USING COVER CROPS IN WHEAT-CORN ROTATIONS TO PROVIDE FORAGE WHILE IMPROVING SOIL

By

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ABSTRACT

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The time window after wheat harvest in a wheat (*Triticum aestivum* L.)- corn (*Zea mays* L.) rotation could be used to grow cover crops (CC) to provide forage while protecting soil from erosion. Field experiments were initiated in East Lansing, MI to determine the consequences of partial removal of CC biomass on soil improvement and crop yield and quality. Soft red winter wheat (‘Hopewell’ and ‘Red Dragon’) was planted in October of 2013 and 2014 and harvested in July 2014 and 2015. Cover crops included: frost-seeded red clover, and summer-seeded alfalfa, cowpea, sunn hemp, radish, oat/field pea mixture, sudangrass, sorghum x sudangrass, and teffgrass. Half of each CC plot was mechanically harvested eight weeks after planting. Harvested forage dry matter yield was greatest for red clover (4.3 Mg ha^{-1}); oat-pea mix (2.5 Mg ha^{-1}), sudangrass/sudex (1.8 Mg ha^{-1}) and radish (1.2 Mg ha^{-1}) ($P < 0.01$) yielded less. Corn grain yield harvested in October averaged 13.7 Mg ha^{-1} and did not differ across CC species or forage harvest treatment (P > 0.05). Harvesting forage reduced total N removal (TNR) in subsequent corn for red clover only; harvesting forage did not affect TNR after any other CC (CC x harvest interaction, $P < 0.05$). In the harvested system, TNR did not differ ($P > 0.05$) between for any CC, but unharvested RCL (374 kg N ha^{-1}) had greater ($P < 0.01$) TNR than oat-pea mix (338 kg N ha^{-1}). There were no differences among treatments for soil permanganate oxidizable carbon POXC ($P > 0.05$). Harvesting cover crops for forage after winter wheat harvest in Michigan can give harvestable forage and acceptable nutritive value.

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CHAPTER 1

LITERATURE REVIEW

Crop Rotations

Crop rotations have been used for centuries. Ancient kingdoms and empires, including the Romans, Grecians, Chinese and Egyptians, documented this agricultural practice (White, 1970; Angus et al., 2015). A three-year crop rotation called “food, feed, and fallow” was documented in the Middle Ages and Roman Empire. This rotation divided the farm acres into three sections; a human food crop such as wheat, an animal feed such as barley or oats, and a section that was not planted (fallow) (White, 1970). Later in the 18th century, European farms increased in size and farmers began to experiment with crop rotations, dividing the greater farm land area into four, four-year crop rotations which consisted of turnip, barley, clover and wheat (Evans, 1998).

Crop rotation is defined as a cropping sequence that contains fallows, forages, or special-use crops in addition to the normally grown species crops that produce food, fiber or fuel such as wheat and corn (Angus et al., 2015). Though the terms “crop rotation” or “cropping sequences” was not used before the 1960’s and documented first in the United Kingdom (Selman, 1969), many understood the benefits that came from growing unusual crops other than the normal species grown. Theophrastus wrote in the 4th Century that ‘wheat exhausts the land more than any other crop’ and ‘beans. . .even seem to manure it’ (Hort, 1926). While an ancient Roman text reads that "some crops are to be planted not so much for the immediate yield as with a view to the following year" (Harrison et al., 1913). The increased yields that are associated with crop rotations are now referred to as the rotation effect (Ellis et al., 1988; Pierce and Rice, 1988).

Decline of Crop Rotations

Before the 1940s and World War II, crop rotation was commonly used for many benefits including controlling insect infestations, controlling weeds, and reducing soil erosion (Zentner et al., 2002). After World War II, use of crop rotations began to decline rapidly, leading to increasing monocultures, and cropping systems that were homogenous with little genetic and plant diversity (Power and Follett, 1987). This decline occurred because of the introduction and availability of inexpensive synthetic fertilizers, coupled with more effective pesticides (Crookston et al., 1991; Bullock, 1992) that could substitute for pest suppression by the rotation. Mechanized farming has had a huge effect on agricultural dynamics in the United States (Bullock, 1992) as well as Europe (Leteinturier et al., 2006), allowing farmers to manage large acreages of monoculture crops. Brazil is also moving towards more industrialized agriculture and crop intensification patterns. This is shown by farming moving away from the typical farming pattern of growing a single crop per year to a more intensified growing pattern of two consecutive cash crops per year, depleting soil water and nutrients (Arvor et al., 2012).

Genetically modified organisms (GMOs), also known as genetically modified (GM) crops, such as corn and soybeans, have also contributed to the decline of crop rotations. To a great extent, GMOs were and are still designed to improve on the conventional crop varieties, for various purposes. For example, in corn, VT Triple PRO® (Monsanto), P1498AM® (DuPont) and DEKALB® GM varieties are used for pest control (DuPont, 2016; Monsanto, 2016) while Roundup Ready® GM varieties are used to improve quality (DuPont, 2016; Monsanto, 2016) by increasing the ease of weed control and increased yields. In the USA, Canada, Brazil, and several other countries, GM crops like corn, soybeans, cotton, and canola are commonly used and have replaced many of the conventional varieties (Gianessi, 2005; James, 2007; Reuter et al., 2011).

With the decline of crop rotation, the increase of industrialized agriculture and the use of GM crops, synthetic fertilizer, and pesticides, negative impacts and costs began to be noticed. Pesticide resistance has increased (Wolfenbarger and Phifer, 2000; Gianessi, 2005), leading to a shift in plant genetics and reducing the effectiveness of pesticides for insect control. Furthermore, the use of pesticides is associated with a decrease in the population of many beneficial insects, such as bees (Crane and Walker, 1983), a noticeable decrease in soil health and organic matter and an increase in soil movement or erosion (Pimentel et al., 1995).

Another negative impact of monocultures is yield drag or depression (Bullock, 1992; Sumner et al., 1990). In the 1980s, it was documented that corn grown on land planted to corn in the previous year or grown as a monoculture yielded up to 15% less grain than corn rotated with other crops (Sundquist et al., 1982). Soybean yields also declined 10 to 15% when grown as a monoculture (Bhowmik and Doll, 1982). With the realization of these potential damaging effects and the rise of the sustainable agriculture movement, additional research occurred to test hypothesizes as to the role of crop rotation in today's modern farming systems.

Benefits of Crop Rotations

Crop rotations benefit agricultural production, and modern farmers and researchers have recognized the need to include rotation for increased crop yields (Bhowmik and Doll, 1982; Sundquist et al., 1982 Ellis et al., 1988; Sumner et al., 1990; Porter et al.,1997), reduced pest damage (Bullock, 1992; Howard et al., 1998; Angus et al., 2015), reduced weeds (Liebman and Dyck, 1993; Colbach and Debaeke, 1998), and increased organic matter leading to a richer and healthier soil (Karlen et al., 2006; Zhang et al., 2014).

