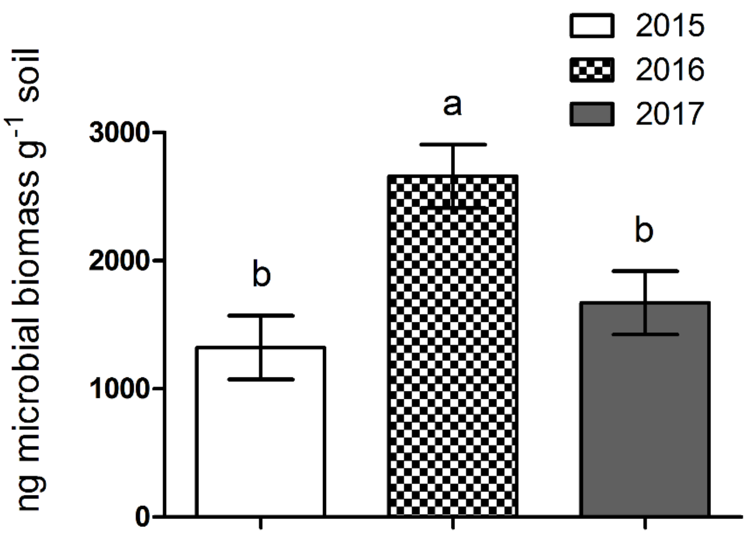

Figure 45. Absaraka mean (±S.E.) total microbial (ng g^{-1} soil) for entry 2 between 2015, 2016, and 2017. Bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD.

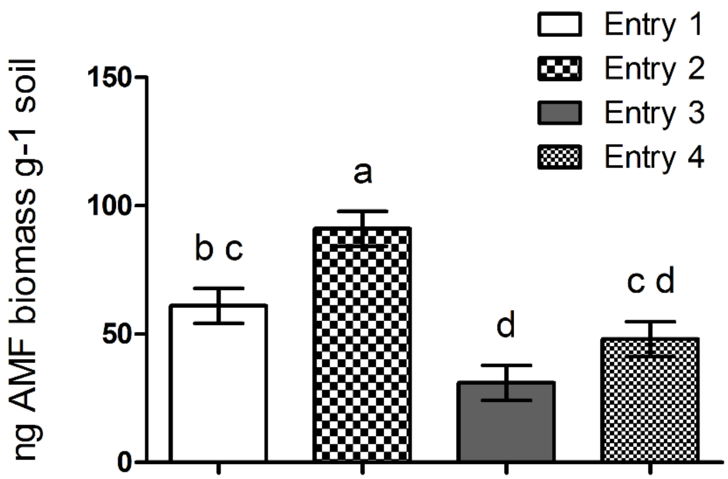

Figure 46. Absaraka mean (±S.E.) total AMF biomass (ng g^{-1} soil) between entries during 2016. Data were pooled across three years. Bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD.

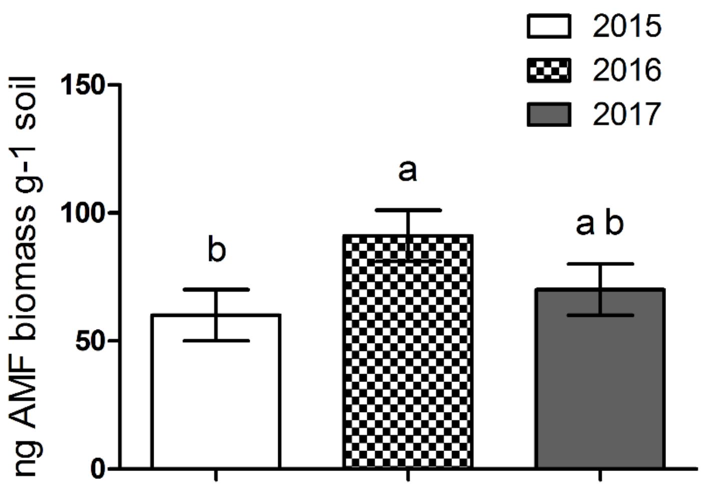

Figure 47. Absaraka mean (±S.E.) total AMF biomass (ng g^{-1} soil) for entry 2 between 2015, 2016, and 2017. Bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD.

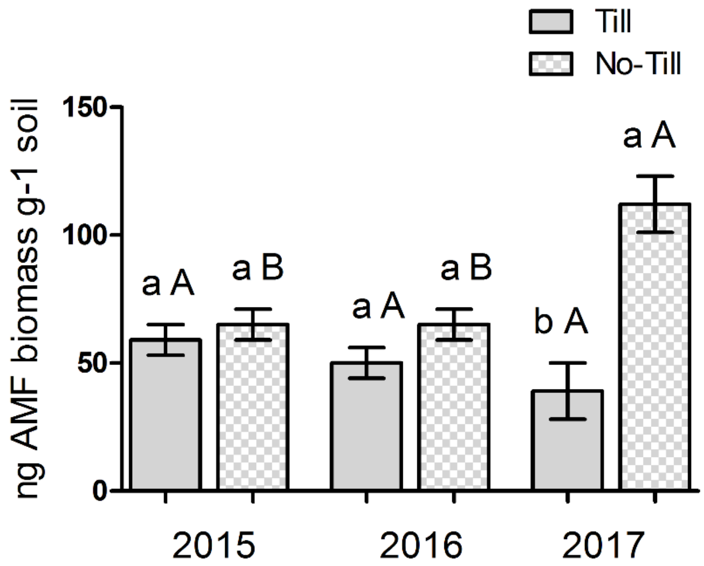

Figure 48. Absaraka mean (±S.E.) total AMF biomass (ng g^{-1} soil) for tillage treatments between years across entry. Bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD.

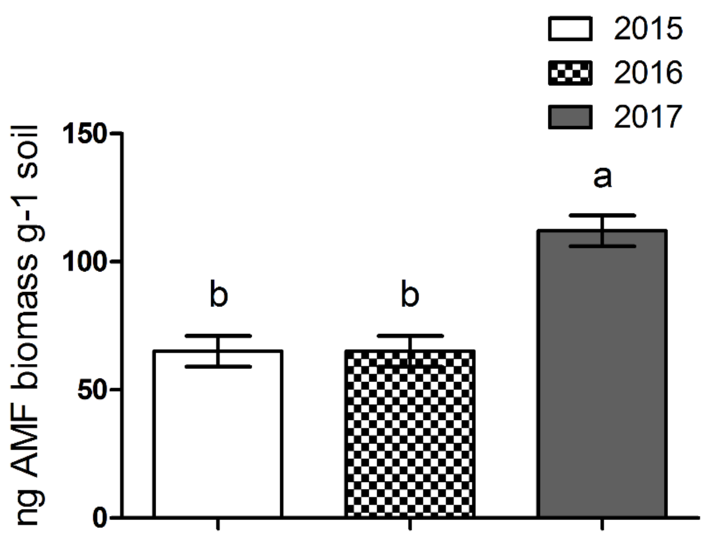

Figure 49. Absaraka mean (±S.E.) total AMF biomass (ng g^{-1} soil) for mulched no-till between 2015, 2016, and 2017. Bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD.

Table 29. Treatment Effects on Microbial Biomass at Dickinson.

Effect	P
Year	0.5749
Tillage	0.0037
Year * Tillage	0.0713
AMF	0.5740
Year * AMF	0.9741
Tillage * AMF	0.2176
Year * Tillage * AMF	0.2703
Entry	0.0864
Year * Entry	0.4233
Tillage * Entry	0.1568
Year * Tillage * Entry	0.9725
AMF * Entry	0.6250
Year * AMF * Entry	0.0524
Tillage * AMF * Entry	0.7371
Year * Tillage * AMF * Entry	0.3310

Table 30. Treatment Effects on Microbial Diversity at Dickinson.

Effect	P
Year	<0.0001
Tillage	0.1647
Year * Tillage	0.0432
AMF	0.9846
Year * AMF	0.9804
Tillage * AMF	0.6799
Year * Tillage * AMF	0.9166
Entry	0.6324
Year * Entry	0.0822
Tillage * Entry	0.0658
Year * Tillage * Entry	0.4641
AMF * Entry	0.3539
Year * AMF * Entry	0.2493
Tillage * AMF * Entry	0.9084
Year * Tillage * AMF * Entry	0.6781

Table 31. Treatment Effects on AMF Biomass at Dickinson.

Effect	P
Year	0.0027
Tillage	0.2544
Year * Tillage	0.0269
AMF	0.7854
Year * AMF	0.9425
Tillage * AMF	0.7904
Year * Tillage * AMF	0.3745
Entry	0.0078
Year * Entry	0.0645
Tillage * Entry	0.0266
Year * Tillage * Entry	0.2560
AMF * Entry	0.6897
Year * AMF * Entry	0.2203
Tillage * AMF * Entry	0.6964
Year * Tillage * AMF * Entry	0.1934

At Dickinson, a simple effect of tillage was observed for MB (Table 29) ($p = 0.0037$). Mulched no-till treatments were associated with greater MB than tilled treatments (1731 vs. 1450 ng microbial biomass g^{-1} soil, respectively) ($p = 0.0037$) (Figure 50).

A year by tillage interaction was observed for microbial diversity (Table 30) ($p = 0.0432$). No differences were observed between tillage treatments within 2015 or 2017 ($p = 0.2186$ and $p = 0.2719$, respectively) (Figure 51). During 2016, differences were found between mulched no-till and tilled treatments, in which mulched no-till treatments were associated with slightly greater microbial diversity than tilled treatments (1.4 vs. 1.3, respectively) ($p = 0.0460$) (Figure 51). Differences were observed for microbial diversity within tilled treatments between years ($p < 0.0001$). Microbial diversity differed within tilled treatments between 2015 and 2016 and between 2015 and 2017 (1.5 vs. 1.3 and 1.5 vs. 1.3, respectively) ($p < 0.0001$ and < 0.0001, respectively), but not between 2016 and 2017 (1.3 vs. 1.3, respectively) ($p = 0.7323$) (Figure 51).

No differences were observed for microbial diversity within mulched no-till treatments between years (Table 30) ($p = 0.0307$). The simple main effect of AMF did not impact MB or microbial diversity (Table 29 and Table 30, respectively) ($p = 0.5740$ and $p = 0.9846$, respectively).

A tillage x entry interaction was found for AMF biomass ($p = 0.0266$) (Table 31). Within tilled treatments, AMF biomass differences were observed between entry ($p = 0.0023$). Differences for AMF biomass were observed between entries 1 and 2 and entries 1 and 3 (41 vs. 18 ng AMF biomass g^{-1} soil and 41 vs. 17 ng AMF biomass g^{-1} soil, respectively) ($p = 0.0011$ and $p = 0.0006$, respectively) (Figure 52). No differences were found between entries 1 and 4, entries 2 and 3, entries 2 and 4, or entries 3 and 4 ($p= 0.0376$, $p = 0.8169$, $p = 0.2016$, and $p = 0.1372$, respectively) (Figure 52). No differences were observed within mulched no-till treatments between entry ($p = 0.1470$). No differences were observed between tillage treatments for entry 1, entry 3, or entry 4 ($p = 0.2988$, $p = 0.1012$, and $p = 0.4153$, respectively). Differences between tillage treatments within entry 2 were observed, in which mulched no-till treatments were associated with greater AMF biomass than within tilled treatments (35 vs. 18 ng AMF biomass g^{-1} soil, respectively) ($p = 0.0113$) (Figure 53).

A year x tillage interaction for AMF biomass was observed (Table 31) ($p = 0.0269$). No difference between tillage treatment was observed during 2015 or 2017 ($p = 0.9930$ and $p = 0.8494$, respectively) (Figure 54.). Tillage treatments differed during 2016, in which mulched no-till treatments were associated with greater AMF biomass (28 vs. 14 ng AMF biomass g^{-1} soil, respectively) ($p = 0.0014$) (Figure 54). No differences were observed for mulched no-till treatments between years ($p = 0.7726$), whereas differences were observed for tilled treatments between years ($p = 0.0002$). Tilled treatments differed between 2015 and 2016 and between 2016 and 2017 (29 vs. 14 ng AMF biomass g^{-1} soil and 14 vs. 34 ng AMF biomass g^{-1} soil, respectively) ($p < 0.0001$ and $p = 0.0052$, respectively) (Figure 55). No differences were observed for tilled treatments between 2015 and 2017 (p = 0.4565). The simple main effect of AMF did not impact AMF biomass ($p = 0.7854$) (Table 31).

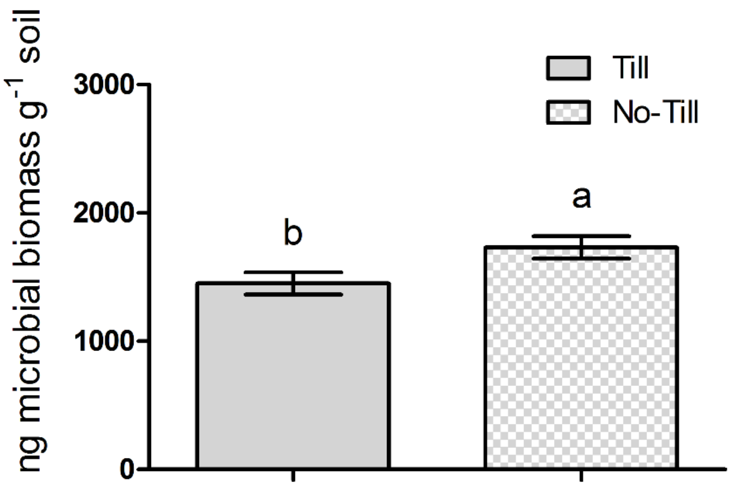

Figure 50. Dickinson mean (±S.E.) total microbial biomass (ng g^{-1} soil) for tillage treatments. Data were pooled across three years. Bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD.

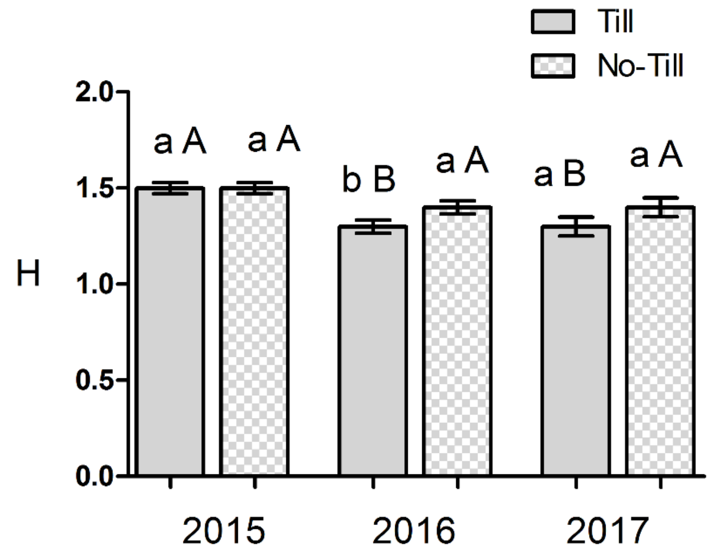

Figure 51. Dickinson mean (±S.E.) microbial diversity as affected by year and tillage treatments. Bars labeled with different lowercase letters differ within year between tillage treatments ($P \leq 0.05$) according to Tukey's HSD. Bars labeled with different uppercase letters differ within tillage between year ($P \leq 0.05$) according to Tukey's HSD.

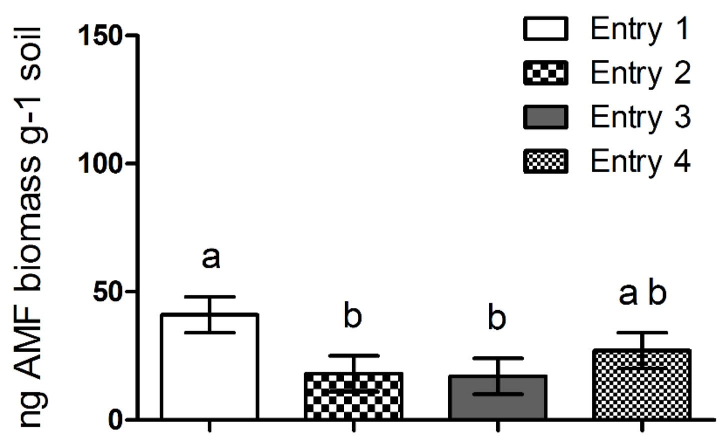

Figure 52. Dickinson mean (±S.E.) AMF biomass (ng g^{-1} soil) as effected by entry within tilled treatments across years. Bars labeled with different lowercase letters differ within entry ($P \leq 0.05$) according to Tukey's HSD.

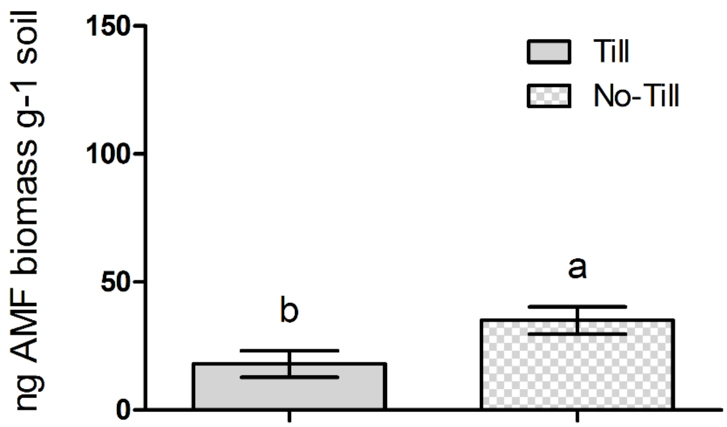

Figure 53. Dickinson mean (±S.E.) AMF biomass (ng g^{-1} soil) between tillage treatments within entry 2 across years. Bars labeled with different lowercase letters differ within entry ($P \leq 0.05$) according to Tukey's HSD.

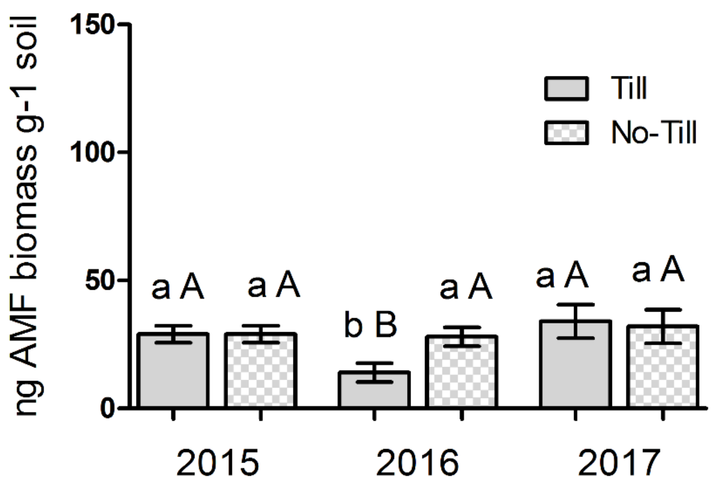

Figure 54. Dickinson mean (±S.E.) AMF biomass (ng g^{-1} soil) between tillage treatments and years across AMF. Bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD.