Daubeny (1845) and Lawes and Gilbert (1894) completed some of the first structured experiments showing the value and justification of a rotation in comparison with continuous cropping. Daubeny (1845) showed his results in a 10-year experiment in Rothamsted, United Kingdom, which three-fourths of the rotating cropping systems out-yielded the continuous cropping systems. The Lawes and Gilbert (1894) experiment showed that yields of broadleaf crops, such as soybeans, were much greater when grown in rotation than when grown continuously; barley yields were similar, and wheat yielded more when grown in rotation. Both experiments showed that the productivity of the crop rotation was greater than that of the continuous cropping system. Several other studies (Bhowmik and Doll, 1982; Sundquist et al., 1982; Ellis et al., 1988; Sumner et al., 1990; Porter et al.,1997; Nevens and Reheul, 2001; Zhang et al., 2014; Angus et al., 2015) also showed that rotations improved sustainability of cropping systems over continuous planting of the same crop.

With the increased intensification of agriculture to meet the food supply demand comes a concern for the environment (Piorr, 2003) and the impacts associated with industrialized farming. Farmers and researchers have found that reintroducing crop rotations into agricultural cropping systems not only increased yields, but improved soil structure and productivity. The realization of the importance of soil, the complexity of the soil ecosystem encompassing plant, water, nutrients, microbes, insects and mammal interactions (Bossio and Scow, 1998; Degens et al., 2000; Girvan et al., 2003) sparked interest in sustainable agriculture (Leteinturier et al., 2006).

Farming systems use cover crops for several reasons, some of the main reasons include weed suppression (Teasdale,1996), reduce soil erosion (Dabney et al., 2001), increase organic matter (Teasdale et al., 2007), and to break pest and disease cycles (Derpsch et al., 2010) and an additional source for nutrients (Blevins et al., 1990; Honeycutt et al., 1996; Hartwig and Ammon 2002; Vyn et al., 2000; Henry et al., 2010; Schipanski and Drinkwater, 2011) to benefit the cash crops. Interest and research in crop rotations, soil communities and interactions, organic matter, tillage and chemical practices, living mulches cover crops and possible interactions between all of them have increased in the past few decades.

Cover Crops

With the abundant, cheap, and fertile farming land that was available during the 1800's (Mitchell et al., 1991) in the United States, farmers did not have a reason to develop an awareness or interest in preserving soil productivity through soil conservation. In the 1920s, the U.S. Department of Agriculture recognized the problem of soil erosion, but little was done to encourage farmers to invest in soil conservation practices (Hartwig and Ammon, 2002). This all changed in the 1930s when the Dust Bowl hit the United States, forcing farmers and the public alike to become concerned about soil erosion and adopt conservation practices that included cover crops and living mulches.

A cover crop is defined as any living ground cover that is planted into or after a main crop and then killed before the next crop is planted (Hartwig and Ammon, 2002), either by winter kill, chemical application, or tillage practice depending on the farming system. Living mulches are cover crops planted either before or with a main crop and maintained as a living ground cover throughout the growing season (Pimentel et al., 1995; Hartwig and Ammon, 2002). An example of a living mulch is red clover or alfalfa planted with wheat One of the main rationales of growing cover crops is to have growing, living plants on fields that would otherwise be fallow. Growing cover crops allows farmers to take better advantage of resources provide by the soil, sun and water while improving soil health and structure (Pimentel et al., 1995). This occurs because living plant cover protects the soil from erosion or loss (Hartwig and Ammon, 2002; Clark, 2007), scavenges nutrients that are otherwise unavailable or leached away during the fallow season (Hartwig and Ammon, 2002; Clark, 2007; Henry et al., 2010), holds and cleans water (Hartwig and Ammon, 2002), and provides nutrients to the cash crop planted after the cover (Mitchell and Teel, 1977; Haystead and Marriot, 1978; Hargrove, 1986; Pimentel et al., 1995; Hartwig and Ammon 2002; Vyn et al., 2000; Henry et al., 2010; Schipanski and Drinkwater, 2011).

Cover crops have a wide variety of species diversity, adaption, uses, and benefits. Choice of cover crop is dependent on the location of the farm and the objectives of the farmer, and specific cover crop benefits are dependent on species choice (Snapp et al., 2005; Clark, 2007). One cover crop will not provide all possible benefits. The benefits of cover crops include; weed competition/suppression (Hartwig and Ammon, 2002; Clark, 2007), pest suppression and sustaining beneficial insect populations (Lazarus and White, 1984; Bugg and Waddington, 1994; Honeycutt et al., 1996; Hartwig and Ammon, 2002; Clark, 2007), nitrogen source and/or scavenger (Kroontje and Kehr, 1956; Mitchell and Teel, 1977; Haystead and Marriot, 1978; Ebelhar et al., 1984; Hargrove, 1986; Fox and Piekielek, 1988; Vyn et al., 2000), wildlife enhancement (Clark, 2007), and grazing/forage value (Moore, 2003; Clark, 2007). Other benefits focus primarily on soil improvement by: building soil organic matter (Dabney et al., 2001; Sainju et al., 2001; Hartwig and Ammon, 2002), improving soil structure and reducing compaction (Clark, 2007), reducing erosion (Pimentel et al., 1995; Kessavalou and Walters, 1999; Stivers-Young and Tucker, 1999; Snapp et al., 2001; Hartwig and Ammon, 2002), recycling nutrients (Wayland et al. 1998; Hartwig and Ammon, 2002; Weinert et al., 2002), enhancing water quality (Danso et al., 1991; Wayland et al., 1998; Vyn et al., 1999; Dabney et al., 2001; Hartwig and Ammon, 2002; Clark, 2007), and supporting increased activity and sustainability of beneficial microbial communities (Hartwig and Ammon, 2002; Morrone and Snapp, 2011).

Cover crops are commonly divided into four groups: legumes, grasses, grains, and brassicas (Clark, 2007; USDA NRCS, 2016). Cover crops are often also categorized by climatic region or a niche where a cover crop is well adapted, using USDA Hardiness Zones or photosynthetic pathway designation as cool- (C3 photosynthesis) or warm- (C4 photosynthesis) season species (USDA NRCS, 2016).

Cover Crop Groups and Niches

In early western Europe agriculture, forage legumes slowly became more common and noticeably improved soil fertility (Stinner et al.,1994). This led to an increase in legume popularity not only as a feed source, but as a cover crop. Legumes used as cover crops include: alfalfa (*Medicago sativa* L.), red clover (*Trifolium pratense* L.), white clover (*Trifolium repens* L.), peas (*Pisum sativum* L.), cowpea (*Vigna unguiculata* L. Walp), sunn hemp (*Crotalaria juncea* L.), and hairy vetch (*Vicia villosa* Roth). Legumes are desirable cover crops because they have the potential for fixing nitrogen, a portion of which will be available in the subsequent rotations for high-nitrogen–requiring crops such as corn (Kroontje and Kehr, 1956; Mitchell and Teel, 1977; Haystead and Marriot, 1978; Hargrove, 1986; Ebelhar et al., 1984; Fox and Piekielek, 1988; Hartwig and Ammon 2002; Vyn et al., 2000; Henry et al., 2010; Schipanski and Drinkwater, 2011). Another added benefit for some legumes is the development of a deep taproot, such as found in alfalfa (Moore, 2003; Clark, 2007), which can break up compaction layers (Waldron and Dakessian, 1982; Disparte, 1987; Meek et al., 1990; Chen and Weil, 2011) and scavenge for nutrients (Mitchell and Teel, 1977; Ebelhar et al., 1984; Hargrove, 1986; Vyn et al., 2000; Chen and Weil, 2011).

Grasses and grains are used for their ability to control erosion and provide high residue (Pimentel et al., 1995; Kessavalou and Walters, 1999; Stivers-Young and Tucker, 1999; Snapp et al., 2001). Several grasses and some grains are also considered for the potential to scavenge for nutrients (Clark, 2007), particularly nitrogen (Weinert et al., 2002; Snapp et al. 2005; Clark, 2007). This reduces loss of vital nutrients from soil and decomposing crop residues between rotations, and once grasses and grain residues are decomposed much of the nutrients are released back into the soil and available for uptake by the next crop. Grasses and grains used for cover crops include: sudangrass (*Sorghum bicolor L.*), sorghum x sudangrass hybrid [*Sorghum bicolor x S. bicolor (Piper) Stapf.*], teff grass (*Eragrostis tef* Zucc.), rye (*Secale cereal* L.), wheat (*Triticum aestivum* L.), oats (*Avena sativa* L.), pearl millet (*Pennisetum glaucum* L.), barley (*Hordeum vulgare* L.), and annual ryegrass (*Lolium multiflorum* L.).

Brassicas have been used for centuries as a food, feed, and oil source for both humans and animals, but were rarely used as a cover crop (Gupta and Pratap, 2007). The major cover crop benefits of the brassica group include N scavenging and weed suppression (Clark, 2007). Some brassicas such as oilseed radish (*Raphanus sativus* L.), rapeseed/canola (*Brassica napus L.*), and forage rape (*Brassica rapa* L.), have a deep tap root that can potentially break up compaction layers (Smith and Collins, 2003; Clark, 2007). Brassicas used as cover crops include: rapeseed/canola, forage turnip, oil seed radish and kale (*Brassica napus var. pabularia (DC.) Alef.*) (Smith and Collins, 2003; Clark, 2007; Gupta and Pratap, 2007).

Cool- and warm-season terms are more broad in terms of determining a cover crop niche (Barnes and Nelson, 2003; Clark, 2007), while USDA Hardiness Zones are more detailed (USDA NRCS, 2016). These terms help farmers know what conditions are required for establishment, growth, and survival as well as possible stressors and causes of cover crop death. Cool-season cover crops using in the Upper Midwest include: alfalfa, red clover, oil seed radish, cereal rye, oat and field pea. Warm-season cover crops in the Upper Midwest include: cowpea, sudangrass, sorghum x sudangrass hybrid and teffgrass.

Cover crops can be planted in mixtures of functional groups to receive a combination of benefits dependent on the species selected. For example, legumes are often used in mixes with grasses or with small grains such as oats to increase nutritive value as forage (Balasko and Nelson, 2003) as well as fixing nitrogen (Haystead and Marriot, 1978; Hargrove, 1986; Ebelhar et al., 1984; Fox and Piekielek, 1988; Hartwig and Ammon 2002; Vyn et al., 2000; Henry et al., 2010; Schipanski and Drinkwater, 2011). Complex mixtures that include multiple cover crop species including grasses, grains, brassicas, and/or legumes are popularly referred to as "cocktail mixtures" (Clark, 2007).

Negative Impacts of Cover Crops

Though there are many benefits to including a cover crop in a crop rotation, there are negatives associated with cover crops as well. Cover crops can be hard to kill and can become weeds in subsequent crop rotations, reducing crop yields (Snapp et al., 2005; Clark, 2007) due to the competition for water, nutrients and light (Hartwig and Ammon, 2002). Residues of cover crops such as cereal rye can be hard to incorporate, which may delay planting of the next cash crop and delay in nutrient release from residues (Snapp et al., 2005). Some cover crops can reservoirs for diseases affecting the following cash crop, such as red clover being a host for *Streptomyces scabiei* (scab), a common disease in potato production (Bugg and Waddington, 1994).

There are other reasons why farmers are hesitant to plant cover crops, including cover crop seed cost and availability (Snapp et al., 2005) as well as establishment of the cover crop. Cost of cover crop establishment can be great, with potential costs for irrigation water, planting, fertilizer, pest control, and weeding (Hartwig and Ammon, 2002; Snapp et al., 2005; Clark, 2007). Weeds cannot be controlled in many of the cover crops once they become established and sometimes the cover crop does not compete well with weeds during early establishment (Smith and Collins, 2003).

Cover Crops as Forage

Another use for cover crops is as a forage. Many species currently being used as covers have a long history of use as annual forage crops in livestock production systems; however, the potential for cover crops to be harvested as forage in cash-cropping systems is an important and relatively recent development in cover crop research. Farmers can receive the benefits of having a cover crop as discussed above, but also receive an added benefit of feed, either for on-farm animals or to sell (Snapp and Mutch, 2003; Snapp et al., 2005). However, there is a common concern that some or all of the environmental and cash crop benefits of the cover crop will be lost if it is harvested early as a forage. In addition, it is not clear if harvesting cover crops as forage is cost-effective. Some species commonly used as both forages and cover crops in the Upper Midwest include: alfalfa, red clover, brassicas, small grains, and field pea.

History of Forage Crops

Forage crops have a long and rich history as livestock feed. Functional groups of forage species include various legumes, cool- and warm- season grasses, and brassicas. Grasses have always been used as a forage, though many of the grasses used as forages today in the US were introduced from Eurasia, the Mediterranean, Africa and Europe. The reason for this introduction of grasses was to replace the less-productive native grasses (Buckner et al., 1979; Conant et al., 2001; Balasko and Nelson, 2003; Barnes and Nelson, 2003; Redfearn and Nelson, 2003).

Many of the grassland acres were lost to cultivation and overgrazing (Seré et al., 1995; Conant et al., 2001) and were poorly managed, and soil degradation (Oldeman, 1994), invasion of weeds, and loss in overall quality of the lands occurred (Oldeman, 1994; Seré et al., 1995; Conant et al., 2001). The annual forages in cropping systems, that replaced the permanent grasslands, can potentially substitute some of the ecosystem services, such as feed for animals, soil and plant biodiversity, and water and nutrient availability and uptake, originally provided by the permanent grasslands that were lost (Conant et al., 2001; Balasko and Nelson, 2003; Barnes and Nelson, 2003; Redfearn and Nelson, 2003; Sanderson et al. 2004; Brussaard et al., 2007; Wrage et al., 2011).