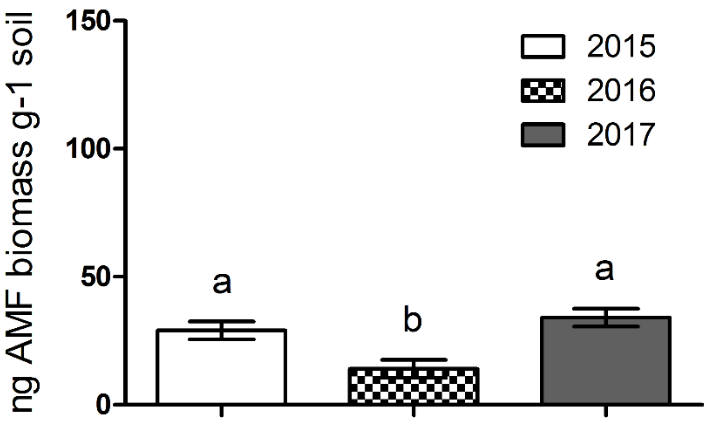

Figure 55. Dickinson mean (±S.E.) AMF biomass (ng g^{-1} soil) between years within tilled treatments. Bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD.

Previous research has shown that soil microbial biomass can be greater in reduced/no-till systems compared to conventional tillage systems (Follett and Schimel, 1989; Liebig et al., 2004; Wang et al., 2011). However, Follett and Schimel (1989) observed no microbial biomass differences between tillage treatment (no-till, stubble mulch, and moldboard plow) and native sod 10 and 36 days after planting on a 16 year wheat-fallow cultivation experiment in Western Nebraska. While tillage treatments differences were only observed during 2017 at Absaraka, microbial biomass at Dickinson was greater overall within mulched no-till treatments compared to tilled treatments.

A study conducted near Mandan, ND found that a continuous crop, no-till system (spring wheat, winter wheat, and sunflower (*Helianthus annuus* L.) was associated with greater soil microbial biomass C after 17 years compared to a crop-fallow, conventional tillage system (spring wheat, fallow) (1010 vs. 424 kg ha^{-1}, respectively) (Liebig et al., 2004). Similarly, Wang et al. (2011) found that after 15 years of continuous tillage and input treatments, no-tillage practices increase microbial biomass C by an average of 101% in conventional input systems and

131% in organic input systems. Sipilä et al. (2012) observed fungal biomass to be greater in shallow soil depths (0-5 cm vs. 10-20 cm) within no-till and when compared to shallow depths under conventionally tilled soils. Overall, our results showed that mulched no-till treatments resulted in greater microbial and AMF biomass.

Arbuscular Mycorrhizal Fungi Colonization

Table 32. Treatment Effects on AMF % Colonization at Absaraka.

Effect	P
Year	<0.0001
Tillage	0.9686
Year * Tillage	0.3486
AMF	0.7931
Year * AMF	0.7314
Tillage * AMF	0.3548
Year * Tillage * AMF	0.8339
Entry	<0.0001
Year * Entry	<0.0001
Tillage * Entry	0.1049
Year * Tillage * Entry	0.9914
AMF * Entry	0.6675
Year * AMF * Entry	0.9762
Tillage * AMF * Entry	0.2327
Year * Tillage * AMF * Entry	0.4851

At Absaraka, a year x entry interaction was observed (Table 32) ($p < 0.0001$). During 2015, differences were observed between entries 1 (pea) and 2 (onion) or between entries 3 (beet) and 4 (squash) (72% vs. 84%, 6%, and 57 %, respectively) ($p = 0.0035$, $p < 0.0001$, and $p = 0.0002$, respectively) (Figure 56). Differences were observed between entries 2 (onion), 3 (beet), and 4 (squash) (84% vs. 6% and 57%, respectively) ($p < 0.0001$ for both comparisons) (Figure 56). Differences were also observed between entries 3 (beet) and 4 (squash) (6% vs. 57%, respectively) ($p < 0.0001$) (Figure 56).

During 2016, differences were observed between entries 1 and 2, entries 2 and 3, and between entries 2 and 4 (65 vs. 2 %, 2 vs. 55%, and 2 vs. 59%, respectively) ($p < 0.0001$ for all three comparisons) (Figure 57). No differences were observed between entries 1 and 3 or 4 ($p = 0.0413$ and $p = 0.1748$, respectively) (Figure 57). No differences were observed between entries 3 and 4 ($p = 0.4700$) (Figure 57).

During 2017, differences were observed between entries 1 and 3 as well as between entries 1 and 4 (6 vs. 37% and 6 vs. 35%, respectively) ($p < 0.0001$ and $p = 0.0002$, respectively) (Figure 58). No differences were observed between entries 1 and 2, entries 2 and 3, entries 2 and 4, or entries 3 and 4 ($p = 0.0099$, $p = 0.0907$, $p = 0.1634$, and $p = 0.7568$, respectively) (Figure 58). The simple main effect of AMF and tillage did not impact AMF % colonization (Table 32) ($p = 0.7931$ and $p = 0.9686$, respectively).

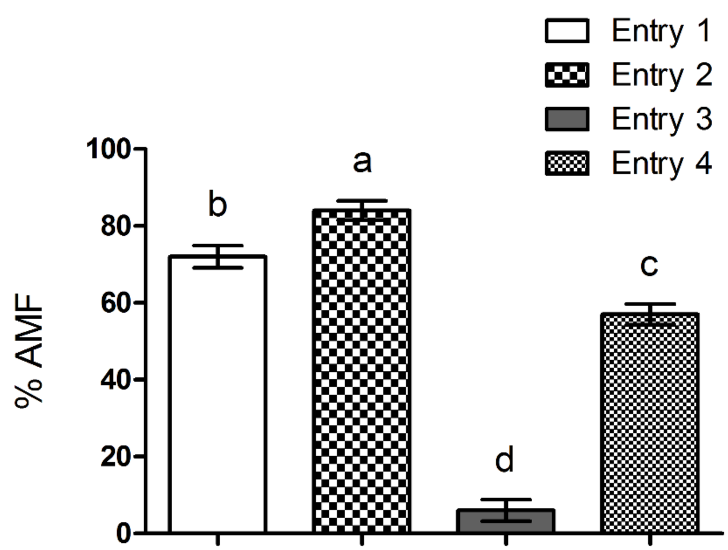

Figure 56. Absaraka mean (±S.E.) AMF colonization (%) between crop entry during 2015 across tillage and AMF treatments. Bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD.

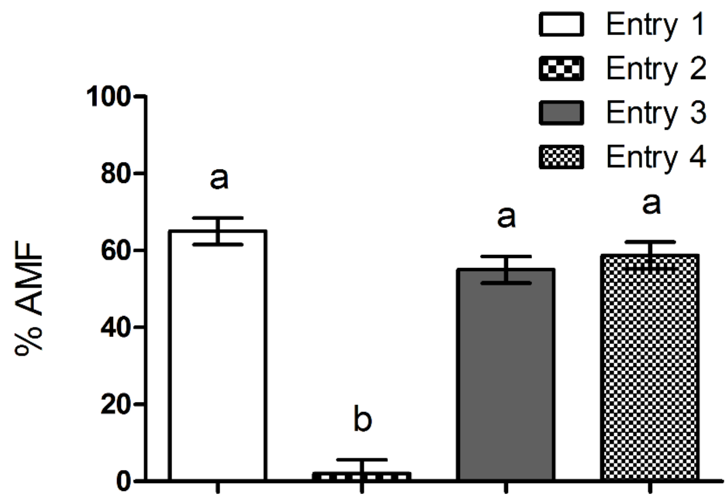

Figure 57. Absaraka mean (±S.E.) AMF colonization (%) between crop entry during 2016 across tillage and AMF treatments. Bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD.

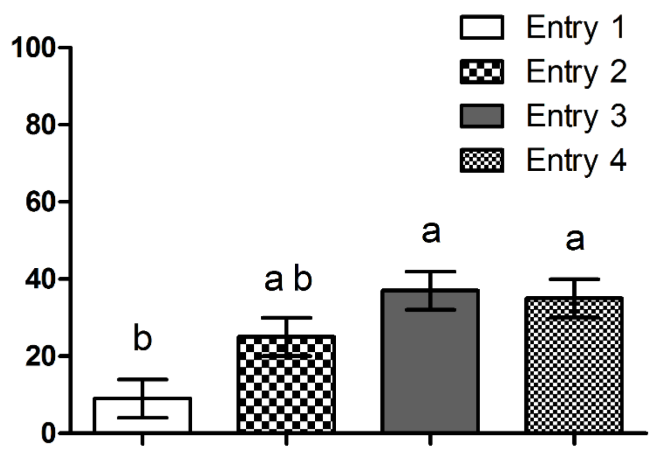

Figure 58. Absaraka mean (±S.E.) AMF colonization (%) between crop entry during 2017 across tillage and AMF treatments. Bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD.

Table 33. Treatment Effects on AMF Colonization for 2015-2016 at Dickinson.

Effect	P
Year	<0.0001
Tillage	0.8901
Year * Tillage	0.2819
AMF	0.9188
Year * AMF	0.2860
Tillage * AMF	0.7654
Year * Tillage * AMF	0.3588
Entry	<0.0001
Year * Entry	<0.0001
Tillage * Entry	0.7372
Year * Tillage * Entry	0.2134
AMF * Entry	0.5617
Year * AMF * Entry	0.0230
Tillage * AMF * Entry	0.8985
Year * Tillage * AMF * Entry	0.6257

At Dickinson, a year x entry effect was observed to influence % AMF colonization for crop roots (Table 33) ($p < 0.0001$). During 2015, differences were observed between entries 1 and 3, entries 2 and 3, and entries 3 and 4 (75 vs. 2%, 76 vs. 2%, and 2 vs. 66%, respectively) ($p < 0.0001$, $p < 0.0001$, and $p < 0.0001$, respectively). No differences were observed between entries 1 and 2, entries 1 and 4, or entries 2 and 4 ($p = 0.9635$, $p = 0.0901$, and $p = 0.0821$, respectively).

During 2016, differences were observed between entries 1 and 2, entries 1 and 3, entries 2 and 3, entries 2 and 4, and entries 3 and 4 (65 vs. 9%, 65 vs. 40%, 9 vs. 40%, 9 vs. 59, and 40 vs. 59%, respectively) ($p < 0.0001$, $p < 0.0001$, $p < 0.0001$, $p < 0.0001$, and $p = 0.0002$, respectively). No differences were observed between entries 1 and 4 ($p = 0.2357$). The simple main effect of AMF and tillage did not affect AMF % colonization (Table 33) ($p = 0.9188$ and $p = 0.8901$, respectively).

Table 34. Treatment Effects on AMF Colonization for 2017 at Dickinson.

Effect	P
Tillage	0.3497
AMF	0.4717
Tillage * AMF	0.9198
Entry	0.2672
Tillage * Entry	0.1747
AMF * Entry	0.6023
Tillage * AMF * Entry	0.8563

Due to crop loss in 2017, only onion and squash crops were compared. During 2017, AMF % colonization was not affected by AMF, tillage, or entry treatments (p = 0.4717, p = 0.3497, and p = 0.2672, respectively) (Table 34).

Overall, beet was associated with less AMF colonization compared to other crop entries at Absaraka during 2015, 2016, and 2017 (Figure 56, 57, and 58, respectively). Aligning with Hirrel et al. (1978), low colonization of beet was observed, which may have been influenced by presence of AMF host weed species. Beet leaf total nitrogen was observed to be reduced within tilled plots with AMF inoculant during 2015 at Absaraka compared to other AMF/tillage treatments (Figure 87) During 2015, onion was observed to have greater colonization compared to pea, squash, and onion (84% vs. 72%, 57%, and 6%, respectively) (Figure 56.). During 2016 and 2017, no differences were observed between colonization % of pea, onion, or squash (Figure 57 and 58). At Absaraka, AMF colonization was not influenced by AMF or tillage treatments (p = 0.7931 and p = 0.9686, respectively) (Table 32). At Dickinson, AMF colonization was not influenced by AMF or tillage treatments during 2015-2016 (p = 0.9188 and p = 0.8901, respectively) (Table 33) or during 2017 (p = 0.4717 and p = 0.3947, respectively) (Table 34).

Rates of AMF root colonization has not been consistently coupled with plant growth (McGonigle, 1988). Increasing soil P levels has been observed to decreases AMF spore density

(Johnson et al., 1991). Limited benefits for AMF plant host species may occur within soils with high levels of P, as lower rates of colonization are possible, due to the plant's allocation of photosynthates to growth; thus, limiting AMF C acquisition (Collins and Foster, 2009). Effects from AMF inoculum are generally understood through studies in which plants are grown within sterilized soil (Lekberg and Koide, 2005). Soil P levels declined over time within tilled treatments at Absaraka, although no differences were found between 2015, 2016, and 2017 (7.5 vs. 6.7 vs. 6.2 mg kg^{-1}, respectively) ($p = 0.4740$) (Figure 30). Soil P levels at Absaraka within tilled treatments ranged between low (0-7 mg kg^{-1} and medium (8-15 mg kg^{-1}) (Rosen and Eliason, 2005). For mulched no-till treatments however, soil P between 2015, 2016, and 2017 (8 vs. 17 vs. 23 mg kg^{-1}, respectively) ($p < 0.0001$ for all three between year comparisons) (Figure 30), at levels considered medium (8-15 mg kg^{-1}) and medium-high (16-25 mg kg^{-1}) (Rosen and Eliason, 2005). At Dickinson, no differences were observed between mulched no-till and tilled treatments (21 vs. 21 mg kg^{-1}, respectively), where soil P levels considered medium-high (16-25 mg kg^{-1}) (Rosen and Eliason, 2005), which may be a result of the beef cattle manure applied before planting in 2015.

Crop Leaf Chlorophyll

Pea

Table 35. Treatment Effects on Pea Leaf Chlorophyll at Absaraka.

Effect	P
Year	0.0148
Tillage	0.2284
Year * Tillage	0.3150
AMF	0.0559
Year * AMF	0.7182
Tillage * AMF	0.1062
Year * Tillage * AMF	0.7182

At Absaraka, pea leaf chlorophyll was not influenced by tillage (Table 35) ($p = 0.2284$). However, the AMF simple effect was marginally insignificant (Table 35) ($p = 0.0559$) and a slight trend was present for AMF inoculant to be associated with greater leaf chlorophyll content compared to non-inoculated plots (data not shown). Differences between years were observed, in which pea leaf chlorophyll was greater overall during 2016 than in 2017, across all treatments (309 vs. 283 mg m-2, respectively) (Figure 59) (Table 35) ($p = 0.0148$).

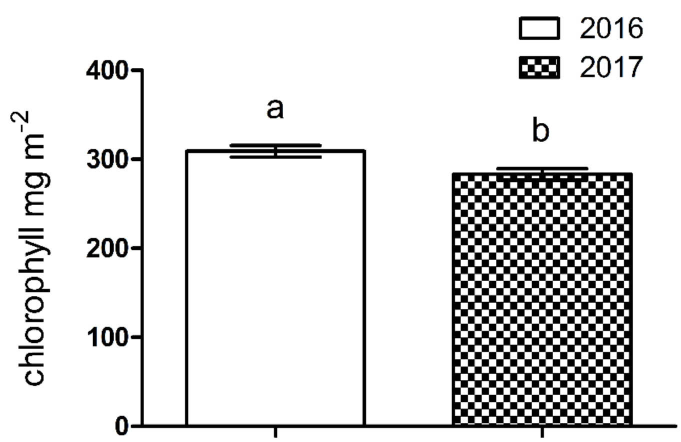

Figure 59. Absaraka mean (±S.E.) pea leaf chlorophyll (mg m^{-2}) between years across tillage treatments. Bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD.

Table 36. Treatment Effects on Pea Leaf Chlorophyll at Dickinson.

Effect	P
Tillage	0.8868
AMF	0.1109
Tillage * AMF	0.9215

At Dickinson, crop failure during 2017 resulted in data only available during 2016. No significance was observed for tillage or AMF (Table 36) ($p = 0.8868$ and $p = 0.1109$, respectively).

Onion

Table 37. Treatment Effects on Onion Leaf Chlorophyll at Absaraka.

Effect	P
Year	0.0004
Tillage	0.0034
Year * Tillage	1.0000
AMF	0.4035
Year * AMF	0.3405
Tillage * AMF	0.4262
Year * Tillage * AMF	0.1707

At Absaraka, a tillage effect was observed for onion leaf chlorophyll (Table 37) (p = 0.0034). Mulched no-till treatments was associated with greater onion leaf chlorophyll in than in tilled treatments (347 vs. 310 mg m^2) (p = 0.0034) (Figure 60). Onion leaf chlorophyll was greater during 2016 than in 2017 (355 vs. 302 mg m^2, respectively) (p = 0.0004) (Figure 61).

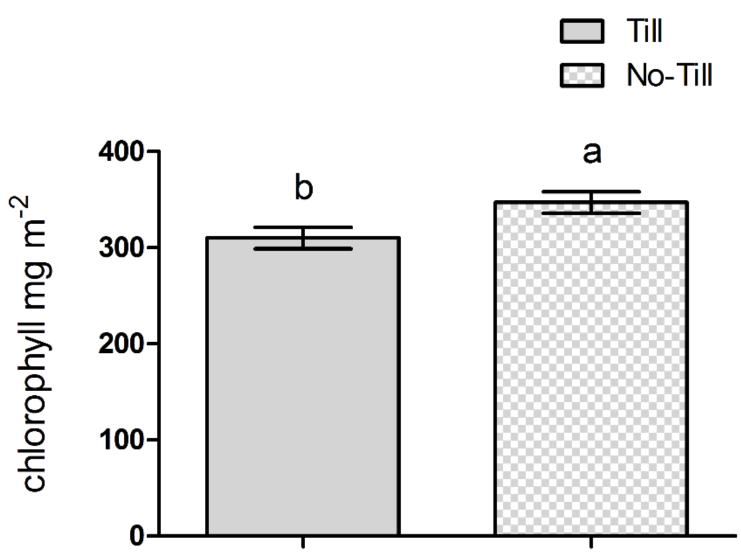

Figure 60. Absaraka mean (±S.E.) onion leaf chlorophyll (mg m^{-2}) between years across tillage treatments. Bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD.

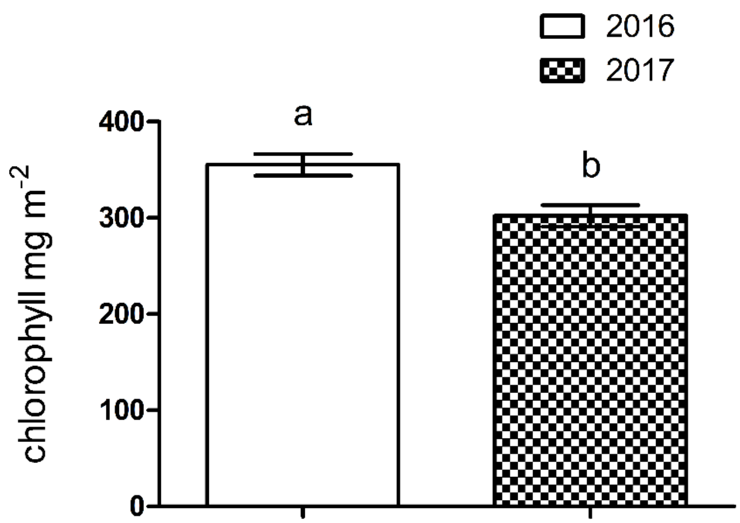

Figure 61. Absaraka mean (±S.E.) onion leaf chlorophyll (mg m^{-2}) between years across tillage treatments. Bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD.

Table 38. Treatment Effects on Onion Leaf Chlorophyll at Dickinson.

Effect	P
Year	<0.0001
Tillage	0.0177
Year * Tillage	0.0645
AMF	0.0154
Year * AMF	0.1778
Tillage * AMF	0.4181
Year * Tillage * AMF	0.8092

At Dickinson, AMF, tillage, and year effects were observed on onion leaf chlorophyll (Table 38) ($p = 0.0154$, $p = 0.0177$, and $p < 0.0001$, respectively). Onion leaf chlorophyll was greater in non-AMF inoculated treatments than in treatments with AMF inoculant (344 vs. 322 mg m^2, respectively) (Figure 62). Mulched no-till treatments were associated with greater onion leaf chlorophyll compared to tilled treatments (343 vs. 323 mg m^2, respectively) (Figure 63).