Forage Quality and Groups

Each group of forages has specific characteristics of nutritive value, often referred to as forage quality. Forage quality is defined as the potential of a forage to produce a chosen animal response (Church, 1988; Fahey et al., 1994; Paterson et al., 1994; Collins and Fritz, 2003; Mitchell and Nelson, 2003). An example of this response can be in optimal milk production on a dairy farm, appropriate weight gain on steers in beef production, or wool production. Characteristics of “good” forage quality is a specific nutrient concentration that is appropriate for acceptable animal production based on animal species and class (Church, 1988; Collins and Fritz, 2003). Not all forages provide good forage quality for all animal classes. Other quality characteristics include palatability (i.e. easy to eat and digest), free of anti-quality factors originating from the plant (i.e. nitrates, dust, toxic secondary compounds), and free of outside contaminants (i.e. mold, toxic plants, soil, weeds, etc.) (Collins and Fritz, 2003).

Legumes have superior forage quality to grasses (Cherney and Cherney, 2002; McGraw and Nelson, 2003) resulting from their high protein content (Church, 1988; Cherney and

Cherney, 2002; Undersander et al., 2004; Evers, 2011), high fiber digestibility (Cherney and Cherney, 2002), high lipids (Undersander et al., 2004), and condensed tannins (for some species of legumes) (McGraw and Nelson, 2003). Also, as discussed earlier, most legumes fix atmospheric nitrogen (N_2) which contributes to overall soil N fertility (Barnes and Nelson, 2003; McGraw and Nelson, 2003; Evers, 2011). With this ability and excellent forage quality, legumes are often seeded into pastures and hayfields. Legumes help meet dietary needs of many animal classes (McGraw and Nelson, 2003; Mitchell and Nelson, 2003; Undersander et al., 2004; Evers, 2011). Some legumes used as forages include alfalfa, clovers (*Trifolium* spp.) and peas.

Grasses are lower in forage quality than legumes and are typically mixed with legumes in pasture and hayfields to improve the nutritive value (McGraw and Nelson, 2003; Balasko and Nelson, 2003). Grass species differ in palatability and physical texture, which in turn affects animal intake and consumption. Softer leaves and fine stem of some grasses such as the ryegrasses (*Lolium* spp) and bluegrasses (*Poa* spp), are easier to consume compared to the stiffer leaves and thicker stems of different grass species (Paterson et al., 1994; Balasko and Nelson, 2003). Another factor is the developmental stage of growth in grasses. Depending on the growth stage, leaves are more palatable in the vegetative stage rather than in the reproductive stage (Paterson et al., 1994; Balasko and Nelson, 2003). Additionally, forage quality decreases in grasses during the reproductive stages because lignin increases with maturity. Lignin can increase rapidly from about two percent to as much as eight percent of dry weight during the reproductive stages (Brown et al., 1968; Balasko and Nelson, 2003).

Cool-season perennial grasses provide most of the forages consumed by beef cattle and sheep in temperate areas of the world (Balasko and Nelson, 2003). Perennial warm-season and summer annual grasses provide forage in northern areas of the US (Barnes, 2003). However, in the Midwest, warm-season grasses typically have a lower forage quality (Kephart and Buxton, 1993; Paterson et al., 1994; Balasko and Nelson, 2003) compared to cool-season grasses. Reduced nutritive value is due to the decrease in the leaf to stem ratio (Paterson et al., 1994; Balasko and Nelson, 2003), reduced protein concentration (Balasko and Nelson, 2003), and greater lignin and other structural tissues in the leaves (Paterson et al., 1994; Balasko and Nelson, 2003). An important development that improved forage quality of some warm-season grasses was the discovery of the brown midrib trait (BMR) which reduces lignin concentration in the plant and thus improves digestibility (Cherney et al., 1991). Commercially available BMR varieties are available for sorghums, sudangrass, and corn.

Forage from small grain crops provides a high-quality feed (Cherney and Marten, 1982; Church, 1988; Coblentz and Walgenbach, 2010), assists with animal growth, increases the quality provided by animal products (i.e. milk and meat, etc.) (Church, 1988), and can be used as an alternative feed. For example, in beef production fall forage growth from small grains provides a source of high-quality feed (Church, 1988) and can extend the grazing season thus reducing the need for supplemental hay during the winter months (Coblentz and Walgenbach, 2010). For other livestock producers, forage growth provided by small grains may also provide extra forage during and after a summer drought (Coblentz and Walgenbach, 2010). Coblentz and Walgenbach (2010) found that a variety of oat yielded more compared to wheat (*Triticum aestivum L*.) cultivars and remained vegetative due to the longer colder temperatures and a long-day photoperiod requirement. In a study conducted by Cherney and Marten (1982), barley (*Hordeum vulgate* L.) forage nutritive value was often greater than oats, wheat, or triticale (*Triticum durum* Desf. × *Secale cereale* L.) and wheat was the lowest yielding forage.

The brassica family of forages have been used for livestock feed for centuries (Smith and Collins, 2003). Brassicas are thought to originate in Asia and have been cultivated for thousands of years (Gupta and Pratap, 2007; Banuelos et al., 2013). In the US during the 1800s, brassicas were used as feedstuffs, providing a high economic return in the harvesting, storing, and feeding of the large roots (Smith and Collins, 2003; Banuelos et al., 2013). Forage brassica economic viability hit a peak in the early 1900s, and use of brassicas then began to decline due to the high labor cost for cultivation, harvest, and feeding (Smith and Collins, 2003). Recently brassicas have made a return because of their value as a forage and potential as a cover crop (Clark, 2007; Gupta and Pratap, 2007; Banuelos et al., 2013). Useful characteristics of brassicas include: high frost tolerance – allowing them to grow and maintain biomass in colder months and lengthen the grazing season (Smith and Collins, 2003), little decline in nutritive value with maturity (Smith and Collins, 2003; Gupta and Pratap, 2007), and high energy content because the large storage roots of turnips, swedes (*Brassica napobrassica* L.) and radish are a good source for nonstructural carbohydrates (Smith and Collins, 2003; Gupta and Pratap, 2007). Therefore, brassicas provide a high-quality feed for their entire growth period. Another benefit is brassicas are easily established and grow quickly, providing suppression of weeds and a quick forage (Wilson et al., 1992). Brassicas include turnips, swedes, forage rape (*Brassica napus* L.), kale, radish (*Brassica rapa* L.) and hybrids such as 'Tyfon' which is a cross between Chinese cabbage (*Brassica rapa* L. subsp. pekinensis) and turnip (Rao and Horn 1995; Guo et al., 2014).

Negative Impacts of Forages

Negative impacts can be associated with forages. Grasses commonly have anti-quality factors such as alkaloids that can cause several types of animal health risks (Collins and Hannaway, 2003). Parturient paresis or commonly known as milk fever, is a complex metabolic disorder that occurs at the onset of lactation in haylage feed or after the birth of a new born calf (Goff, 2008). Cows fed high potassium (K) or high sodium (Na) diets can reduce the ability of the cow to maintain Ca homeostasis (Goff and Horst 1997). Low blood calcium (Ca) concentrations found in cow blood is a problem associated with milk fever and can cause a cow to lose the ability to rise to her feet as Ca is necessary for nerve and muscle function (Horst et al., 1997; Goff, 2008). Other symptoms of this disease include inappetence, tetany, inhibition of urination and defecation, lateral recumbency, and eventual coma and death if left untreated (Horst et al., 1997). In a study conducted by Cherney and Marten (1982) oat, barley, wheat, and triticale were tested barley had the greatest milk fever potential, which was estimated by Ca/P ratios. Other potential negatives of forages include persistence of forages (i.e. become weedy) (Clark, 2007), hosts for pests/insects (Martin, 2004) and high seed cost (DeGregorio et al., 1995; Labarta et al., 2002).

Potential Double Crops in Michigan and the Upper Midwest

Depending on location in Michigan and the Upper Midwest, the typical fallow period from mid-summer harvest of winter wheat to planting of the subsequent crop (usually corn in Michigan) is nine to ten months long (July through May). This includes 90 growing days in the late summer and fall after wheat is harvested in July. The long fallow period leaves soil susceptible to water and wind erosion, allows loss of N and C from the system, and encourages weed proliferation (Snapp and Mutch, 2003). Farmers in Michigan and the upper Midwest have frost seeded red clover into wheat in late March or early April for many years, providing a cover on the soil following wheat harvest that fixes nitrogen (Vyn et al., 1999; Snapp et al., 2005). Alternatively, a farmer could harvest wheat and then plant a cover crop to improve soil health (Snapp et al., 2005), fix nitrogen for the next row crop in the rotation (Tanaka et al., 1997), and provide a harvestable double crop of forage (Snapp and Mutch, 2003). Farmers are uncertain which cover crops planted in or after wheat would have the greatest potential for return on investment under Upper Midwest growing conditions, and if any of these cover crops would be advantageous compared to red clover seeded into the growing wheat crop in early spring. Additionally, farmers have questions concerning the harvesting of red clover or other cover crops for forage. Would forage harvest adversely affect soil organic matter (SOM) accumulation and future crop productivity and yield (Snapp et al., 2005)? Finally, cover crops which survive winter including red clover, require a termination operation, thus increasing expense or delaying spring planting. Annual legumes or other covers that do not survive Michigan winters might be able to provide similar benefits as red clover without the added expense of termination.

In order to establish during the hot dry weather typically encountered in July and August in Michigan, a cover crop needs to be tolerant of such conditions. To be valuable as a forage, cover crops should have documented feeding value. Alfalfa (*Medicago sativa* L.) can be frost seeded into wheat in March/April or established in July to provide high quality forage within 60 days (Barnes et al, 1988; Pfarr, 1988; Sheaffer et at., 1988; Sheaffer et al., 1989; Sheaffer et al., 1992). The non-dormant alfalfa (non-winter-hardy variety) varieties that are used as cover crops should winterkill under Michigan conditions. Other legume options include heat-tolerant species such as sunn hemp (*Crotalaria juncea* L.) and cowpea [*Vigna unguiculata* (L.) Walp.]) which have been used as forage crops as far north as Virginia (Schomberg et al., 2007) but not tested for forage use in Michigan. Cowpea and sunn hemp can provide the benefits of a legume and can withstand hotter temperatures usually found during Michigan summers. ‘Tropic Sun’ sunn hemp was developed with forage potential in mind. Oat/ (*Avena sativa* L.) field pea (*Pisum sativum* L.) mixtures are an accepted forage mixture in Michigan, providing forage throughout the growing season, especially during the latter part of the growing season in fall. Warm-season grasses include BMR varieties of sorghum (*Sorghum bicolor*) and sorghum x sudangrass (*Sorghum bicolor x S. bicolor (Piper) Stapf*), which have superior fiber digestibility that simultaneously makes them valuable as a forage (Cherney et al., 1991) and increases rate of residue decomposition to active organic matter fractions in soil. Also, depending on the variety, sorghum cover crops can have a fast growth rate and reach maximum cover in short growing periods. Teff grass [*Eragrostis tef* (Zuccagni) Trotter] is another warm-season grass option for Michigan (Roseberg et al., 2006; Miller, 2009; Young et al., 2014), reaching harvestable biomass for hay within 60 days after planting. Oil-seed radish is a cover crop that is attracting farmer interest across Michigan. As a forage, radish is more typically used as pasture (Monjardino et al., 2004) rather than as hay or haylage due to its high moisture content; when grown in combination with volunteer wheat it may be a viable option as a haylage double crop.

Why Cover Crops as Forages?

Total farm and crop acreages are decreasing, NASS (2012a) reported a long-term decline of farms, 2.5 million farms in 1982 to 2.1 million in 2012. Farmland acres are decreasing as shown in a five-year period, 922.1 in 2007 to 914.4 acres in 2012, which is a 0.8% decline of farmland acres (NASS, 2012a). With this decline, corn and soybean acres are increasing, 1% and 19% respectively, and forage acres are decreasing by 9% in the 2007-2012 five-year period (NASS, 2012a). Nationally, there is a total of 55.7 million (813,583 farms with forage acres) acres for harvested forage, land used for all hay and all haylage, grass silage, and greenchop, in 2012 in the United States (NASS, 2012b). More specifically, of the total 55.7 million harvested forage acres, there was 3 million harvested haylage or greenchop from alfalfa or alfalfa acres in the United States in 2012 (NASS, 2012c). All other haylage, grass silage, and greenchop consisted of 2.4 million harvested acres in the United States in 2012 (NASS, 2012d). Additionally, there were a total of 17.5 million milk cows (NASS, 2012e) and a total of 53.6 million beef cattle in the United States in 2012 (NASS, 2012f) which is a decline from 2007, 0.1% and 0.4% respectively, (NASS, 2012a).

U.S. Department of Agriculture's 2012 Census of Agriculture reported 10.3 million acres of cover crops planted in 2012 (NASS, 2012g). SARE (2016) reported a steady increase in the number of planted to cover crops acres from 2010-2015, and predicted a continued increase in acreage to be planted to cover crops in the late summer or fall of 2016. The mean number of cover crop acres planted in 2015 among 1,379 users was 298, a 25% increase in acreage over 2014. The respondents expected to increase that figure to a mean of 339 in the 2016 season, a 14% projected increase in the average user's cover crop acreage in 2016. Based on the trend line of SARE's (2012) survey data, today's current cover crop acreage is projected to be several million acres higher than in 2012.