Onion leaf chlorophyll was greater overall during 2017 than in 2016 (365 vs. 301 mg m^2, respectively) ($p < 0.0001$) (Figure. 64).

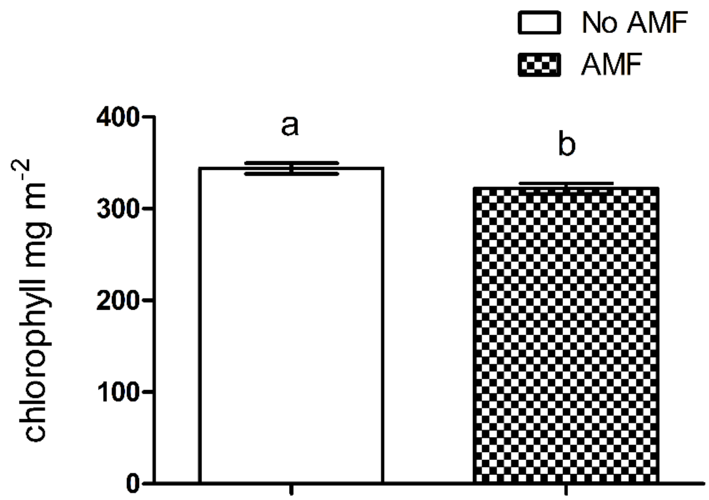

Figure 62. Dickinson mean (±S.E.) onion leaf chlorophyll (mg m^{-2}) between AMF treatments across year and tillage treatments. Bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD.

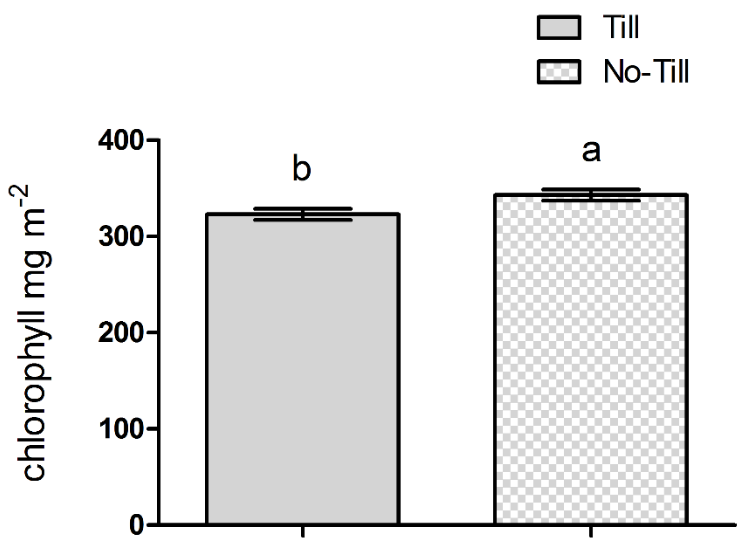

Figure 63. Dickinson mean (±S.E.) onion leaf chlorophyll (mg m^{-2}) between tillage treatments across year and AMF treatments. Bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD.

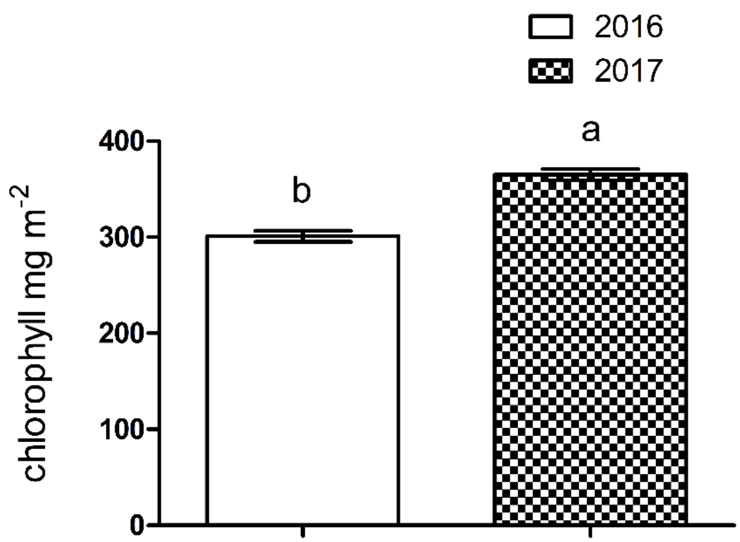

Figure 64. Dickinson mean (±S.E.) onion leaf chlorophyll (mg m^{-2}) between tillage treatments across year and AMF treatments. Bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD.

Beet

Table 39. Treatment Effects on Beet Leaf Chlorophyll at Absaraka.

Effect	P
Year	<0.0001
Tillage	0.0008
Year * Tillage	0.9433
AMF	0.3787
Year * AMF	0.8776
Tillage * AMF	0.7138
Year * Tillage * AMF	0.6115

At Absaraka, a tillage effect was observed for beet leaf chlorophyll (Table 39) (p = 0.0008). Beet chlorophyll was greater within tilled treatments overall than within no-till plots (234 vs. 193 mg m^2, respectively) (Figure 65). Beat leaf chlorophyll was greater overall during 2016 than in 2017 (286 vs. 142 mg m^2, respectively) (Figure 66).

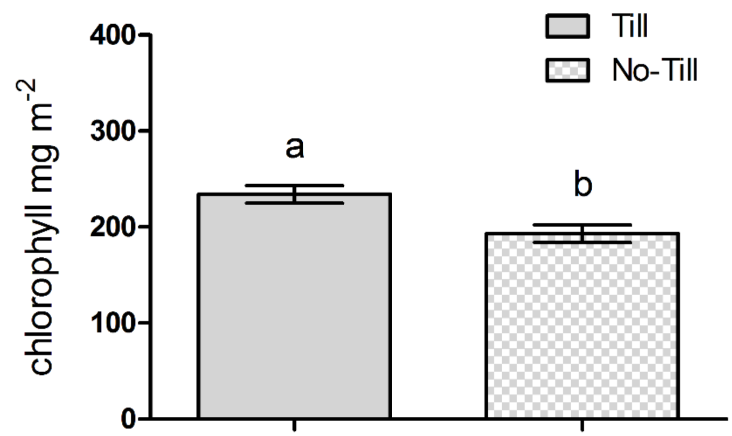

Figure 65. Absaraka mean (±S.E.) beet leaf chlorophyll (mg m^{-2}) between tillage treatments across year and AMF treatments. Bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD.

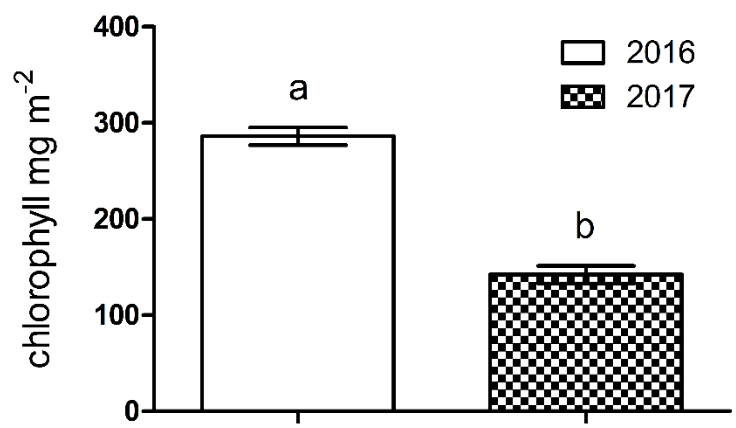

Figure 66. Absaraka mean (±S.E.) beet leaf chlorophyll (mg m^{-2}) between year across tillage and AMF treatments. Bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD.

Table 40. Treatment Effects on Beet Leaf Chlorophyll at Dickinson.

Effect	P
Tillage	0.2615
AMF	0.8747
Tillage * AMF	0.3408

At Dickinson, crop failure during 2017 resulted in data only available during 2016. No significance was observed for tillage or AMF (Table 40) (p = 0.2615 and p = 0.3408, respectively).

Squash

Table 41. Treatment Effects on Squash Leaf Chlorophyll at Absaraka.

Effect	P
Year	0.7630
Tillage	0.5189
Year * Tillage	0.7985
AMF	0.6667
Year * AMF	0.7553
Tillage * AMF	0.5831
Year * Tillage * AMF	0.6496

At Absaraka, squash leaf chlorophyll was not influenced by AMF, tillage, or year (Table 41) (p = 0.6667, p = 0.5189, and p = 0.7630, respectively).

Table 42. Treatment Effects on Squash Leaf Chlorophyll at Dickinson.

Effect	P
Year	<0.0001
Tillage	0.3979
Year * Tillage	0.8858
AMF	0.5649
Year * AMF	0.4678
Tillage * AMF	0.3175
Year * Tillage * AMF	0.2153

At Dickinson, squash leaf chlorophyll was not influenced by AMF or tillage (Table 42) (p = 0.5649 and p = 0.3979, respectively). A difference was observed between years for squash leaf chlorophyll (Table 42) ($p < 0.0001$). During 2017, squash leaf chlorophyll was greater than in 2016 (319 vs. 187 mg m^2, respectively) (Figure 67).

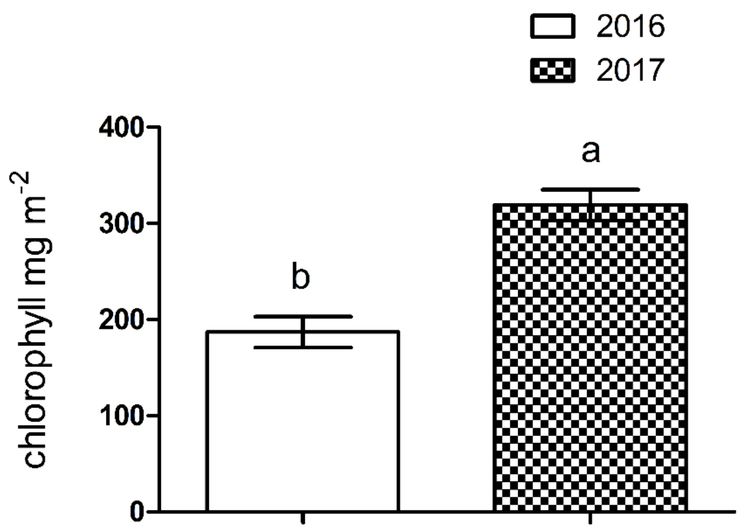

Figure 67. Dickinson mean (±S.E.) beet leaf chlorophyll (mg m^{-2}) between tillage treatments across year and AMF treatments. Bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD.

Crop leaf chlorophyll will be discussed for each respective crop within the crop yield section below.

Crop Stomatal Conductance

Pea

Table 43. Treatment Effects on Pea Stomatal Conductance at Absaraka.

Effect	P
Year	0.3994
Tillage	0.4913
Year * Tillage	0.3587
AMF	0.5884
Year * AMF	0.8512
Tillage * AMF	0.1145
Year * Tillage * AMF	0.0378

At Absaraka, an interaction effect of year, tillage, and AMF was observed for pea stomatal conductance (Table 43) ($p = 0.0378$). A difference was observed within tilled treatments during 2016 between AMF treatments, in which tilled treatments without AMF were associated with greater pea stomatal conductance (337 vs. 218 mmol m2s^{-1}, respectively) (p = 0.0481) (Figure 68.).

No difference was observed within mulched no-till treatments between AMF treatments during 2016 (p = 0.0913), although plots with AMF were associated with increases in stomatal conductance (Figure 69). No difference was observed within tilled treatments between AMF treatments during 2017 (p = 0.9544, or within mulched no-till treatments between AMF treatments during 2017 (p = 0.5037). During 2016, treatments with AMF and without AMF did not differ between tillage treatments (p = 0.0814 and p = 0.7238, respectively). During 2017, treatments with AMF and without AMF did not observe differences between tillage treatments (p = 0.7758 and p = 0.9630, respectively). Tilled treatments with and without AMF did not differ between years (p = 0.1236 and p = 0.4176, respectively). Mulched no-till treatments with and without AMF did not differ between years (p = 0.5966 and p = 0.6735, respectively).

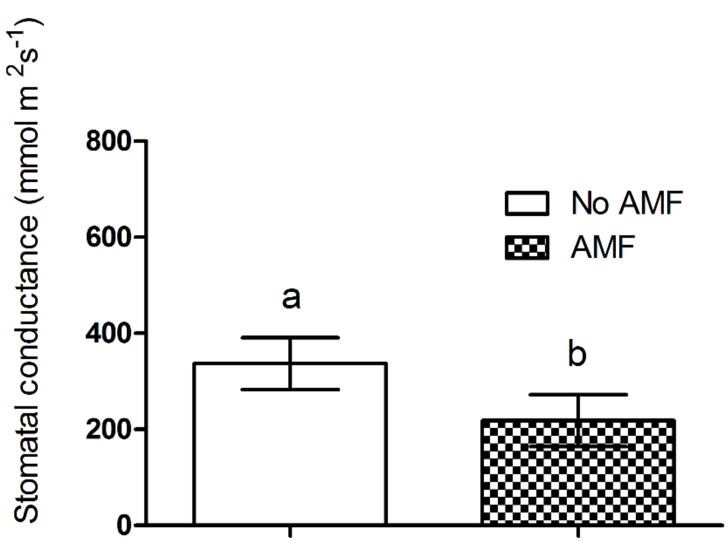

Figure 68. Absaraka mean (±S.E.) pea stomatal conductance (mmol m^{2}s^{-1}) between AMF treatments within tilled treatments during 2016. Bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD.

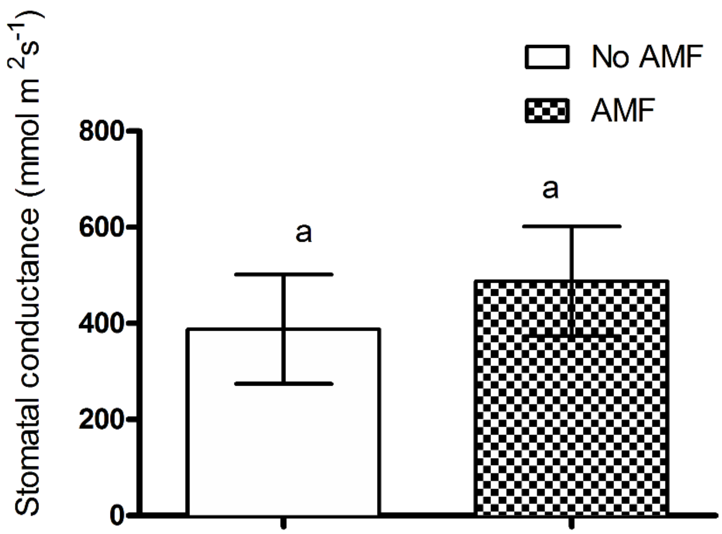

Figure 69. Absaraka mean (±S.E.) pea stomatal conductance (mmol m^2s^{-1}) between AMF treatments within mulched no-till treatments during 2016. Bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD.

Table 44. Treatment Effects on Pea Stomatal Conductance at Dickinson.

Effect	P
Tillage	0.0259
AMF	0.1137
Tillage * AMF	0.1011

At Dickinson, crop failure during 2017 resulted in data only available during 2016. Pea stomatal conductance was not influenced by AMF treatment (Table 44) (p = 0.1137). Pea stomatal conductance was influenced by tillage treatments (Table 44) (p = 0.0259). During 2016, tilled treatments were associated with greater stomatal conductance than in mulched no-till treatments (459 vs. 353 mmol m^2s^{-1}, respectively) (Figure 70).

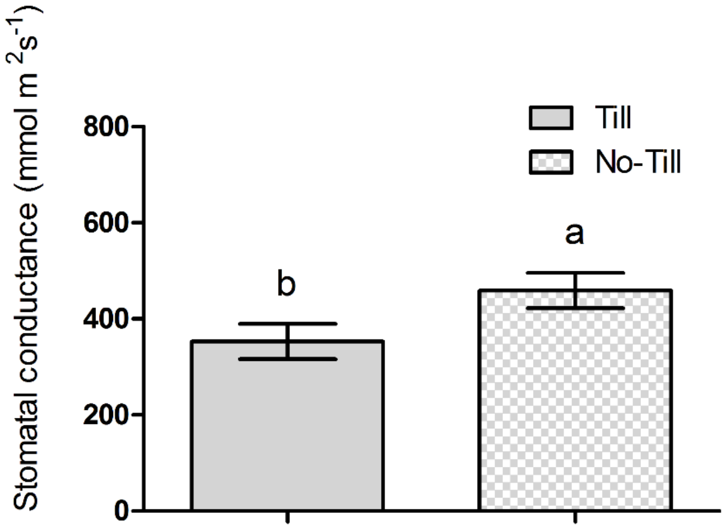

Figure 70. Dickinson mean (±S.E.) pea stomatal conductance (mmol m^2s^{-1}) between tillage treatments across year and AMF treatments. Bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD

Onion

Table 45. Treatment Effects on Onion Stomatal Conductance at Absaraka.

Effect	P
Year	0.0230
Tillage	0.0749
Year * Tillage	0.5652
AMF	0.3220
Year * AMF	0.0567
Tillage * AMF	0.4859
Year * Tillage * AMF	0.3455

At Absaraka, onion stomatal conductance was not influenced by AMF treatment and tillage treatment was marginally insignificant (Table 45) (p = 0.3220 and p = 0.0749, respectively). While not significant, tilled treatments were associated with slightly greater stomatal conductance compared to mulched no-till treatments (590 vs. 505 mmol m^2s^{-1}, respectively) (data not shown). A year effect was observed for onion stomatal conductance (p =

0.0230) (Table 45). During 2016, onion stomatal conductance was greater than in 2017 across AMF and tillage treatments (605 vs. 489 mmol m^2s^{-1}, respectively) (Figure 71).

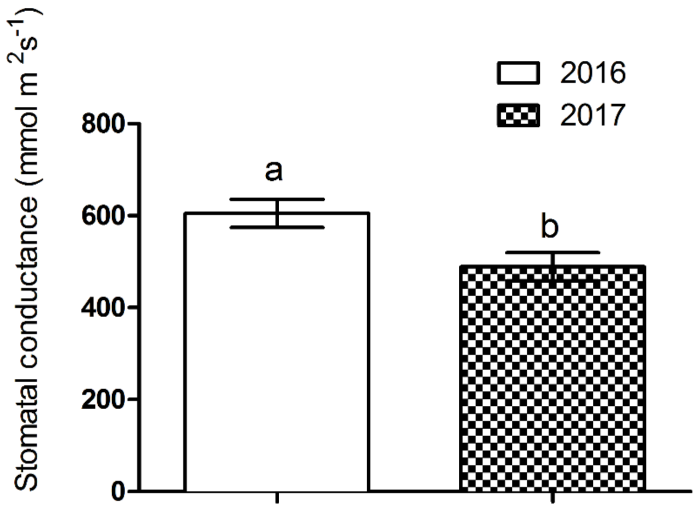

Figure 71. Absaraka mean (±S.E.) pea stomatal conductance (mmol m^2s^{-1}) between year across tillage and AMF treatments. Bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD

Table 46. Treatment Effects on Onion Stomatal Conductance at Dickinson.

Effect	P
Year	<0.0001
Tillage	0.7206
Year * Tillage	0.6837
AMF	0.3282
Year * AMF	0.6584
Tillage * AMF	0.2629
Year * Tillage * AMF	0.8436

At Dickinson, onion stomatal conductance was not influenced by AMF treatment or tillage treatment (Table 46) ($p = 0.3282$ and $p = 0.7206$, respectively). A year effect was observed, in which 2016 was associated with greater onion stomatal conductance compared to mulched no-till treatments (589 vs. 306 mmol m^2s^{-1}, respectively) ($p < 0.0001$) (Figure 72)

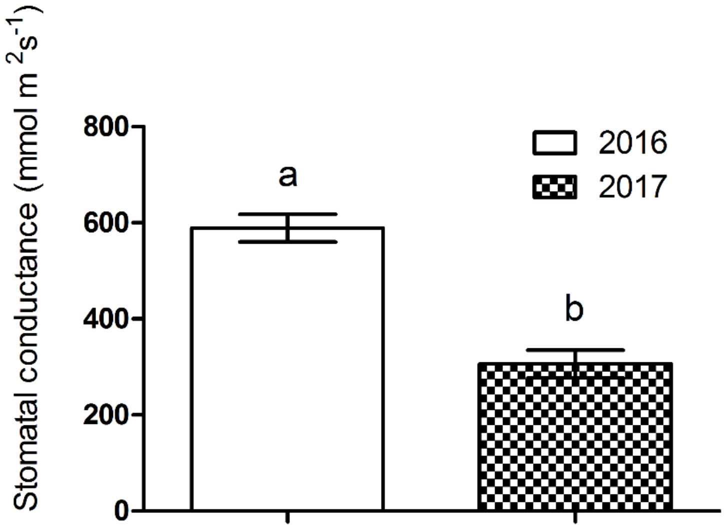

Figure 72. Dickinson mean (±S.E.) onion stomatal conductance (mmol m^2s^{-1}) between year across tillage and AMF treatments. Bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD.

Beet

Table 47. Treatment Effects on Beet Stomatal Conductance at Absaraka.

Effect	P
Year	0.0961
Tillage	0.7919
Year * Tillage	0.4019
AMF	0.7399
Year * AMF	0.6058
Tillage * AMF	0.6857
Year * Tillage * AMF	0.6338

At Absaraka, beet stomatal conductance was not affected by AMF, tillage, or year (Table 47) (p = 0.7399, p = 0.7919, and p = 0.0961, respectively). Although not significant, 2017 was associated with greater onion stomatal conductance than in 2016 (447 vs. 369 mmol m^2s^{-1}, respectively) (data not shown).

Table 48. Treatment Effects on Beet Stomatal Conductance at Dickinson.

Effect	P
Tillage	0.2734
AMF	0.3752
Tillage * AMF	0.4849

At Dickinson, crop failure during 2017 resulted in data only available during 2016. Beet stomatal conductance was not influenced by AMF or tillage treatments (Table 48) ($p = 0.3752$ and $p = 0.2734$, respectively).

Squash

Table 49. Treatment Effects on Squash Stomatal Conductance at Absaraka.

Effect	P
Year	0.2510
Tillage	0.5577
Year * Tillage	0.4507
AMF	0.6993
Year * AMF	0.4251
Tillage * AMF	0.1311
Year * Tillage * AMF	0.6284

At Absaraka, squash stomatal conductance was not affected by AMF, tillage, or year (Table 49) ($p = 0.6993$, $p = 0.5577$, and $p = 0.2510$, respectively).

Table 50. Treatment Effects on Squash Stomatal Conductance at Dickinson.

Effect	P
Year	0.0032
Tillage	0.0014
Year * Tillage	0.0085
AMF	0.5910
Year * AMF	0.2878
Tillage * AMF	0.2844
Year * Tillage * AMF	0.0536

At Dickinson, squash stomatal conductance was not influenced by AMF treatment (Table 50) (p = 0.5910). A year x tillage effect was observed (Table 50) (p = 0.0085). During 2016, stomatal conductance did not differ between tillage treatments (p = 0.5881) (Figure 73). During 2017, mulched no-till treatments were associated with greater squash stomatal conductance compared with tilled treatments (659 vs. 427 mmol m^2s^{-1}, respectively) (p = 0.0001) (Figure 73). Within tilled treatments, no differences were observed between 2016 and 2017 (p = 0.7670) (Figure 73). Mulched no-till treatments during 2017 were associated with greater squash stomatal conductance compared with mulched no-till during 2016 (659 vs. 439 mmol m^2s^{-1}, respectively) (p = 0.0002) (Figure 73).

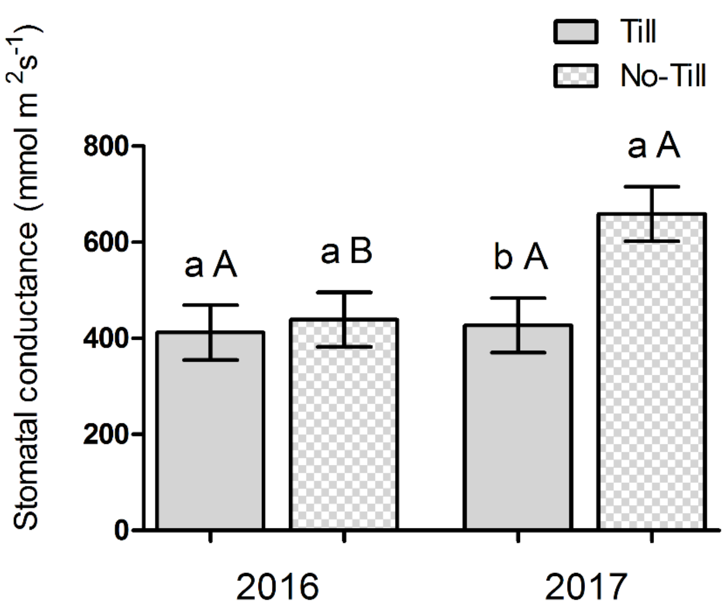

Figure 73. Dickinson mean (±S.E.) squash stomatal conductance (mmol m^2s^{-1}) between year across tillage and AMF treatments. Bars labeled with different lowercase letters differ between tillage within year ($P \leq 0.05$) according to Tukey's HSD. Bars labeled with different uppercase letters differ between year within tillage ($P \leq 0.05$) according to Tukey's HSD.

Crop leaf stomatal conductance will be discussed for each respective crop within crop yield section below.

Crop Leaf Nutrients

Pea

<u>Total Nitrogen</u>

Table 51. Treatment Effects on Pea Leaf Total Nitrogen at Absaraka.

Effect	P
Year	0.0012
Tillage	0.1259
Year * Tillage	0.4067
AMF	0.5485
Year * AMF	0.7321
Tillage * AMF	0.7190
Year * Tillage * AMF	0.7799

At Absaraka, pea leaf total nitrogen was not affected by AMF or tillage treatments (Table 51) (p = 0.5485 and p = 0.1259, respectively). Pea total nitrogen was greater during 2016 compared to 2015 (5.6 vs. 4.5 mg kg^{-1}, respectively) (Table 51) (p = 0.0012) (Figure 74).

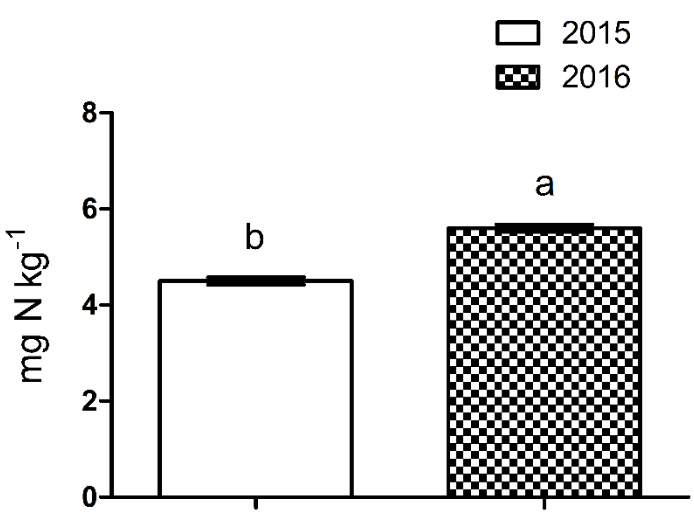

Figure 74. Absaraka mean (±S.E.) pea leaf total N (mg kg^{-1}) between year across tillage and AMF treatments. Bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD.

Table 52. Treatment Effects on Pea Leaf Total Nitrogen at Dickinson.

Effect	P
Year	<0.0001
Tillage	0.3023
Year * Tillage	0.5166
AMF	0.3963
Year * AMF	0.4663
Tillage * AMF	0.1000
Year * Tillage * AMF	0.9962

At Dickinson, pea leaf total nitrogen was not affected by AMF or tillage treatments (Table 52) (p = 0.3963 and p = 0.3023, respectively). A year effect was observed (Table 52) (p < 0.0001). During 2016, total nitrogen for pea crop was greater than during 2015 (5 vs. 3.7 mg kg^{-1}, respectively) (Figure 75).

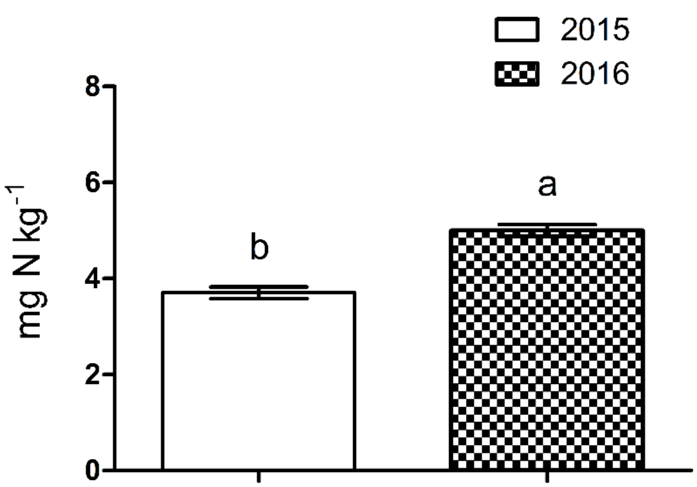

Figure 75. Dickinson mean (±S.E.) pea leaf total N (mg kg^{-1}) between year across tillage and AMF treatments. Bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD.

Phosphorus

Table 53. Treatment Effects on Pea Leaf Phosphorus at Absaraka.

Effect	P
Year	<0.0001
Tillage	0.0576
Year * Tillage	0.0649
AMF	0.7626
Year * AMF	0.7686
Tillage * AMF	0.8300
Year * Tillage * AMF	0.9314

At Absaraka, pea leaf phosphorus was not affected by AMF or tillage treatments (Table 53) (p = 0.7626 and p = 0.0576). A year effect was observed, wherein 2016 was associated with greater pea leaf phosphorus than during 2015 (2 vs. 0.5 mg kg^{-1}, respectively) (Table 53) ($p <$ 0.0001) (Figure 76). While not significant, mulched no-till treatments were associated with greater pea leaf phosphorus compared to tilled treatments (1.5 vs. 1 mg kg^{-1}, respectively) (data not shown).

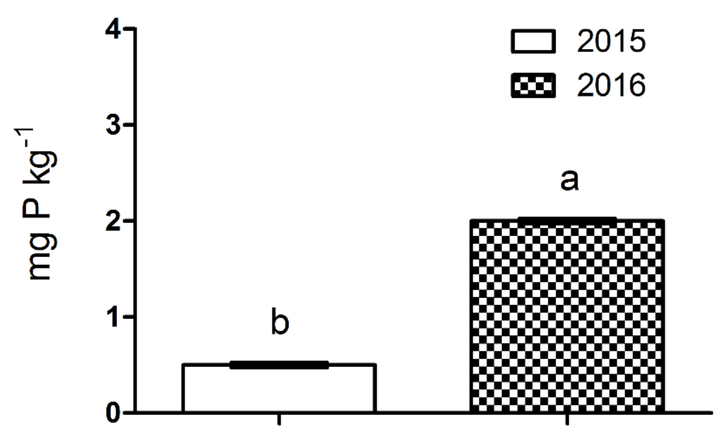

Figure 76. Absaraka mean (±S.E.) pea leaf P (mg kg^{-1}) between year across tillage and AMF treatments. Bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD.

Table 54. Treatment Effects on Pea Leaf Phosphorus at Dickinson.

Effect	P
Year	<0.0001
Tillage	0.7343
Year * Tillage	0.8317
AMF	0.3010
Year * AMF	0.3550
Tillage * AMF	0.7413
Year * Tillage * AMF	0.6589

In Dickinson, pea leaf phosphorus was not affected by AMF or tillage treatments (Table 54) (p = 0.3010 and p = 0.7343). During 2016 pea leaf phosphorus was greater than during 2015 (1.2 vs. 0.4 mg kg^{-1}) (Table 54) (p < 0.0001) (Figure 77).

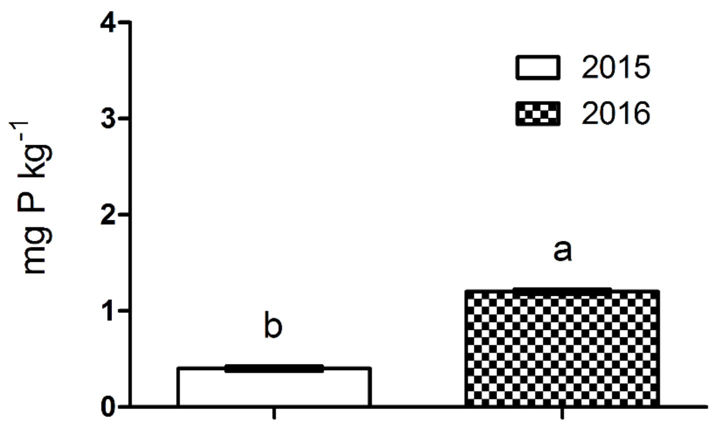

Figure 77. Absaraka mean (±S.E.) pea leaf P (mg kg^{-1}) between year across tillage and AMF treatments. Bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD.

Potassium

Table 55. Treatment Effects on Pea Leaf Potassium at Absaraka.

Effect	P
Year	<0.0001
Tillage	0.0032
Year * Tillage	0.0079
AMF	0.9238
Year * AMF	0.9899
Tillage * AMF	0.7797
Year * Tillage * AMF	0.9385

At Absaraka, a year x tillage interaction was observed (Table 55) (p = 0.0079). During 2015, differences were observed between tillage treatments, where mulched no-till treatments were associated with greater pea leaf potassium than tilled treatments (2.2 vs. 1.9 mg kg^{-1}, respectively) (p = 0.0462) (Figure 78).

During 2016, differences between tillage treatments were observed, where mulched no-till treatments were associated with greater pea leaf potassium than tilled treatments (9.5 vs. 5.2 mg kg^{-1}, respectively) (p = 0.005) (Figure 78). Within tilled treatments, differences were observed between years, where 2016 was associated with greater pea leaf potassium than tilled treatments (5.2 vs. 1.9 mg kg^{-1}, respectively) (p = 0.0018) (Figure 78). Within mulched no-till treatments, differences were observed between years, where 2016 was associated with greater pea leaf potassium than 2015 (9.5 vs. 2.2 mg kg^{-1}, respectively) ($p < 0.0001$) (Figure 78). Pea leaf potassium was not affected by AMF (Table 55) (p = 0.9238).

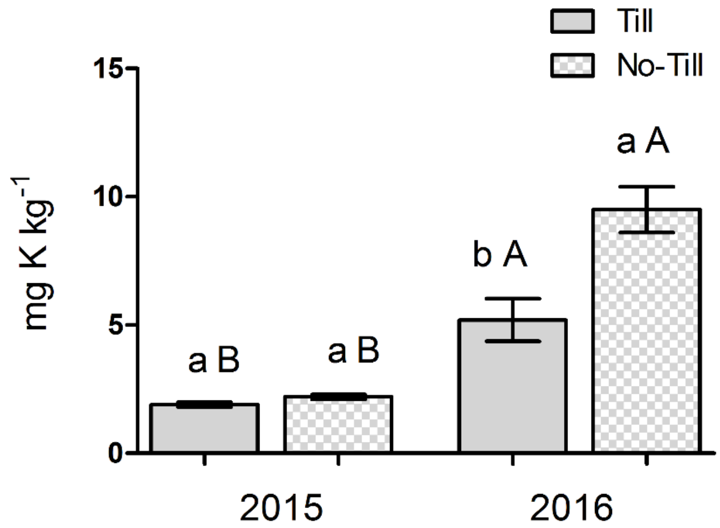

Figure 78. Absaraka mean (±S.E.) pea leaf K (mg kg^{-1}) between tillage and year across AMF treatments. Bars labeled with different lowercase letters differ between tillage within year ($P \leq 0.05$) according to Tukey's HSD. Bars labeled with different uppercase letters differ between year within tillage ($P \leq 0.05$) according to Tukey's HSD.

Table 56. Treatment Effects on Pea Leaf Potassium at Dickinson.

Effect	P
Year	<0.0001
Tillage	0.7252
Year * Tillage	0.3144
AMF	0.4030
Year * AMF	0.1986
Tillage * AMF	0.6016
Year * Tillage * AMF	0.9955

At Dickinson, pea leaf potassium was not affected by AMF or tillage treatments (Table 56) ($p = 0.4030$ and $p = 0.7252$, respectively). During 2016, pea leaf potassium was greater than during 2015 (6.7 vs. 2.8 mg kg^{-1}, respectively) (Table 56) ($p < 0.0001$) (Figure 79).

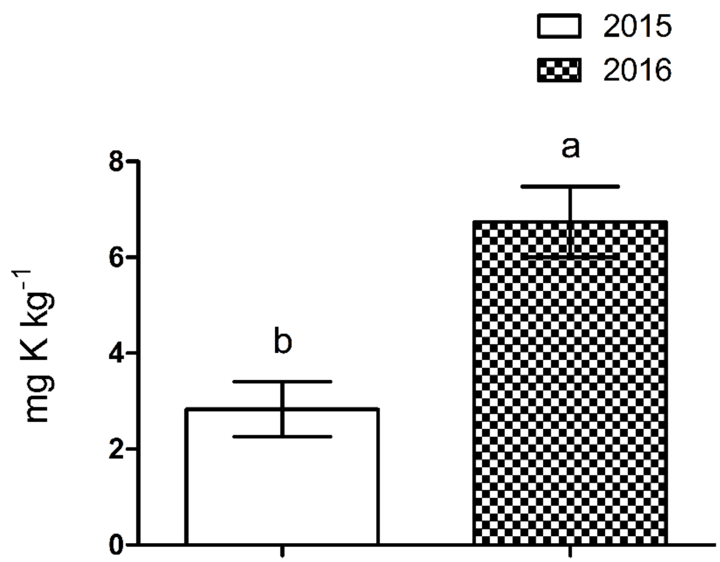

Figure 79. Dickinson mean (±S.E.) pea leaf K (mg kg^{-1}) between year across tillage and AMF treatments. Bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey’s HSD.

Onion

Total Nitrogen

Table 57. Treatment Effects on Onion Leaf Total Nitrogen at Absaraka.

Effect	P
Year	<0.0001
Tillage	0.5229
Year * Tillage	0.3592
AMF	0.7649
Year * AMF	0.9940
Tillage * AMF	0.3512
Year * Tillage * AMF	0.5119

At Absaraka, onion leaf total nitrogen was not affected by AMF or tillage treatments (Table 57) ($p = 0.7649$ and $p = 0.5229$, respectively). During 2016, onion leaf total nitrogen was greater than during 2015 (4.2 vs. 2.9 mg kg^{-1}, respectively) (Table 53) ($p < 0.0001$) (Figure 80).