With forage land on the long-term decline a need for forage crops is needed to provide feed for animals. Trends for animal production is also declining, but not as drastically as the decline of forage acres. The increase demand for food requires a change to be made (Piorr, 2003). Cover crops could provide an additional benefit to farmers, not only as a cover crop, but as a harvestable forage to be used for livestock production therefore possibly increasing the economic value for cover crops and their adoption on farms. This can help improve farm sustainability by providing a cover before and after row crops such as corn (Teasdale, 1996; SARE, 2016). In addition, adding value to cover crops as harvested forage may help mitigate added costs of buying cover seed and planting it (Snapp et al., 2005), thus encouraging farmers to use cover crops after small grains, such as wheat (Tanaka et al., 1996; Angus et al.,2015).

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CHAPTER 2

USING COVER CROPS IN WHEAT-CORN ROTATIONS TO PROVIDE FORAGE WHILE IMPROVING SOIL

ABSTRACT

The time window after wheat harvest in a wheat (*Triticum aestivum* L.)- corn (*Zea mays* L.) rotation could be used to grow cover crops (CC) to provide forage while protecting soil from erosion. However, the impact of forage harvest on soil fertility and sequential crop growth is not well quantified. Field experiments were initiated in East Lansing, MI to determine the consequences of partial removal of CC biomass on soil improvement and crop yield and quality. Soft red winter wheat ('Hopewell' and 'Red Dragon') was planted in October of 2013 and 2014 and harvested in July 2014 and 2015. Cover crops included: frost-seeded red clover, and summer-seeded alfalfa, cowpea, sunn hemp, radish, oat/field pea mixture, sudangrass, sorghum x sudangrass, and teffgrass. Half of each CC plot was mechanically harvested eight weeks after planting. Harvested forage dry matter yield was greatest for red clover (4.3 Mg ha^{-1}); oat-pea mix (2.5 Mg ha^{-1}), sudangrass/sudex (1.8 Mg ha^{-1}) and radish (1.2 Mg ha^{-1}) ($P < 0.01$) yielded less. Corn grain yield harvested in October averaged 13.7 Mg ha^{-1} and did not differ across CC species or forage harvest treatment ($P > 0.05$). Harvesting forage reduced total N removal (TNR) in subsequent corn for red clover only; harvesting forage did not affect TNR after any other CC (CC x harvest interaction, $P < 0.05$). In the harvested system, TNR did not differ ($P > 0.05$) between red clover (297 kg ha^{-1}) and oat-pea mix (284 kg ha^{-1}), but unharvested RCL (374 kg ha^{-1}) had greater ($P < 0.01$) TNR than oat-pea mix (338 kg ha^{-1}). There were no differences among treatments for soil permanganate oxidizable carbon POXC ($P > 0.05$). Harvesting cover crops for

forage after winter wheat harvest in Michigan can give harvestable forage and acceptable nutritive value.

INTRODUCTION

Total farm and crop acreages are decreasing, NASS (2012a) reported a long-term decline of farms, 2.5 million farms in 1982 to 2.1 million in 2012. Farmland acres are decreasing as shown in a five-year period, 922.1 in 2007 to 914.4 million acres in 2012, which is a 0.8% decline of farmland acres (NASS, 2012a). With this decline, forage acres are in a decreasing by 9% in the 2007-2012 five-year period (NASS, 2012a). Nationally, there is a total of 55.7 million acres for harvested forage, land used for all hay and all haylage, grass silage, and greenchop, in 2012 in the United States (NASS, 2012b). Additionally, there were a total of 17.5 million milk cows (NASS, 2012e) and a total of 53.6 million beef cattle in the United States in 2012 (NASS, 2012f) which is a decline from 2007, 0.1% and 0.4% respectively, (NASS, 2012a).

With forage land on the long-term decline, forage crops are still needed to provide feed for animals. Even though cattle numbers are declining, it is not as drastic as the decline of forage acres. The increased demand for food requires a change to be made (Piorr, 2003). Cover crops (CC) could provide an additional benefit to farmers, not only as a CC, but as a harvestable forage to be used for livestock production therefore possibly increasing the economic value for CC and their adoption on farms. U.S. Department of Agriculture's 2012 Census of Agriculture reported 10.3 million acres of CC planted in 2012 (NASS, 2012g). SARE (2016) reported a steady increase in the number of planted to CC acres from 2010-2015, and predicted a continued increase in acreage. Using CC can help improve farm sustainability by providing a cover before and after row crops such as corn (Teasdale, 1996; SARE, 2016). Adding CC to crop rotations takes advantage of resources provided by the soil, sun and water (Andraski and Bundy 2005; Wortman et al. 2012) while improving soil health and structure (Pimentel et al., 1995; Andraski and Bundy 2005; Clark, 2007) thus benefiting by protecting against soil erosion or loss (Hartwig and Ammon, 2002; Andraski and Bundy 2005), scavenging of nutrients that would otherwise be unavailable or leached (Ranells and Wagger, 1997; Clark, 2007), holding and cleaning water (Hartwig and Ammon, 2002), and providing nitrogen to the cash crop planted subsequently (Decker et at., 1994; Pimentel et al., 1995; Andraski and Bundy, 2005). Additionally, adding value to CC as harvested forage may help mitigate added costs of buying cover seed and planting it (Snapp et al., 2005), thus encouraging farmers to use CC after small grains, such as wheat (Tanaka et al., 1996; Angus et al.2015), though there is little to no information on the effects of harvesting CC as forage on CC benefits.

The typical fallow period from mid-summer harvest of winter wheat to planting of the subsequent crop (usually corn in Michigan) is nine to ten months long (July through May). This includes 90 growing days in the late summer and fall after wheat is harvested in July. The long fallow period leaves soil susceptible to water and wind erosion, allows loss of N and C from the system, and encourages weed proliferation (Snapp and Mutch, 2003). Farmers in Michigan and the upper Midwest have frost-seeded red clover into wheat in late March or early April for many years, providing a cover on the soil following wheat harvest that fixes nitrogen (Vyn et al., 1999; Snapp et al., 2005). Alternatively, a farmer could harvest wheat and then plant a cover crop to improve soil health (Snapp et al., 2005), fix nitrogen for the next row crop in the rotation (Tanaka et al., 1997), and provide a harvestable double crop of forage (Snapp and Mutch, 2003). Farmers are uncertain which cover crops planted in or after wheat would have the greatest potential for return on investment under Upper Midwest growing conditions, and if any of these cover crops would be advantageous compared to red clover seeded into the growing wheat crop in early spring. Additionally, farmers have questions concerning the harvesting of red clover or other cover crops for forage. Would forage harvest adversely affect soil organic matter (SOM) accumulation and future crop productivity and yield (Snapp et al., 2005)? Finally, cover crops which survive winter including red clover, require a termination operation, thus increasing expense or delaying spring planting. Annual legumes or other covers that do not survive Michigan winters might be able to provide similar benefits as red clover without the added expense of termination.