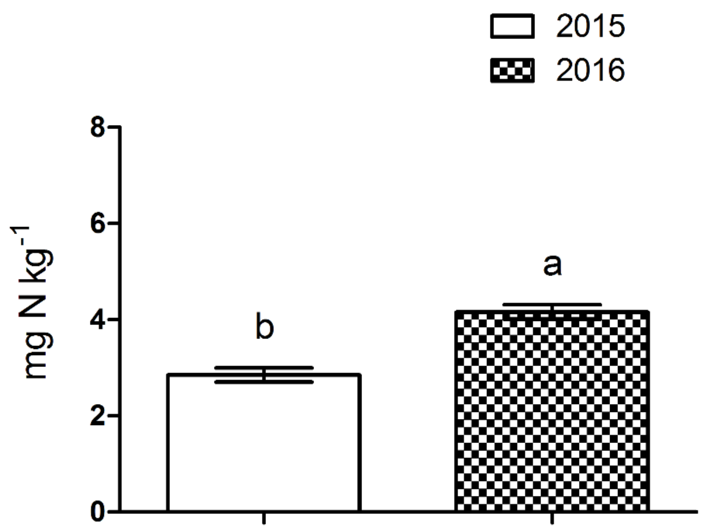

Figure 80. Absaraka mean (±S.E.) onion leaf total N (mg kg^{-1}) between year across tillage and AMF treatments. Bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD.

Table 58. Treatment Effects on Onion Leaf Total Nitrogen at Dickinson.

Effect	P
Year	0.0003
Tillage	0.0015
Year * Tillage	<0.0001
AMF	0.9773
Year * AMF	0.2533
Tillage * AMF	0.2691
Year * Tillage * AMF	0.4094

At Dickinson, onion leaf total nitrogen was not affected by AMF (Table 58) (p = 0.9773). A year x tillage interaction was observed (Table 58) ($p < 0.0001$). During 2015, tillage treatments did not differ (p = 0.2454). During 2016, mulched no-till treatments were associated with greater onion leaf total nitrogen compared to tilled treatments (3.7 vs. 2.8 mg kg^{-1}, respectively) ($p < 0.0001$) (Figure 81). Within tilled treatments, no differences were observed between 2015 and 2016 (p = 0.5022).Within mulched no-till treatments, 2016 was associated with greater onion leaf total nitrogen compared to 2015 (3.7 vs. 2.7 mg kg^{-1}, respectively) (p < 0.0001). (Figure 81)

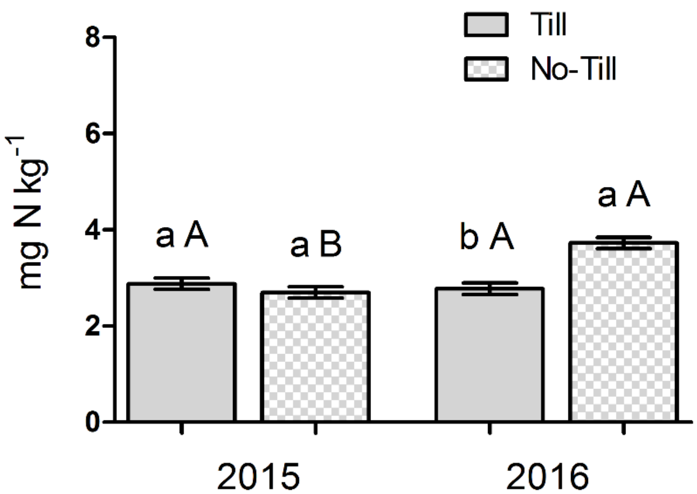

Figure 81. Dickinson mean (±S.E.) onion leaf total N (mg kg^{-1}) between tillage and years across AMF treatments. Bars labeled with different lowercase letters differ between tillage within year ($P \leq 0.05$) according to Tukey's HSD. Bars labeled with different uppercase letters differ between year within tillage ($P \leq 0.05$) according to Tukey's HSD.

<u>Phosphorus</u>

Table 59. Treatment Effects on Onion Leaf Phosphorus at Absaraka.

Effect	P
Year	0.6157
Tillage	0.3474
Year * Tillage	0.0002
AMF	0.1512
Year * AMF	0.5532
Tillage * AMF	0.5152
Year * Tillage * AMF	0.1929

At Absaraka, a year x tillage interaction was observed (Table 59) (p = 0.0002). During 2015, tilled treatments were associated with greater onion leaf phosphorus compared to mulched no-till treatments (0.54 vs. 0.43 mg P kg^{-1}, respectively) (p = 0.0192) (Figure 82). During 2016, no differences were observed for onion leaf phosphorus between tillage treatments (p = 0.3364)

(Figure 82). Within tilled treatments, 2015 was associated with greater onion leaf phosphorus compared to 2016 (0.54 vs. 0.47 mg P kg^{-1}, respectively) (p = 0.0092) (Figure 82). Within mulched no-till treatments, 2016 was associated with greater onion leaf phosphorus compared to 2015 (0.51 vs. 0.43 mg P kg^{-1}, respectively) (p = 0.0019) (Figure 82). Onion leaf phosphorus was not affected by AMF treatments (Table 59) (p = 0.1512).

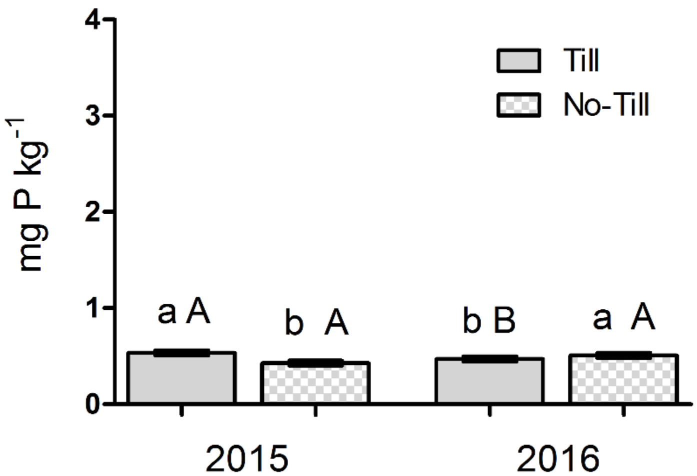

Figure 82. Absaraka mean (±S.E.) onion leaf P (mg kg^{-1}) between tillage and years across AMF treatments. Bars labeled with different lowercase letters differ within year between tillage ($P \leq$ 0.05) according to Tukey's HSD. Bars labeled with different uppercase letters differ within tillage between year ($P \leq 0.05$) according to Tukey's HSD.

Table 60. Treatment Effects on Onion Leaf Phosphorus at Dickinson.

Effect	P
Year	0.0391
Tillage	0.9643
Year * Tillage	0.0156
AMF	0.3445
Year * AMF	0.6347
Tillage * AMF	0.4983
Year * Tillage * AMF	0.5619

At Dickinson, a year x tillage interaction was observed (Table 60) (p = 0.0156). Onion leaf phosphorus was not affected by AMF treatments (Table 60) (p = 0.3445). During 2015 and

2016, tillage treatments did not differ for onion leaf phosphorus ($p = 0.0816$ and $p = 0.0722$, respectively) (Figure 83). Within tilled treatments, onion leaf phosphorus was greater during 2016 compared to 2015 (0.49 vs. 0.37 mg P kg^{-1}, respectively) ($p = 0.0026$) (Figure 83). Within mulched no-till treatments, no differences were observed between 2015 and 2016 ($p = 0.7629$) (Figure 83).

Figure 83. Dickinson mean (±S.E.) onion leaf P (mg kg^{-1}) between tillage and years across AMF treatments. Bars labeled with different lowercase letters differ within year between tillage ($P \leq 0.05$) according to Tukey's HSD. Bars labeled with different uppercase letters differ within tillage between year ($P \leq 0.05$) according to Tukey's HSD.

<u>Potassium</u>

Table 61. Treatment Effects on Onion Leaf Potassium at Absaraka.

Effect	P
Year	0.0026
Tillage	0.0002
Year * Tillage	<0.0001
AMF	0.3147
Year * AMF	0.0066
Tillage * AMF	0.0085
Year * Tillage * AMF	0.0286

At Absaraka, a year x tillage x AMF interaction was observed (Table 61) (p = 0.0286). No differences were observed during 2015 between tilled treatments with AMF or without AMF (p = 0.1146 and p = 0.0536, respectively) (Figure 84). During 2015 within tilled treatments, plots without AMF were associated with greater onion leaf potassium compared to tilled without AMF treatments (4 vs. 3.6 mg K kg^{-1}, respectively) (p = 0.0402) (Figure 84). Conversely, during 2016 within tilled treatments, plots with AMF were associated with greater onion leaf potassium (3.2 vs. 2.5 mg K kg^{-1}, respectively) (p = 0.0120) (Figure 84). During 2015 within mulched no-till treatments, plots without AMF were associated with greater onion leaf potassium (4.4 vs. 4 mg K kg^{-1}, respectively) (p = 0.0133) (Figure 84). During 2016, within mulched no-till treatments, no differences were observed between AMF treatments (p = 0.2079) (Figure 84).

Within tilled treatments without AMF, 2015 was associated with greater leaf onion potassium compared to 2016 (4 vs. 2.5 mg K kg^{-1}, respectively) (p < 0.0001) (Figure 85). Within tilled treatments with AMF, no differences were observed between 2015 and 2016 (p = 0.0907) (Figure 85). Within mulched no-till treatments without AMF, 2016 was associated with greater onion leaf potassium compared to 2015 (5.9 vs. 4.4 mg K kg^{-1}, respectively) (p < 0.0001) (Figure 85). Similarly, within mulched no-till treatments with AMF, 2016 was associated with greater onion leaf potassium compared to 2015 (5.6 vs. 4 mg K kg^{-1}, respectively) (p < 0.0001) (Figure 85).

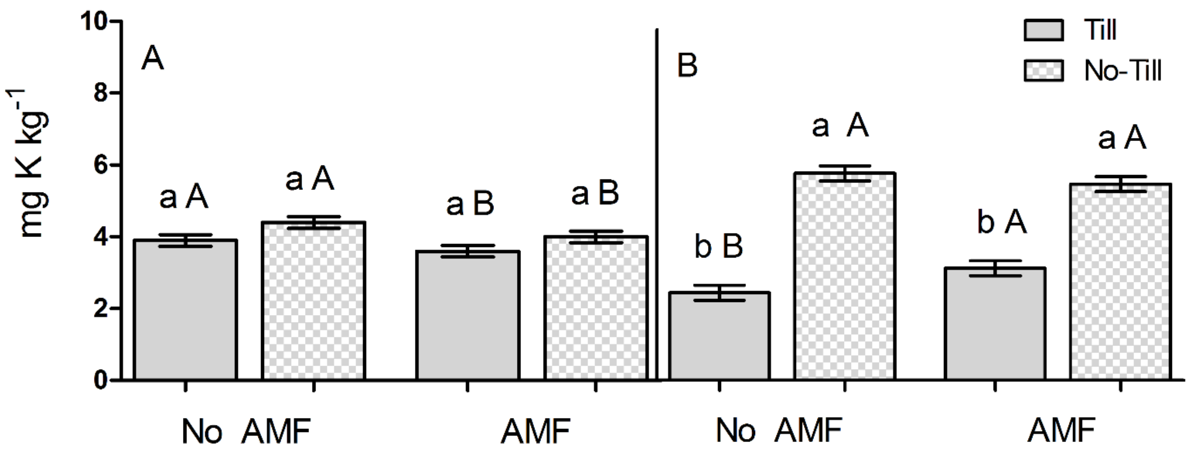

Figure 84. Absaraka mean (±S.E.) onion leaf K (mg kg^{-1}) between tillage and AMF pairwise comparisons during 2015 (left) and 2016 (right). Bars labeled with different lowercase letters differ between tillage within AMF treatments ($P \leq 0.05$) according to Tukey's HSD. Bars labeled with different uppercase letters differ between AMF within tillage treatments ($P \leq 0.05$) according to Tukey's HSD.

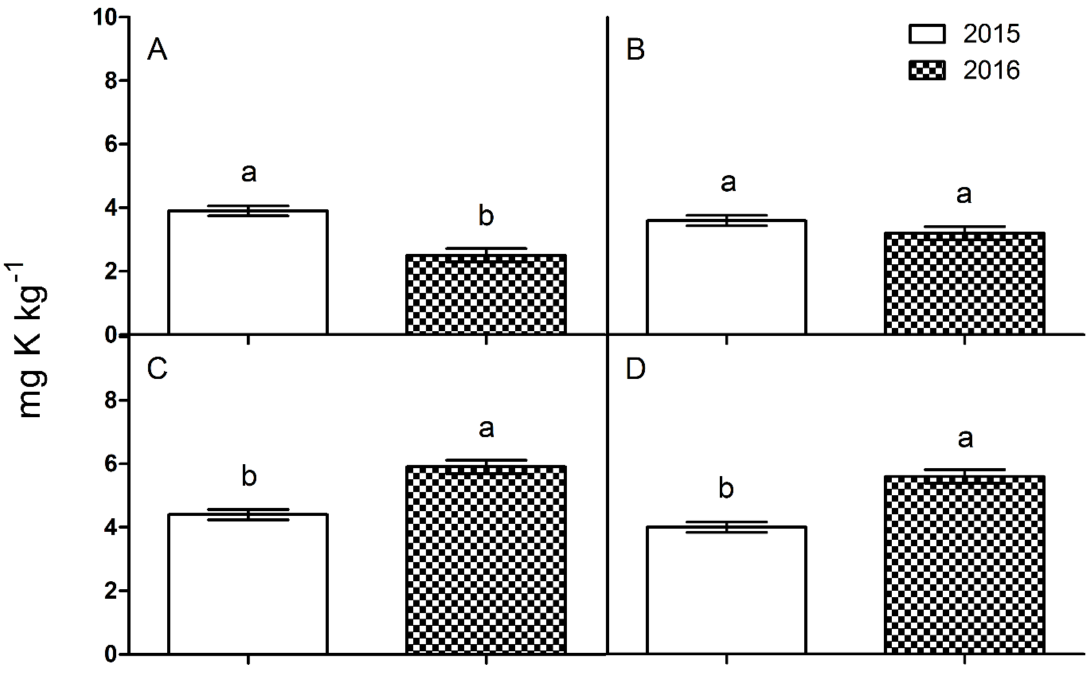

Figure 85. Absaraka mean (±S.E.) onion leaf K (mg kg^{-1}) within tillage and AMF pairwise comparisons between year. A) Tilled + No AMF, B) Tilled + AMF, C) No-Till + No AMF, and D) No-Till + AMF. Bars labeled with different lowercase letters differ between year within respective pairwise comparisons ($P \leq 0.05$) according to Tukey's HSD.

Table 62. Treatment Effects on Onion Leaf Potassium at Dickinson.

Effect	P
Year	<0.0001
Tillage	<0.0001
Year * Tillage	0.5347
AMF	0.0504
Year * AMF	0.5249
Tillage * AMF	0.1422
Year * Tillage * AMF	0.4636

At Dickinson, a tillage and year effect was observed for onion leaf potassium (Table 62) (p <0.0001 for both effects). Onion leaf potassium was greater within mulched no-till compared with tilled treatments and also during 2016 compared to 2015 (5 vs. 4 mg K kg^{-1} and 5 vs. 4 mg K kg^{-1}, respectively) (Figure 86). The simple effect of AMF was marginally insignificant, in which treatments without AMF were associated with greater onion leaf K compared to treatments with AMF (4.6 vs. 4.3 mg K kg^{-1}, respectively) (p = 0.0504) (data not shown).

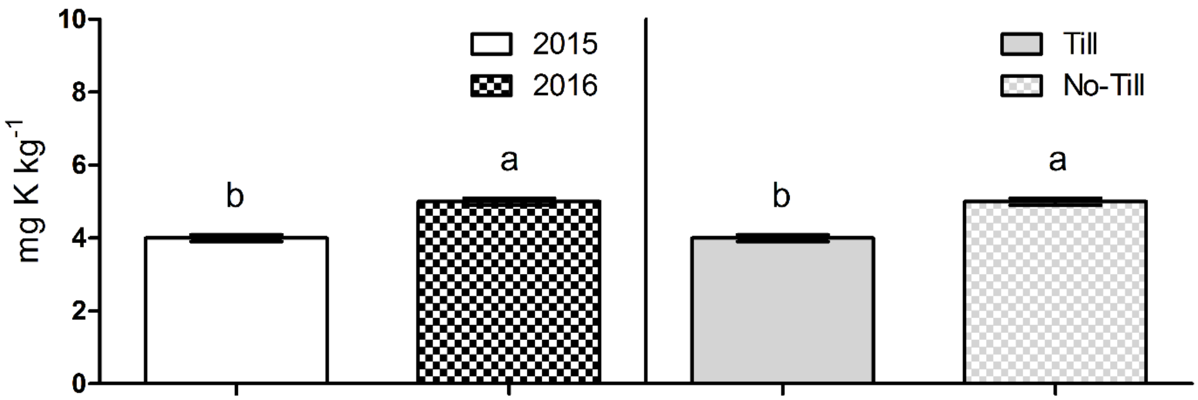

Figure 86. Dickinson mean (±S.E.) onion leaf K (mg kg^{-1}) between years across tillage and AMF treatments (left) and between tillage across year and AMF treatments (right). Bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD.

Beet

Total Nitrogen

Table 63. Treatment Effects on Beet Leaf Total Nitrogen at Absaraka.

Effect	P
Year	<0.0001
Tillage	0.0103
Year * Tillage	0.0095
AMF	0.6322
Year * AMF	0.1661
Tillage * AMF	0.8642
Year * Tillage * AMF	0.0433

At Absaraka, a year x tillage x AMF interaction was observed (Table 63) (p = 0.0433). During 2015, within tilled and mulched no-till treatments, no differences were observed between plots with AMF and without AMF for beet leaf total nitrogen (p = 0.1506 and p = 0.6004, respectively) (Figure 87). During 2016, within tilled and mulched no-till treatments, no differences were observed between plots with and without AMF for beet leaf total nitrogen (p = 0.0677 and p = 0.8545, respectively) (Figure 87).

Overall, 2016 was associated with greater beet leaf total nitrogen compared to 2015 for tilled treatments without and with AMF, as well as for mulched no-till treatments without and with AMF (6 vs. 5.3 mg kg^{-1}, 6.4 vs. 3.9 mg kg^{-1}, 6.2 vs. 4.6 mg kg^{-1}, and 6.2 vs. 4.7 mg kg^{-1}, respectively) ($p < 0.0001$ for all comparisons) (Figure 88).

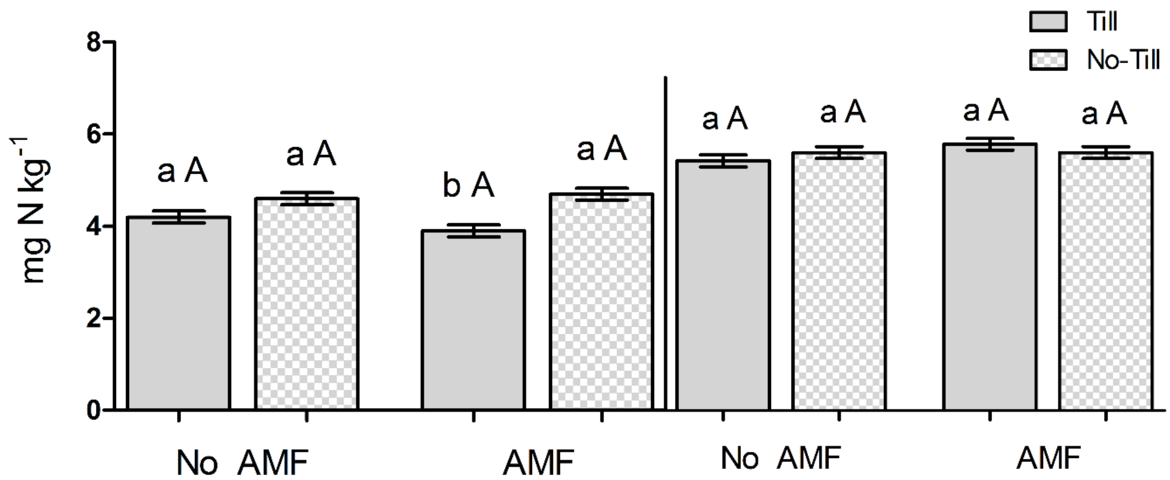

Figure 87. Absaraka mean (±S.E.) beet leaf total N (mg kg^{-1}) between tillage and AMF pairwise comparisons during 2015 (left) and 2016 (right). Bars labeled with different lowercase letters differ between tillage and AMF pairwise treatments within year ($P \leq 0.05$) according to Tukey's HSD. Bars labeled with different uppercase letters differ between year within AMF and tillage pairwise treatments ($P \leq 0.05$) according to Tukey's HSD.

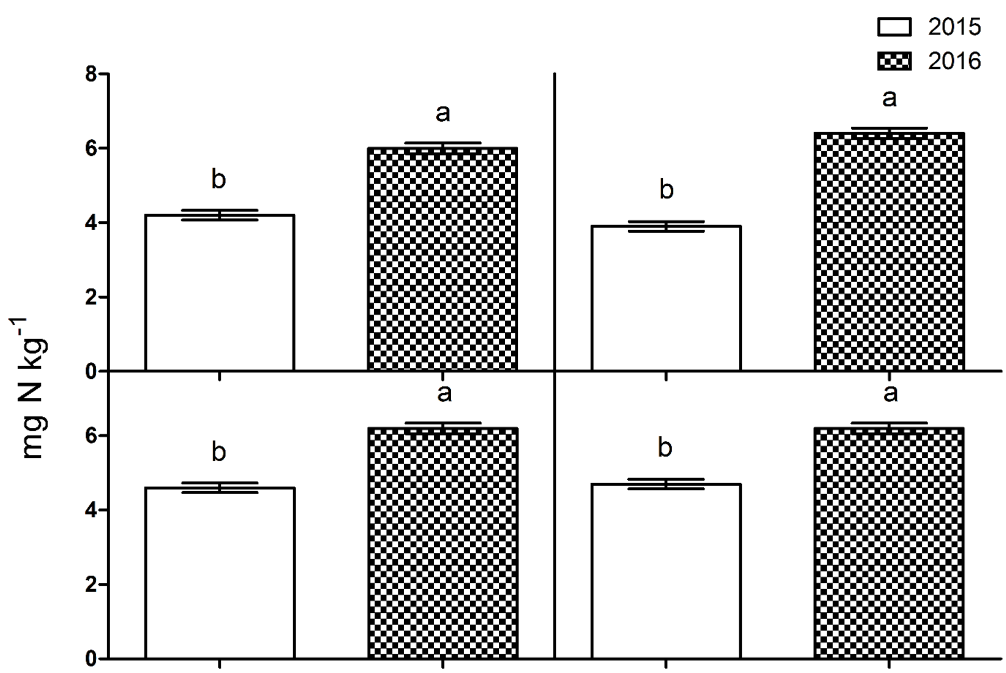

Figure 88. Absaraka mean (±S.E.) beet leaf total N (mg kg^{-1}) within tillage and AMF pairwise comparisons between year. A) Tilled + No AMF, B) Tilled + AMF, C) No-Till + No AMF, and D) No-Till + AMF. Bars labeled with different lowercase letters differ between year within respective pairwise comparisons ($P \leq 0.05$) according to Tukey's HSD.

Table 64. Treatment Effects on Beet Leaf Total Nitrogen at Dickinson.

Effect	P
Year	<0.0001
Tillage	0.0410
Year * Tillage	0.9255
AMF	0.8606
Year * AMF	0.4627
Tillage * AMF	0.6915
Year * Tillage * AMF	0.7416

At Dickinson, a tillage and year effect was observed (Table 64) ($p = 0.0410$ and $p < 0.0001$, respectively). Beet leaf total nitrogen was greater within mulched no-till treatments compared with tilled treatments (4.2 vs. 3.9 mg kg^{-1}, respectively) (Figure 89). Beet leaf total nitrogen was also greater overall during 2016 compared to 2015 (4.5 vs. 3.6 mg kg^{-1}, respectively) (Figure 90). The simple effect of AMF did not affect beet leaf total nitrogen (Table 64) ($p = 0.8606$).

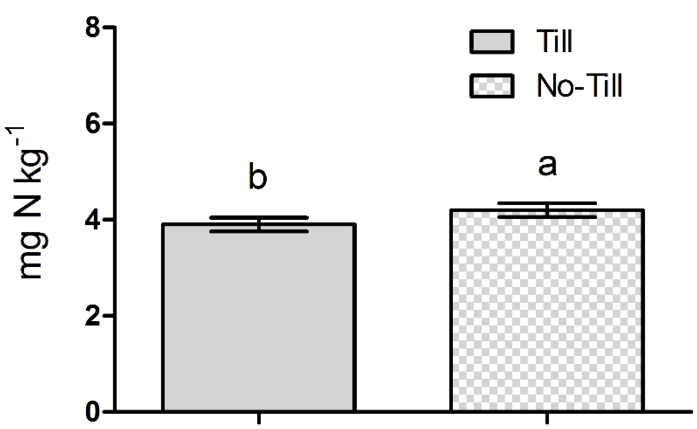

Figure 89. Dickinson mean (±S.E.) beet leaf total N (mg kg^{-1}) between tillage across year and AMF treatments. Bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD.

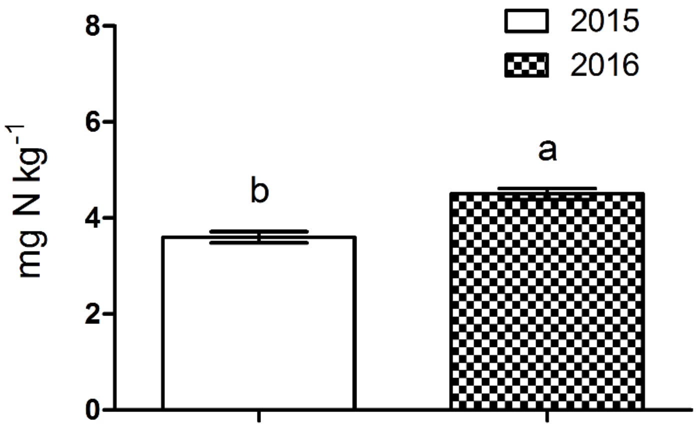

Figure 90. Dickinson mean (±S.E.) beet leaf total N (mg kg^{-1}) between year across tillage and AMF treatments. Bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD.

Phosphorus

Table 65. Treatment Effects on Beet Leaf Phosphorus at Absaraka.

Effect	P
Year	<0.0001
Tillage	0.0017
Year * Tillage	<0.0001
AMF	0.7256
Year * AMF	0.4375
Tillage * AMF	0.1414
Year * Tillage * AMF	0.8894

At Absaraka, a year x tillage interaction was observed (Table 65) ($p < 0.0001$). During 2015, no differences were observed for beet leaf phosphorus between tillage treatments (p = 0.8248). During 2016, mulched no-till treatments were associated with greater beet leaf phosphorus compared to tilled treatments (0.81 vs. 0.57 mg kg^{-1}, respectively) ($p < 0.0001$) (Figure 91). Overall, beet leaf phosphorus was greater during 2016 than in 2015 for mulched no-till and tilled treatments (0.81 vs. 0.43 mg kg^{-1} and 0.57 vs. 0.43 mg kg^{-1}, respectively) (p <

0.0001 for both comparisons) (Figure 91). The simple effect of AMF did not affect beet leaf phosphorus (Table 65) (p = 0.7256).

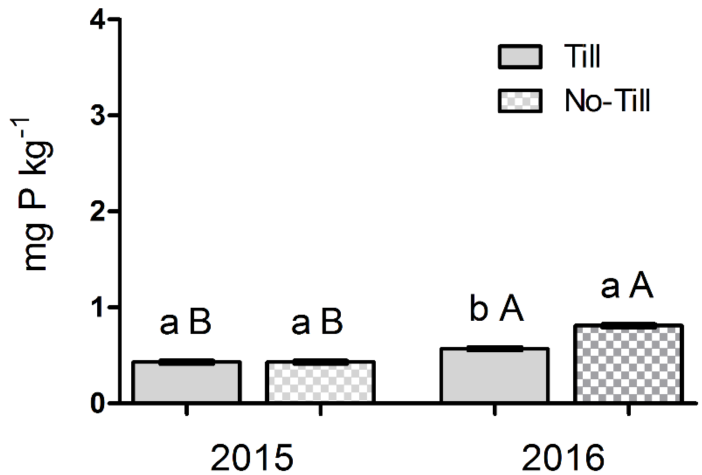

Figure 91. Absaraka mean (±S.E.) beet leaf P (mg kg^{-1}) between tillage within year and between year within tillage across AMF treatments. Bars labeled with different lowercase letters differ between tillage within year ($P \leq 0.05$) according to Tukey's HSD. Bars labeled with different uppercase letters differ between year within tillage ($P \leq 0.05$) according to Tukey's HSD.

Table 66. Treatment Effects on Beet Leaf Phosphorus at Dickinson.

Effect	P
Year	<0.0001
Tillage	<0.0001
Year * Tillage	0.0293
AMF	0.9122
Year * AMF	0.8133
Tillage * AMF	0.4953
Year * Tillage * AMF	0.6217

At Dickinson, a year x tillage interaction was observed (Table 66) (p = 0.0293). During 2015 and 2016, mulched no-till treatments were associated with great beet leaf phosphorus compared to tilled treatments (0.39 vs. 0.25 mg kg^{-1} and 0.88 vs. 0.54 mg kg^{-1}, respectively) (p = 0.0007 and p = 0.0012 , respectively) (Figure 92). Within tillage, 2016 was associated with greater beet leaf phosphorus compared to 2015 for both mulched no-till and till treatments (0.88

vs. 0.39 mg $kg^{-1}$and 0.54 vs. 0.25 mg kg^{-1}, respectively) ($p < 0.0001$ and $p = 0.0002$, respectively) (Figure 92). The simple effect of AMF did not affect beet leaf phosphorus (Table 66) ($p = 0.9122$).

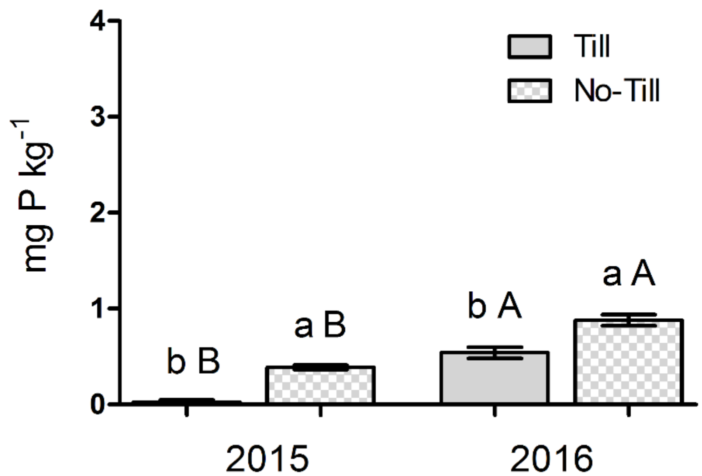

Figure 92. Dickinson mean (±S.E.) beet leaf P (mg kg^{-1}) between tillage within year and between year within tillage across AMF treatments. Bars labeled with different lowercase letters differ between tillage within year ($P \leq 0.05$) according to Tukey's HSD. Bars labeled with different uppercase letters differ between year within tillage ($P \leq 0.05$) according to Tukey's HSD.

<u>Potassium</u>

Table 67. Treatment Effects on Beet Leaf Potassium at Absaraka.

Effect	P
Year	<0.0001
Tillage	<0.0001
Year * Tillage	0.0510
AMF	0.0755
Year * AMF	0.1456
Tillage * AMF	0.1434
Year * Tillage * AMF	0.4544

At Absaraka simple effects of tillage and year were observed (Table 67) ($p < 0.0001$ for both effects). Overall, mulched no-till treatments were associated with greater beet leaf potassium compared to tilled treatments (5.6 vs. 4 mg kg^{-1}, respectively) (Figure 93). Overall, 2015 was associated with greater beet leaf potassium compared to 2016 (5.4 vs. 4.2 mg kg^{-1}, respectively) (Figure 93). The simple effect of AMF did not affect beet leaf potassium (Table 67) (p = 0.0755).

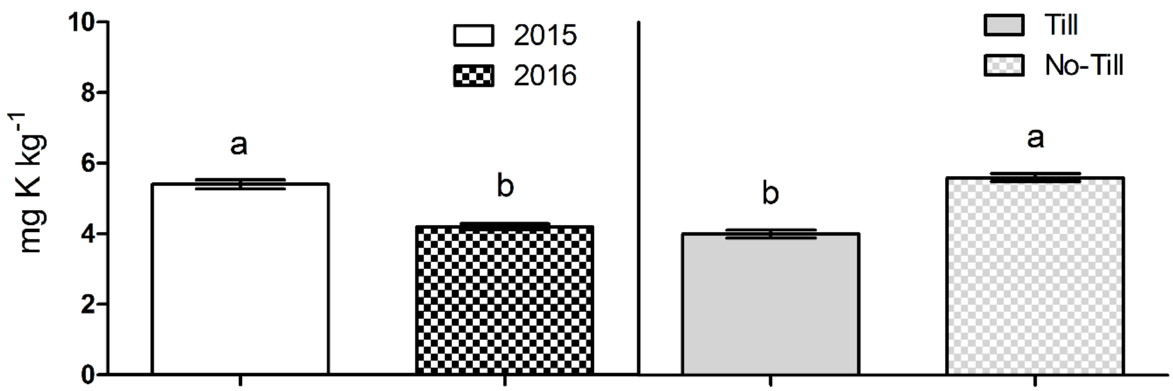

Figure 93. Absaraka mean (±S.E.) beet leaf K (mg kg^{-1}) between years across tillage and AMF treatments (left) and between tillage across year and AMF treatments (right). Bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD.

Table 68. Treatment Effects on Beet Leaf Potassium at Dickinson.

Effect	P
Year	<0.0001
Tillage	0.0010
Year * Tillage	0.7916
AMF	0.9042
Year * AMF	0.4047
Tillage * AMF	0.3683
Year * Tillage * AMF	0.5972

At Dickinson, simple effects of tillage and year were observed (Table 68) (p = 0.0010 and p < 0.0001, respectively). Similar to Absaraka, mulched no-till treatments were associated with greater beet leaf potassium compared to tilled treatments (6.3 vs. 5.5 mg kg^{-1}, respectively) (Figure 94). Beet leaf potassium was also greater during 2015 compared to 2016 (6.4 vs. 5.4 mg kg^{-1}, respectively) (Figure 94). The simple effect of AMF did not affect beet leaf potassium (Table 68) (p = 0.9042).

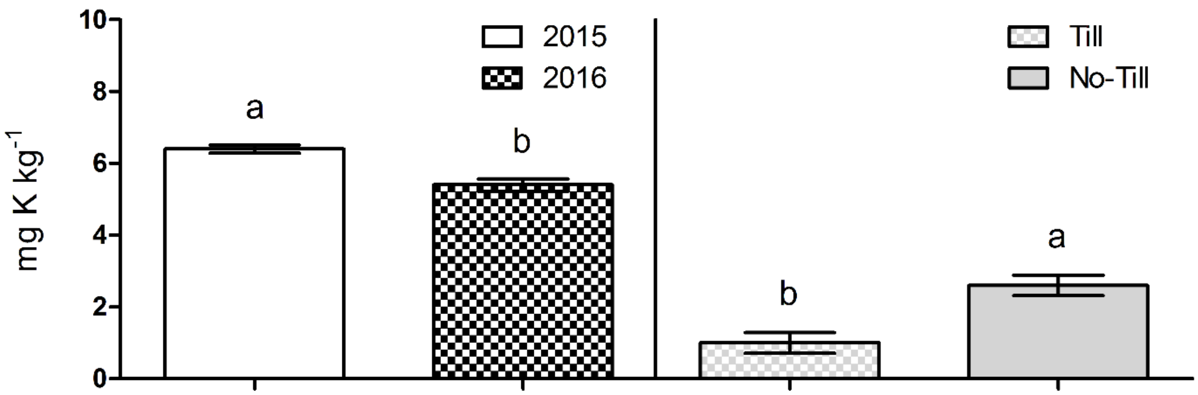

Figure 94. Dickinson mean (±S.E.) beet leaf K (mg kg^{-1}) between years across tillage and AMF treatments (left) and between tillage across year and AMF treatments (right). Bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD.

Squash

<u>Total Nitrogen</u>

Table 69. Treatment Effects on Squash Leaf Total Nitrogen at Absaraka.

Effect	P
Year	<0.0001
Tillage	<0.0001
Year * Tillage	0.3461
AMF	0.9652
Year * AMF	0.8740
Tillage * AMF	0.1641
Year * Tillage * AMF	0.5116

At Absaraka, simple effects of tillage and year were observed for squash leaf total nitrogen (Table 69) ($p < 0.0001$ for both effects). Mulched no-till treatments resulted in greater squash leaf total nitrogen compared to tilled treatments (5.4 vs. 4.7 mg kg^{-1}, respectively).

Squash leaf nitrogen was also found to be greater overall during 2016 compared to 2015 (6.2 vs. 3.8 mg kg^{-1}, respectively). The simple effect of AMF did not affect squash leaf total nitrogen (Table 69) ($p = 0.9652$).

Figure 95. Absaraka mean (±S.E.) squash leaf total N (mg kg^{-1}) between years across tillage and AMF treatments (left) and between tillage across year and AMF treatments (right). Bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD.

Table 70. Treatment Effects on Squash Leaf Total Nitrogen at Dickinson.

Effect	P
Year	0.6100
Tillage	0.0004
Year * Tillage	0.1812
AMF	0.7099
Year * AMF	0.8351
Tillage * AMF	0.8313
Year * Tillage * AMF	0.8903

At Dickinson, the simple effect of tillage was observed (Table 70) ($p = 0.0004$). Mulched no-till treatments were associated with greater squash leaf total nitrogen compared to tilled treatments (4 vs. 2.9 mg kg^{-1}, respectively) (Figure 96). The simple effect of AMF did not affect squash leaf total nitrogen (Table 70) ($p = 0.7099$).

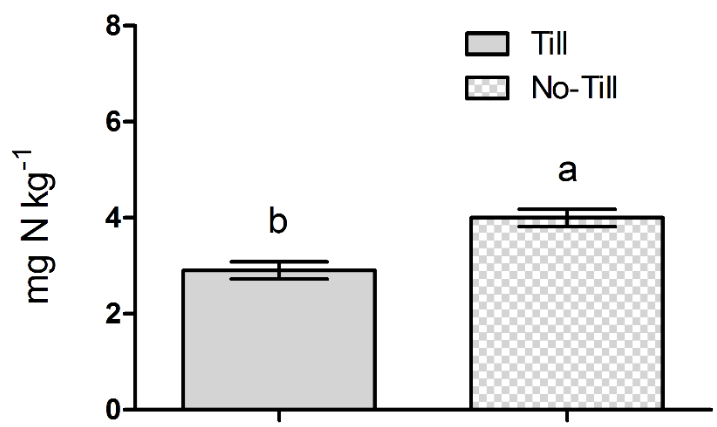

Figure 96. Dickinson mean (±S.E.) squash leaf total N (mg kg^{-1}) between tillage across year and AMF treatments. Bars labeled with different lowercase letters differ between tillage treatment ($P \leq 0.05$) according to Tukey's HSD.