Choice of CC or forage species is dependent on the location and the specific benefits desired by the producer. A single species will not provide all possible benefits, so species should be chosen with specific goals in mind. Our selection criteria for potential forage double-cropping with wheat in Michigan were the ability to establish during hot, dry weather in July and August, acceptable forage nutritive value at harvest, maintenance of winter ground cover, natural winter-kill to avoid the cost of spring termination, and maintenance or improvement of subsequent corn grain yield and quality. Red clover (*Trifolium pratense* L.) served as the positive control treatment. Non-dormant alfalfa (*Medicago sativa* L.) can provide high quality forage within 60 days after a late summer planting and should winterkill (Barnes et al, 1988; Pfarr, 1988; Sheaffer et at., 1988; Sheaffer et al., 1989; Sheaffer et al., 1992). Heat-tolerant legumes like sunn hemp (*Crotalaria juncea* L.) and cowpea [*Vigna unguiculata* (L.) Walp.] have been used as forage crops as far north as Virginia (Schomberg et al., 2007), but not tested for forage use in Michigan. Oat/field pea (*Avena sativa* L./*Pisum sativum* L.) mixtures are an accepted annual forage crop in Michigan (Johnson et al., 1998). Brown-midrib cultivars of the warm-season grasses sorghum (*Sorghum bicolor* L.) and sorghum x sudangrass [*S. bicolor x S. bicolor* (Piper) Stapf] hybrids, popularly called sudex, accumulate biomass quickly in summer and have superior fiber digestibility, compared to other warm-season grasses, that simultaneously makes them valuable as a forage (Cherney et al., 1991) and increases rate of residue decomposition to active organic matter fractions in soil. Warm-season teffgrass [*Eragrostis tef* (Zuccagni) Trotter] reaches harvestable biomass within 60 d after planting in Michigan (Roseberg et al., 2006; Miller, 2009; Young et al., 2014). Finally, oilseed radish is attracting interest as a CC across Michigan. As forage, radish is typically used as pasture (Monjardino et al., 2004) rather than as hay or haylage due to its high moisture content, but it may be a viable haylage crop if grown in combination with a small grain.

With the increasing CC acres and decreasing forge acres, the potential for CC to be double cropped is a viable option and could close the growing gap between available forage and animals. CC diversity can be applicable to different farming types to meet the various needs of farmers and CCs double-cropped as a forage can provide feed for various animal types. CC, with growing application and acres, will grow shorter time periods of the growing season allowing farmers to gain CC benefits, double-cropping benefits and still allow cash crops to grow without impediment. Given the interesting potential opportunity to use CC as a double-crop, a forage, our objectives were: 1) determine whether harvesting CC planted after wheat could provide useful forage yields and nutritive value, (2) determine whether specific CC species change labile soil organic matter, soil C, or soil N, and (3) determine how partial removal of CC biomass affects corn grain and stover yield and quality.

MATERIALS AND METHODS

Site Description

This research was conducted at the Michigan State University Agronomy Farm, East Lansing, Michigan (42º42’N, 84º28’W, elevation 262 m) on two adjacent fields. Soil taxonomy and initial fertility characteristics for rotation sequences initiated in 2013 and 2014 were: 2013, Capac silt loam (fine-loamy, mixed, active, mesic Aquic Glossudalfs), pH 7.3, 110 g kg^{-1} P, and 1100 g kg^{-1} K, 30 g kg^{-1} soil organic matter (SOM); 2014, Brookston silt loam (fine-loamy, mixed, superactive, mesic Typic Argiaquolls), pH 7.0, 300 g kg^{-1} P, and 2080 g kg^{-1} K, 35 g kg^{-1} SOM. Monthly total precipitation, minimum, average, and maximum monthly air temperature, soil temperature and moisture (10 cm depth), and growing degree days (GDD, 5°C base for alfalfa/CC and 10°C base for corn) data were obtained from a weather station located within 1 km of the research site (MAWN, 2016). Twenty-five-year weather norms were obtained from the National Oceanic and Atmospheric Administration (NOAA, 2016).

Experimental Design

The cropping system was a no-till rotation consisting of winter wheat-cover crop-corn. The rotation sequence was initiated in 2013 and again in 2014 for a total of two independent site-year sequences (first-year and second-year). Fields used for first-year and second-year were immediately adjacent to each other. The experimental design was a randomized compete block (RCBD) with four replications and a split plot treatment arrangement. The main plots were ten CC treatments: fallow, red clover frost-seeded (RCL), and alfalfa, cowpea, oat/pea mix (OPmix), oilseed radish (Radish), sunn hemp, sudangrass (SUD), sudex (SDX), and teffgrass (Teff) seeded no-till following wheat harvest. The subplots were two CC harvest treatments (NH—not harvested, or H— harvested). Plots measured 3 x 7 m for first-yearand 3 x 8 m for second-year.

Crop Management

Soft red winter wheat was planted at 168 kg ha^{-1} on 29 October 2013 (cultivar 'Hopewell') and 20 September 2014 (cultivar 'Red Dragon') to begin the rotation in each year. Wheat was harvested 21 July 2014 and 23 July 2015 using plot combines (SPC40 and SPC20 in 2014 and 2015, respectively, Almaco Co., Nevada, Iowa). No CC were planted on the negative control fallow plots. To allow assessment of volunteer wheat as a "cover crop," volunteer wheat was not controlled in untreated volunteer wheat (UTVW) fallow subplots, but was removed from fallow subplots through application of glyphosate at 5 kg a.i. ha^{-1} plus 4 kg ha^{-1} ammonium sulfate on 13 September 2015 and 20 August 2015. The red clover was frost-seeded into wheat using a hand-pulled drop spreader on 28 March 2014 and 18 March 2015. All other CC treatments were seeded into wheat stubble at a row spacing of 19 cm on 4 August 2014 and 27 July 2015 using a no-till drill (Great Plains Manufacturing, Inc., Salina, KS). The CC seeding rates and varieties are given in Table 1. The H treatment was harvested approximately 60 days after planting using a flail-type forage plot harvester (Carter MFG CO., Inc. Brookston, IN) at a stubble height of 10 cm. Post-harvest regrowth in the harvested cover crop treatments was left in place over the winter; the entire biomass remained overwinter in the NH treatments. Two weeks prior to corn planting, weeds and overwintering CC were terminated with an application of 5 kg a.i. ha^{-1} glyphosate plus 4 kg ha^{-1} ammonium sulfate. Corn (Dekalb 'DKC44-13RIB,' glyphosate resistant) was no-tilled into each plot at a row spacing of 75 cm (four corn rows per subplot) on 1 May 2015 and 9 May 2016. Corn plots were sprayed twice with glyphosate at a rate of 5 kg a.i. ha^{-1} plus 4 kg ha^{-1} ammonium sulfate during the early growing season to control weeds. All corn plots were fertilized according to fall soil test results (see soil measurements) and nutrient recommendations for crops in Michigan (Warncke et al., 2009). Wheat plots were fertilized with 101 kg ha^{-1} of N. Corn was fertilized with a 100 kg ha^{-1} of K at the time of corn planting and a recommend (MRTN 2016) 84 kg ha^{-1} of N (UAN 28%), was knifed in at the V4 corn stage on all plots for each year.