Phosphorus

Table 71. Treatment Effects on Squash Leaf Phosphorus at Absaraka.

Effect	P
Year	<0.0001
Tillage	0.0122
Year * Tillage	0.0210
AMF	0.9684
Year * AMF	0.8540
Tillage * AMF	0.3940
Year * Tillage * AMF	0.5310

At Dickinson, a year x tillage interaction was observed (Table 71) ($p = 0.0210$). No differences were observed for squash leaf phosphorus between tillage treatments during 2015 ($p = 0.4626$). Differences were observed during 2016 for squash leaf phosphorus between tillage treatments, in which mulched no-till treatments were associated with greater squash leaf phosphorus compared to tilled treatments (1.1 vs. 0.8 mg kg^{-1}, respectively) ($p = 0.0004$) (Figure 97). Within mulched no-till treatments, 2016 was associated with greater squash leaf phosphorus compared to 2015 (1.1 vs. 0.52 mg kg^{-1}, respectively) ($p = < 0.0001$) (Figure 97). Within tilled treatments, 2016 was associated with greater squash leaf phosphorus compared to 2015 (0.78 vs. 0.47 mg kg^{-1}, respectively) (p = 0.0004) (Figure 97). The simple effect of AMF did not affect squash leaf phosphorus (Table 71) (p = 0.9684).

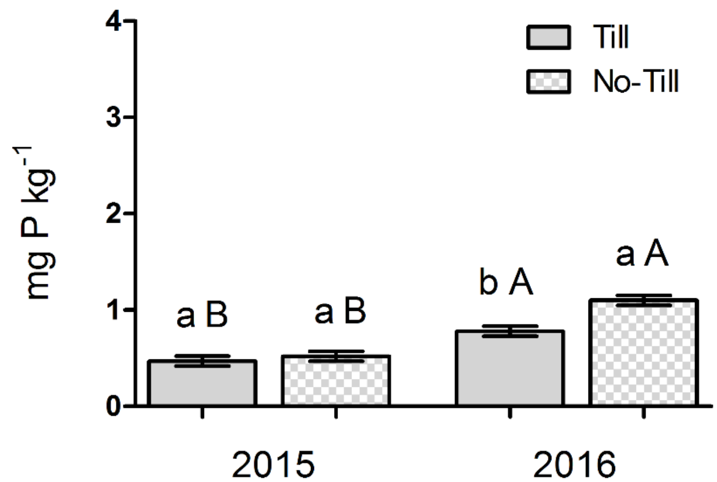

Figure 97. Absaraka mean (±S.E.) squash leaf P (mg kg^{-1}) between tillage across year and AMF treatments. Bars labeled with different lowercase letters differ between tillage within year ($P \leq 0.05$) according to Tukey's HSD. Bars labeled with different lowercase letters differ between year within tillage treatment ($P \leq 0.05$) according to Tukey's HSD.

Table 72. Treatment Effects on Squash Leaf Phosphorus at Dickinson.

Effect	P
Year	<0.0001
Tillage	0.0028
Year * Tillage	0.0052
AMF	0.3246
Year * AMF	0.1202
Tillage * AMF	0.9312
Year * Tillage * AMF	0.4146

At Dickinson, a year x tillage interaction was observed (Table 72) (p = 0.0052). No differences were observed between tillage treatments during 2015 (p = 0.8497). Differences were observed between tillage treatments during 2016, in which mulched no-till treatments were associated with greater squash leaf phosphorus compared to tilled treatments (0.69 vs. 0.48 mg kg^{-1}, respectively) (p = 0.0002) (Figure 98). Overall, 2016 was associated with greater squash leaf phosphorus compared to 2015 for mulched no-till treatments (0.69 vs. 0.32 mg kg^{-1}, respectively) (p < 0.0001) and for tilled treatments (0.48 vs. 0.31 mg kg^{-1}, respectively) (p = 0.0018) (Figure 98). The simple effect of AMF did not affect squash leaf phosphorus (Table 72) (p = 0.3246).

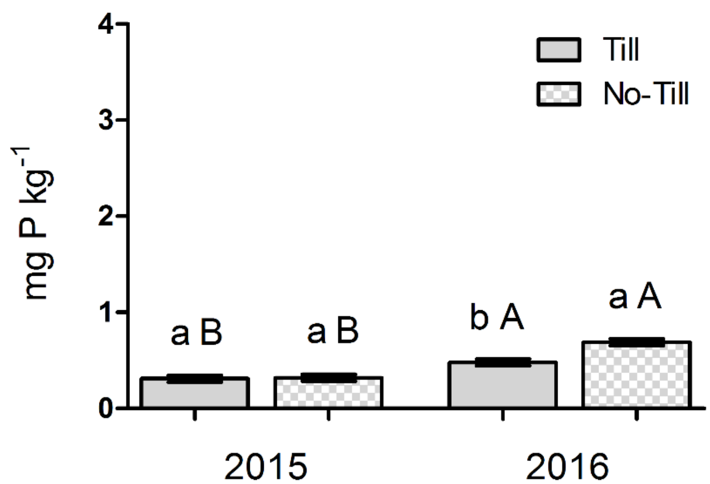

Figure 98. Dickinson mean (±S.E.) squash leaf P (mg kg^{-1}) between tillage across year and AMF treatments. Bars labeled with different lowercase letters differ between tillage within year ($P \leq 0.05$) according to Tukey's HSD. Bars labeled with different lowercase letters differ between year within tillage treatment ($P \leq 0.05$) according to Tukey's HSD.

Potassium

Table 73. Treatment Effects on Squash Leaf Potassium at Absaraka.

Effect	P
Year	0.0007
Tillage	0.1964
Year * Tillage	0.2276
AMF	0.7138
Year * AMF	0.8418
Tillage * AMF	0.5538
Year * Tillage * AMF	0.7487

At Absaraka, 2015 was associated with greater squash leaf potassium compared to 2016 (6.6 vs. 4 mg kg^{-1}, respectively) ($p = 0.0007$) (Figure 99). The simple effects of tillage and AMF did not affect squash leaf potassium (Table 73) ($p = 0.1964$ and $p = 0.7138$, respectively).

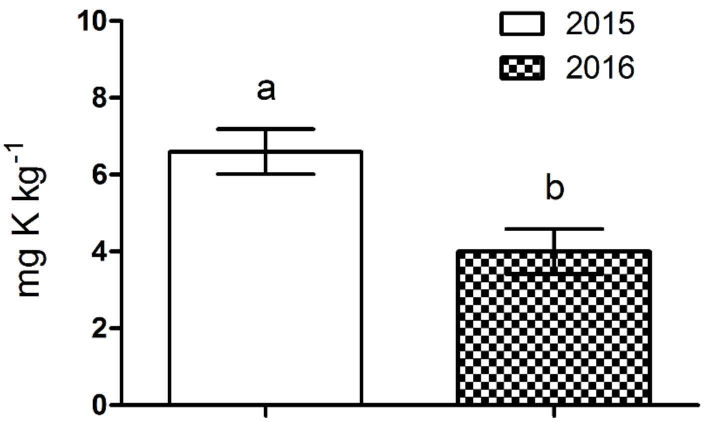

Figure 99. Absaraka mean (±S.E.) squash leaf K (mg kg^{-1}) between year across tillage and AMF treatments. Bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD.

Table 74. Treatment Effects on Squash Leaf Potassium at Dickinson.

Effect	P
Year	0.2327
Tillage	<0.0001
Year * Tillage	0.7823
AMF	0.6800
Year * AMF	0.4443
Tillage * AMF	0.9197
Year * Tillage * AMF	0.4589

At Dickinson, mulched no-till treatments were associated with greater squash leaf potassium compared to tilled treatments (3.7 vs. 3.1 mg kg^{-1}, respectively) ($p < 0.0001$) (Figure 100). The simple effect of AMF did not affect squash leaf potassium (Table 74) ($p = 0.6800$).

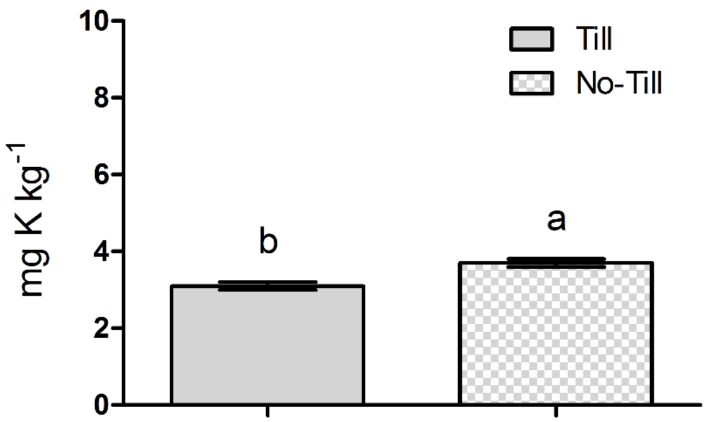

Figure 100. Dickinson mean (±S.E.) squash leaf K (mg kg^{-1}) between year across tillage and AMF treatments. Bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD.

Crop leaf nutrients will be discussed for each respective crop within crop yield below.

Crop Yield

Pea

Table 75. Treatment Effects on Pea Yield at Absaraka.

Effect	P
Year	<0.0001
Tillage	0.0016
Year * Tillage	0.0135
AMF	0.8263
Year * AMF	0.5141
Tillage * AMF	0.7747
Year * Tillage * AMF	0.5942

At Absaraka, a year x tillage interaction was present for pea yield (p = 0.0135). During 2016, mulched no-till were associated with greater pea yield than in tilled treatments (94 vs. 53 g plant-1, respectively) (p = 0.0002) (figure 101). Pea yield did not differ between tilled and no-till treatments during 2015 or 2017 (p = 0.7999 and p = 0.1579, respectively). Within tilled treatments, differences were observed for pea yield between 2015 and 2016 and between 2015 and 2017 (27 vs. 53 g plant^{-1} and 27 vs. 56 g plant^{-1}, respectively) ($p = 0.0059$ and $p = 0.0026$, respectively) (Figure 101). No differences were observed between 2016 and 2017 within tilled treatments ($p = 0.7010$). Within mulched no-till treatments, differences were observed between 2015 and 2016, between 2015 and 2017, and between 2016 and 2017 (29 vs. 94 g plant^{-1}, 29 vs. 69 g plant^{-1}, and 94 vs. 69 g plant^{-1}, respectively) ($p < 0.0001$, $p = 0.0002$, and $p = 0.0084$, respectively) (Figure 101). The simple effect of AMF did not affect pea yield (Table 75) (p = 0.8263).

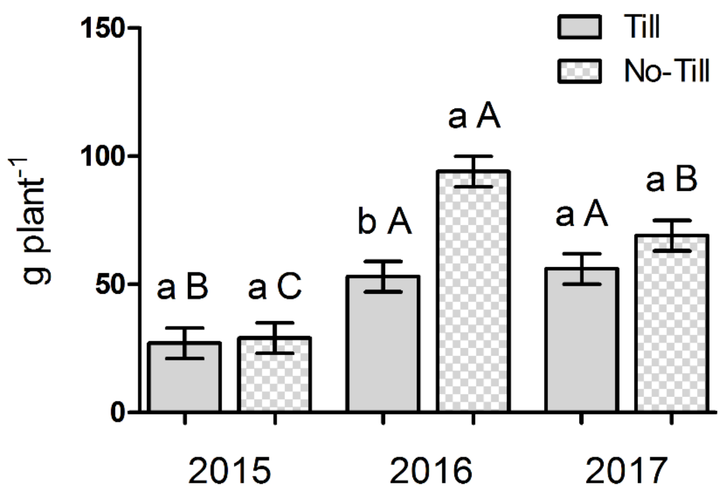

Figure 101. Absaraka mean (±S.E.) pea yield (g plant^{-1}) between tillage and year across AMF treatments. Bars labeled with different lowercase letters differ between tillage within year ($P \leq 0.05$) according to Tukey's HSD. Bars labeled with different uppercase letters differ between year within tillage ($P \leq 0.05$) according to Tukey's HSD.

Table 76. Treatment Effects on Pea Yield at Dickinson.

Effect	P
Year	0.1255
Tillage	0.0245
Year * Tillage	0.1008
AMF	0.6747
Year * AMF	0.7483
Tillage * AMF	0.3814
Year * Tillage * AMF	0.5503

At Dickinson, a tillage effect was observed for pea yield ($p = 0.0245$). Mulched no-till treatments were associated with greater pea yield compared to tilled treatments (39 vs. 31 g plant^{-1}, respectively) (Figure 102). The simple effect of AMF did not affect pea yield (Table 76) ($p = 0.6747$).

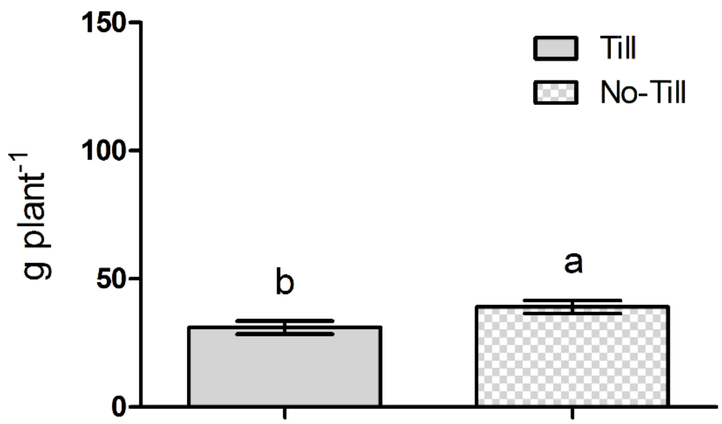

Figure 102. Dickinson mean (±S.E.) pea yield (g plant^{-1}) between tillage across year and AMF treatments. Bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD.

Our results are similar to those of Orion and Masiunas (2004), who reported that no-till with winter killed mustard cover crop residue treatment was associated with greater snap pea yield compared to conventionally tilled treatments with no cover residues. Conversely, Weston (1990) observed poor germination and slowed growth rates for pea crops grown in no-till systems that utilized herbicides to terminate fall seeded cover crop species. Al-Khatib et al. (1997) found that green pea combined with fall-planted and spring-incorporated rye, rapeseed, and white mustard was associated with greater green pea yield when compared to typical wheat/green pea rotation.

Regarding Absaraka results, the reduction of soil nitrogen over time (Figure 28) could be a factor accounting for the reduction of chlorophyll between 2016 and 2017 (Figure 59).

Mulched no-till was consistently associated with greater soil NO_3-N compared to tillage (Figure 28), which may explain the greater pea chlorophyll and yield results for no-till treatments compared with tilled treatments. For Dickinson, soil NO_3-N was greatest for no-till treatments during 2017 and overall greater in no-till than in till treatments across all years (Figure 29). This could explain the greater yield results for no-till treatments.

Another explanation for yield differences between tillage treatments might be soil moisture conservation provided by the deep-mulch no-till. At Absaraka, irrigation was not applied until 2017, when precipitation was limited (Table 2). Pea leaf stomatal conductance did not differ by tillage type at Absaraka, but was influenced by AMF (Figure 68). At Dickinson, pea leaf stomatal conductance was greater within mulched no-till treatments compared to tilled treatments (Figure 70), perhaps due to limited ambient precipitation which may have been more limiting under tilled treatments (Table 3).

Soil NO_3-N did not differ between 2016 and 2017 in tilled treatments, but both years had lower soil NO_3-N than in 2015. However, low levels of soil NO_3-N during 2016 and 2017 within tilled treatments may have been offset by nitrogen fixation provided by the crop and rhizobium symbiosis. This may explain why leaf chlorophyll content did not vary between 2016 and 2017 (Table 36). While significant differences were observed for pea yield between tillage treatments, the economical differences between no-till and till yields may not be as significant (39 vs. 31 g $plant^{-1}$, respectively).

Onion

Table 77. Treatment Effects on Onion Yield at Absaraka.

Effect	P
Year	<0.0001
Tillage	<0.0001
Year * Tillage	<0.0001
AMF	0.9519
Year * AMF	0.6016
Tillage * AMF	0.6290
Year * Tillage * AMF	0.2659

At Absaraka, a year x tillage interaction was observed (Table 77) ($p < 0.0001$). No differences were observed for onion yield between tillage treatments during 2015 ($p = 0.1261$). During 2016 and 2017, mulched no-till treatments were associated with greater onion yield compared to tilled treatments (496 vs. 321 g $bulb^{-1}$ and 488 vs. 246 g $bulb^{-1}$, respectively) ($p < 0.0001$ for both comparison) (Figure 103). Within tilled treatments, differences were observed between 2016 and 2017 (283 vs. 321 g $bulb^{-1}$, respectively) ($p = 0.0029$) (Figure 103). No differences were observed between 2015 and 2016 or between 2015 and 2017 within tilled treatments ($p = 0.0972$ and $p = 0.1079$, respectively). Within mulched no-till treatments, differences were observed between 2015 and 2016 and between 2015 and 2017 (318 vs. 496 g $bulb^{-1}$ and 318 vs. 488 g $bulb^{-1}$, respectively) ($p < 0.0001$ for both comparisons) (Figure 103). No differences were observed between 2016 and 2017 within mulched no-till treatments ($p = 0.7243$). The simple effect of AMF did not affect onion yield (Table 77) ($p = 0.9515$).

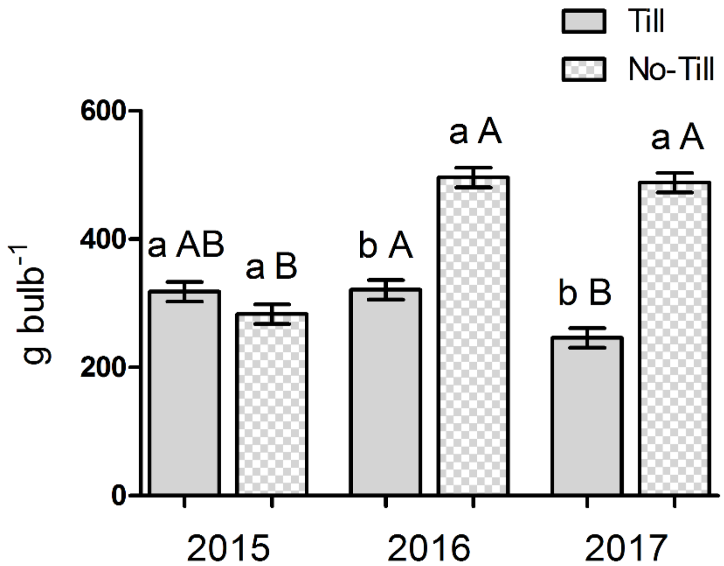

Figure 103. Absaraka mean (±S.E.) onion yield (g bulb^{-1}) between tillage and year across AMF treatments. Bars labeled with different lowercase letters differ between tillage within year ($P \leq 0.05$) according to Tukey's HSD. Bars labeled with different uppercase letters differ between year within tillage ($P \leq 0.05$) according to Tukey's HSD.

Table 78. Treatment Effects on Onion Yield at Dickinson.

Effect	P
Year	0.0348
Tillage	<0.0001
Year * Tillage	0.0001
AMF	0.1735
Year * AMF	0.3508
Tillage * AMF	0.2295
Year * Tillage * AMF	0.9067

At Dickinson, a year x tillage interaction was observed (Table 78) ($p = 0.0001$). Mulched no-till treatments were associated with greater onion yield compared to tilled treatments during 2015, 2016, and 2017 (326 vs. 187 g bulb^{-1}, 249 vs. 159 g bulb^{-1}, and 356 vs. 76 g bulb^{-1}, respectively) ($p < 0.0001$, $p = 0.0031$, and $p < 0.0001$, respectively) (Figure 104). Within tilled treatments, 2015 and 2016 were associated with greater onion yield compared to 2017 (187 vs.

76 g bulb^{-1} and 159 vs. 76 g bulb^{-1}, respectively) (p = 0.0004 and p = 0.0062, respectively) (Figure 104). No differences were observed within tilled treatments between 2015 and 2016 (p = 0.3328). Within mulched no-till treatments, 2015 was associated with greater onion yield compared to 2016 (326 vs. 249 g bulb^{-1}) (p = 0.0108) and 2017 was associated with greater onion yield compared to 2016 (356 vs. 249 g bulb^{-1}, respectively) (p = 0.0006) (Figure 104). No differences for onion yield were observed between 2015 and 2017 within mulched no-till treatments (p = 0.2900). The simple effect of AMF did not affect onion yield (Table 78) (p = 0.1735).

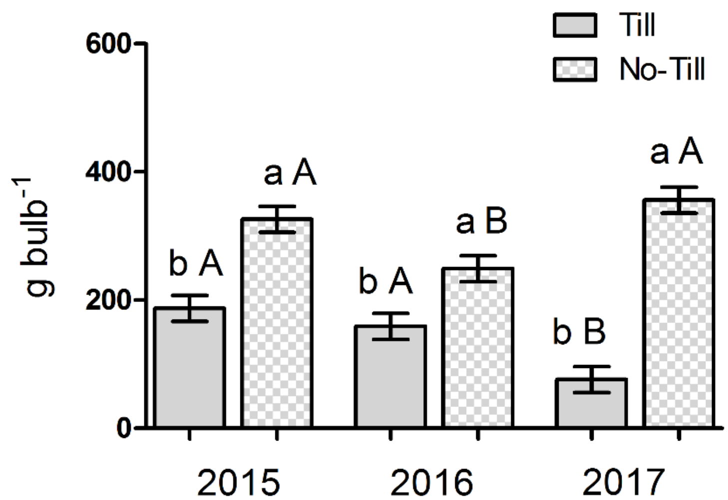

Figure 104. Dickinson mean (±S.E.) onion yield (g bulb^{-1}) between tillage and year across AMF treatments. Bars labeled with different lowercase letters differ between tillage within year ($P \leq$ 0.05) according to Tukey's HSD. Bars labeled with different uppercase letters differ between year within tillage ($P \leq 0.05$) according to Tukey's HSD.

Onion yield was consistently greater within mulched no-till treatments compared to tilled treatments (Figure 103 and 104). This yield increase may be linked greater leaf chlorophyll content in mulched plots (Figure 60 and 63), which may have resulted from greater soil NO_3-N (Figure 28 and 29). Mulched no-till treatments were also associated with greater soil P levels at Absaraka (Figure 30). Onion leaf stomatal conductance varied only in year, where 2016 was greater than 2017 at both Absaraka and Dickinson (Figure 71 and Figure 72), perhaps due to precipitation variation between years (Table 2 and Table 3). Our results are not consistent with those of Campbell and Anderson (1980), who observed onion yield to be consistently greater within tilled plots when compared to no-till plots, regardless of herbicide used to control weeds. Vollmer et al. (2010) conducted a study that evaluated over-wintering no-till onion systems, which incorporated winter killed cover crop residue for weed suppression and included three levels of supplemental nitrogen at 0%, 75%, and 150% of recommended rates (0, 105, and 210 kg ha^{-1}, respectively). Bare ground (no cover crop residue mulch) was found to have higher large-grade onions, however, marketable yields were determined to be no different between bare ground and cowpea residue no-till treatments.

Beet

Table 79. Treatment Effects on Beet Yield at Absaraka.

Effect	P
Year	0.7111
Tillage	0.0003
Year * Tillage	0.5432
AMF	0.5822
Year * AMF	0.3517
Tillage * AMF	0.6900
Year * Tillage * AMF	0.1602

At Absaraka, the simple effect of tillage affected beet yield ($p = 0.0003$). Mulched no-till treatments were associated with greater beet yield compared to tilled treatments (305 vs. 225 g $plant^{-1}$, respectively) (Figure 105). The simple effect of AMF did not affect beet yield (Table 79) ($p = 0.5822$).

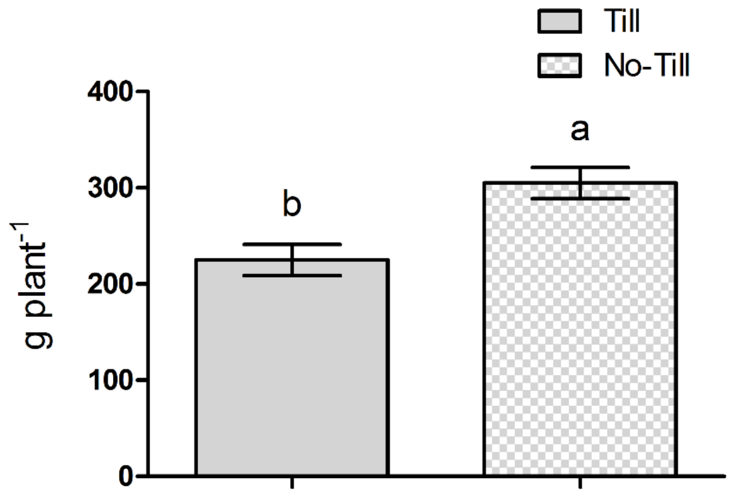

Figure 105. Absaraka mean (±S.E.) beet yield (g plant^{-1}) between tillage across year and AMF treatments. Bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD.

Table 80. Treatment Effects on Beet Yield at Dickinson.

Effect	P
Year	<0.0001
Tillage	0.0537
Year * Tillage	0.4914
AMF	0.7232
Year * AMF	0.7417
Tillage * AMF	0.0528
Year * Tillage * AMF	0.2517

No differences for beet yield were observed from simple effects of AMF or tillage, although mulched no-till treatments tended to have greater yield compared to tilled treatments (149 vs. 106 g plant^{-1}, respectively) (data not shown) ($p = 0.7232$ and $p = 0.0537$, respectively). Beet yield was greater within mulched no-till treatments compared to tilled treatments at Absaraka (Figure 105). Tilled treatments were associated with greater beet leaf chlorophyll content (Figure 65), despite consistent greater soil NO_3-N within mulched no-till treatments (Figure 28 and 29). Mulched no-till treatments were also associated with greater beet leaf P

(Figure 91 and Figure 92) which may be related to our findings of greater soil P levels at Absaraka (Figure 30). Mulched no-till treatments resulted in greater beet leaf K (Figure 93 and Figure 94), which may be related to mulched no-till treatment soil K levels being consistently greater than tilled treatments at Absaraka and at Dickinson during 2016 and 2017. A previous study observed similar beet yields between no-till with rye residue (only fresh weight was provided at 5 kg m^{-2}) and conventionally tilled treatments. Conversely, Koch et al. (2009) attributed reductions in beet yield from no-till from crop sensitivities to elevated soil strength (magnitude of shear stress a soil can sustain).

Squash

Table 81. Treatment Effects on Squash Yield at Absaraka.

Effect	P
Year	0.0647
Tillage	0.0121
Year * Tillage	0.0511
AMF	0.4814
Year * AMF	0.4860
Tillage * AMF	0.9005
Year * Tillage * AMF	0.4108

At Absaraka, a tillage interaction was observed (p = 0.0121). Mulched no-till treatments were associated with greater squash yield compared to tilled treatments (16 vs. 13 kg $plant^{-1}$, respectively) (Figure 106). The simple effect of AMF did not affect beet yield (Table 81) (p = 0.4814).

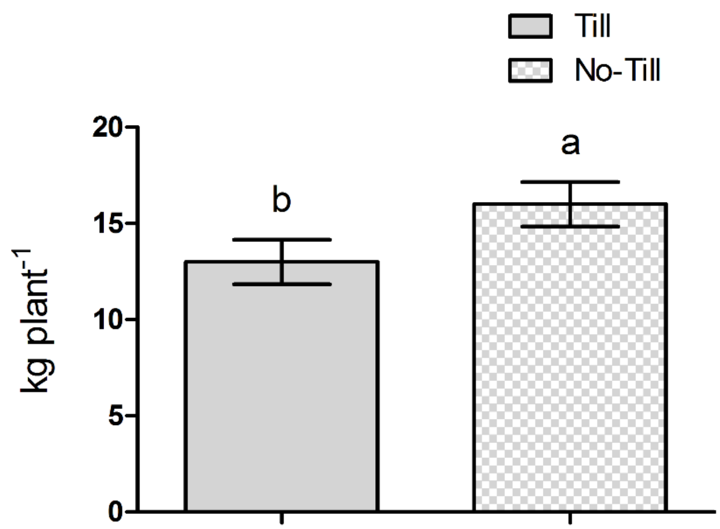

Figure 106. Absaraka mean (±S.E.) squash yield (kg plant^{-1}) between tillage across year and AMF treatments. Bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD.

Table 82. Treatment Effects on Squash Yield at Dickinson.

Effect	P
Year	<0.0001
AMF	0.0571
Tillage * AMF	0.4372

At Dickinson, a tillage effect observed ($p < 0.0001$). Mulched no-till treatments were associated with greater squash yield compared to tilled treatments (3 vs. 1.7 kg plant^{-1}, respectively) (Figure 107). The simple effect of AMF did not affect squash yield (Table 82) (p = 0.0571). While not significant, plots without AMF tended to have greater squash yield compared to plots with AMF (2.5 vs. 2.1 kg plant^{-1}, respectively) (data not shown).

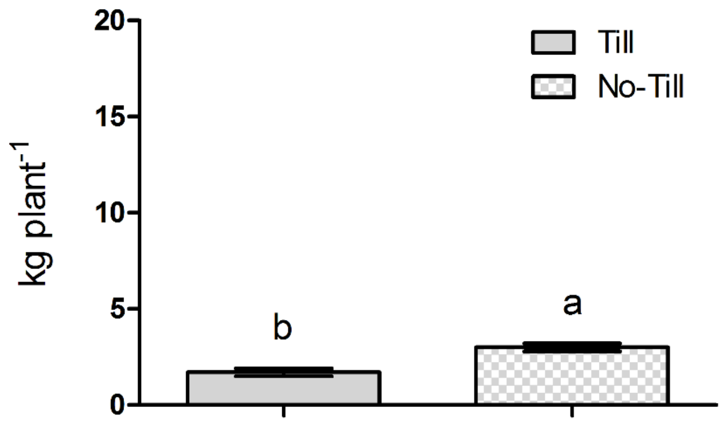

Figure 107. Dickinson mean (±S.E.) squash yield (kg plant^{-1}) between tillage across year and AMF treatments. Bars labeled with different lowercase letters differ ($P \leq 0.05$) according to Tukey's HSD.

Squash yield was consistently greater within mulched no-till treatments compared with tilled treatments (Figure 106 and Figure 107). This may be attributed to greater levels of soil NO_3-N, P, and K (Figure 28, 29, 30, 32, and 33). Squash leaf total nitrogen was observed to be greater within mulched no-till treatments compared to tilled treatments (Figure 95 and 96). Squash leaf phosphorus was consistently greater within mulched no-till treatments compared to tilled treatments (Figure 97 and 98). Squash leaf potassium was also greater within mulched no-till treatments compared to tilled treatments, particularly, at Dickinson (Figure 100). Squash leaf chlorophyll was not influenced by tillage or AMF treatments, despite squash leaf total nitrogen being greater within mulched no-till treatments compared to tilled treatments (Figure 95 and 96) and greater Soil NO_3-N within mulched no-till treatments at both Absaraka and Dickinson (Figure 28 and 29). Squash leaf stomatal conductance was greater within mulched no-till treatments compared to tilled treatments only during 2017 at Dickinson, and may be attributed to greater amounts of precipitation during 2017 (Table 3). Yield for squash plants at Absaraka and Dickinson differed between mulched no-till treatments and tilled treatments (16 vs. 13 kg plant^{-1}

and 3 vs. 1.7 kg plant^{-1}, respectively) (Figure 106 and 107, respectively). Despite these differences in yield, squash yield at Dickinson was fairly poor. This may have been due to greater competition with weeds, inconsistent watering, and root disturbance from rodents. Stresses on squash crop may have resulted in poor growth, particularly in 2017, thus shifting photosynthate allocation towards greater chlorophyll production.

Leavitt et al. (2011) observed a reduction in zucchini yield when grown under no-till, roller-crimped winter rye, hairy vetch, and winter rye/hairy vetch mixture cover crops. An exception of one year at one site resulted in no-till with hairy vetch residue yielding similarly to conventionally tillage with residue treatment. One difference between Leavitt et al (2011) and our study, is within the method of planting. Leavitt et al. (2011) transplanted 3 week old starts whereas we directly sowed our squash. Leavitt et al. (2011) attributed low zucchini yields to a reduction in the number of soil growing degree-days, which differed between no-till with roller-crimped cover crop and roto-tilled with no cover crop treatments, particularly at early and mid season (4 and 8 weeks after rolling, respectively). Early season (2-4 weeks after rolling) residue biomass for winter rye and hairy vetch/rye mixture differed between 2008 and 2009 (8000 kg ha^{-1} and 5800 kg ha^{-1} and 5000 kg ha^{-1} and 2900 kg ha^{-1}, respectively). Our strategy of opening the mulch in the spring may have allowed for a capturing greater solar radiation; thus, avoiding potential emergence, growth, and development issues between crop and soil growing degree days. O'Rourke and Peterson (2016) observed similar yield results to ours, and reported that overall average fruit weight was greater within no-till than in strip-till and conventional-till treatments for pumpkins. A number of studies have determined that with a reasonable degree of weed management, squash grown in no-till systems yields no differently than squash grown in conventional tillage systems (Knavel and Herron, 1986; NeSmith et al., 1994; Walters et al., 2005; Walters and Kindhart, 2002).

When combining cultural and biological strategies, use of dead winter rye cover crop residue as a mulch can either enhance or suppress squash yields depending on ambient climactic conditions of a given growing season (Walters et al., 2005). Walters and Young (2008) concluded that herbicide-suppressed winter rye living mulch systems are not practical given crop injury attributed to allelopathy on winter squash, while NeSmith et al. (1994) observed no difference in yields of summer squash under no-till systems with winter rye residues compared with conventional tillage systems. Chung and Miller (1995) observed some allelopathic effects on weed species; however, aqueous extracts were more effective compared to alfalfa residue incorporated into silica sand at 2 g kg^{-1}. Our results most likely differ due to our residue mulch source, as rye is often used and is recognized as having allelopathic properties. Organic systems often suffer from low soil N, as such, use of alfalfa mulch assists in overcoming both potential allelopathic effects on crop as well as adding soil N.

CONCLUSIONS

Mulched no-till treatments were associated with reductions in weed densities throughout each growing season, at both of the research sites. Squash crops were consistently associated with reductions in weed densities for both tilled and mulched plots at Absaraka and Dickinson during 2016 and 2017, demonstrating that squash is highly competitive against weeds. Weed seedbanks were reduced within both tillage treatments at Absaraka, likely due to frequent weeding events throughout each season. Mulched no-till treatments resulted in more pronounced reductions in weed seedbank densities at Absaraka, whereas seedbank densities at Dickinson did not change over time for mulched no-till, tillage treatments resulted in increases of seedbank density over time. Producers may be able to save time/money by focusing on weed seedbank management, as densities decline over time, germinable seeds are reduced over time; thus, requiring fewer labor resources for removing weeds.

Time required for weeding was affected by crop entry, where squash was associated with less time needed to remove weeds. At both sites, less weeding time was required within mulched no-till plots compared to tilled plots. Although the time required within tilled treatments increased between 2015 and 2016 at Absaraka (Figure 15), this could be due to more seeds within the seedbank germinating from annual tillage disturbance, thus decreasing the seedbank densities over time. Time required for applying mulch was not considered, which may impact time saved in weeding. Differences in weeding times between tillage at Dickinson were marginal, likely due to the mulch selected during 2015, which was evidently contaminated with weed seeds, which highlights the need to carefully select mulches free from weed seed contamination. Costs and time associated with tilled, growing, and bailing or purchasing mulch were not considered, which also may impact a producers decision in utilizing this mulch no-till practice. Ideally, a producer would grow the alfalfa on-farm, using the alfalfa phase on a field as a means to improve soil nutrients and to manage creeping perennial weeds, which frequently increase over time in organically managed fields. Using this approach, growing alfalfa would provide additional valuable agroecosystem benefits, although labor and appropriate machinery would be required to grow and harvest the alfalfa.

Soil quality was generally improved by the mulched no-till approach. For example, aggregate stability decreased within tillage treatments over time at Absaraka. However, a more perplexing result occurred at Dickinson, where both tillage treatments were associated with increased aggregate stability over time, and during 2017 no differences between tillage treatments were observed for aggregate stability. Mulched no-till treatments were associated with greater soil NO_3-N compared to tilled treatments, which may reduce the need and cost for fertilizer inputs annually sufficient for crop growth. Soil P increased over time within mulched no-till treatments, whereas slight declines were observed within subsequent years for tilled treatments. At Dickinson, soil P levels did not change over time or differ between tillage treatments and were considered high. This could have resulted from repeated applications of cow manure for N fertility. AMF colonization could have been affected by abundant levels of soil P, and furthermore AMF inoculation may be more efficacious in soils where soil P is scarce and endemic AMF populations have been diminished. Soil respiration was observed to decrease over time within tilled treatments at Absaraka, while at Dickinson, mulched no-till was associated with increased soil respiration. This could be due to precipitation differences between sites, as well as edaphic properties of each soil. AMF colonization of crops were not affected by tillage or by inoculant, but differed between crop species. Within our study, AMF inoculation did not result in greater AMF root colonization. However, we only quantified % AMF colonization, but did not identify which species were colonizing roots. Linking AMF species identity to specific functions would add more mechanistic insights about the roles that endemic AMF and AMF added via inoculation play in enhancing crop health. Future research should be designed to better quantify land management practice impacts on AMF, using a single crop and including crop specific AMF species. Crop leaf nutritional status could often be attributed to soil chemical properties which differed between tillage systems, especially at Absaraka. Factors that may have influenced soil nutrient contributions of mulch include source and residue of the mulch itself, initial soil fertility, and fertilizer source. Overall, crops grown under mulched no-till yielded greater or similar to tilled treatments.

Overall, mulched no-till treatments resulted in a reduction within the weed density and seedbank density. Despite a lack of data for time required in applying mulch each year, time required for weed removal within mulched no-till treatments was decreased compared to tilled treatments. Mulch no-till treatments maintained or increased soil quality indices, resulting in greater levels of soil NO_3-N, P, K, organic matter, and active carbon. Mulched no-till treatments were associated with greater quantities of soil respiration, microbial biomass, and AMF biomass compared to tilled treatments. Mulched no-till were associated with greater total N, P, and K within crop leaf tissue compared to tilled treatments. Mulched no-till were associated with greater or similar crop yield compared to tilled treatments. AMF inoculant had marginal effects on soil quality and may be a better investment in soils lacking endemic AMF. Future research should focus on economic analysis to compare both production systems to include time and costs for tilling applications compared to planting, cutting, bailing, and applying alfalfa hay mulch as to provide producers with information for decision making regarding management practices.

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