Measurements

Wheat and corn grain yields were measured using weigh functions on the respective plot combines. Grain samples were taken at harvest for each plot by placing grain in a cloth bag and then were tested for grain moisture content. Grain moisture content from subsamples was determined using a grain analysis scanner (Model No. GAC 2100, Dicky-John, Co., Auburn, Illinois), and grain yield was corrected to standard moisture levels of 13.5%. At CC harvest, subsamples were obtained for nutritive value and botanical composition analyses. The CC harvest consisted of recording a fresh weight from each harvested plot using a flail type harvester (Carter MFG CO., Inc. Brookston, IN) which harvested 10 cm above ground. Subsamples of harvested herbage were collected from the fresh weight sample at random with approximately 4-6 hand samples, per plot, placed in paper bags and were dried in a forced air dryer for 3 days at 60 C, and used to calculate moisture at harvest and correct forage yield to a DM basis. Botanical composition samples were taken directly after CC harvest from 60 cm of remaining row along the harvested strip, selected so each sample was representative of the whole plot. Nutritive value samples were then ground sequentially in Wiley (Thomas Scientific, Swedesboro, NJ) and UDY (UDY Corporation, Fort Collins, Co.) mills with 4- and 1-mm screens.

Forage quality samples were analyzed for crude protein (CP), neutral detergent fiber (NDF), and acid detergent fiber (ADF). The percent of nitrogen (N) and total carbon (C) was determined by dry combustion, using a Costech-elemental combustion system (Model No. Costech ECS 4010 and Zero Blank Autosampler, Costech Analytical Technologies Inc., Valencia, CA). The CP was calculated by multiplying percent of N by 6.25 (Conklin-Brittain et al., 1999).

Percentages of NDF and ADF were determined sequentially using the procedures of Goering and Van Soest (1970); however, sodium sulfite was not used in the NDF analysis per the recommendation of Van Soest and Robertson (1980). An ANKOM Fiber analyzer (Model No. 200, Ankom Technology, Fairport, NY) and F57 25-micron porosity Fiber Filter Bags (Ankom Technology, Fairport, NY) were used to conduct NDF and ADF analysis.

A visual estimate of ground cover components, which included volunteer wheat, bare ground, weeds, and CC, was taken biweekly starting on 10 September 2014 and 11 August 2015 after CC planting. The percent of each ground cover component was determined by the same observer using visual estimation in three 1.2-m^2 quadrats per plot, and averaged. Visual ratings were obtained by dividing the quadrat into four sections, each equaling 25% of the area. When the quadrat was placed on the plots, a visual estimation of the components in each section was taken at 5% increments starting at zero and added together to equal 100%. Spring ground cover was also visually estimated biweekly beginning 13 April 2015 and 18 April 2016 and ending approximately 4 weeks after corn planting. A corn category was added to the cover components after corn was planted. Plant canopy height, for both CC and corn, was measured using a meter stick at the same time as cover measurements. Canopy height was recorded from three plants and averaged per 1.2-m^2 quadrat. Corn population and height was taken in May 2015 and June 2016 by measuring three meters of the two middle rows of each plot. To further analyze the ground cover, CC and volunteer wheat mix (planted CC + volunteer wheat), live cover (planted CC +

volunteer wheat + weeds) and total cover (crop + volunteer wheat + weeds + residue/straw) groups were created and analyzed.

Three corn ear leaf samples were randomly taken at the V12 stage during 27 July 2015 and 8 August 2016 from each plot. SPAD meter readings were taken using PhotosynQ (Venturit, Inc., East Lansing, MI) meters in 22 July 2015 and 3 August 2016 to determine light interception, plant stress, and potential corn yield. On 9 October 2015 and 7 October 2016, 60 cm of the yield rows of corn for each plot was hand-harvested for grain. On 12-13 October 2015 and 11 October 2016, stover was harvested from the same yield rows. Corn ear samples were placed in cloth bags, dried in a forced air oven for 24 h at 60 C, and shelled in a corn sheller (John Deere, Co., Moline, IL). Corn stover biomass was measured by cutting stalks from two row-feet of the center two rows at ~45cm above the base, and recording fresh weight and number of stalks. Corn stalks were then chopped in a yard-scale wood chipper and subsampled. Subsamples were dried in a forced air oven at 60 C for 3 days to determine DM percentage and allow calculation of dry stover biomass. The remaining corn in plots was mechanically harvested using a Massey Ferguson Combine (AGCO Co., Duluth, GA) with HarvestMaster (Juniper Systems and HarvestMaster, Logan, UT) software which provided yield and moisture content. The hand-sampled grain yields were added to machine-harvested yields to give total grain yield per plot.

All corn grain and stover samples were subsampled for N analysis and ground in Wiley (Thomas Scientific, Swedesboro, NJ) and UDY (UDY Corporation, Fort Collins, Co.) mills with 4- and 1 mm screens, respectively. Corn ear leaf samples were subsampled for N analysis and ground in a twenty-centimeter lab mill (Christy Turner Ltd., Suffolk, England). Nitrogen content of corn grain, stover, and ear leaf was determined by using the Costech-elemental combustion system (Model No. Costech ECS 4010, Costech Analytical Technologies Inc., Valencia, CA) and methods as previously described.

Soil samples were taken from each plot on 15 Nov. 2014 for the first-year plots; 30 Oct. 2015 for the second-year plots (15-cm depth, 10 to 12 cores composited per plot per sampling date). The soil samples were crumbled by hand, and air dried for a week. A 100-g subsample was analyzed for pH (2:1 water: soil) (Crowther, 1925), Mehlich III available K_2O, available P (Mehlich III corrected to report as Bray) (Bray and Kurtz, 1945), Mehlich III cation exchange capacity (Mehlich, 1984), and soil organic matter (SOM) by the loss on ignition method (Walkley and Black, 1934) at a commercial soil analysis laboratory (A and L Great Lakes Laboratories, Fort Wayne, IN). Soil concentration of C and N was determined on the soil samples obtained from each plot after CC harvest on 15 Nov. 2014 and 30 Oct. 2015. A 5-g subsample was oven dried at 60 C for 24 h, and placed in glass vials with stainless steel hexagonal tumblers (Mavco Industries, Inc. Science Hill, Kentucky), 3.8-cm height, 1.2-cm diameter, 30.6 g, and ground using a SampleTek Model 200 Vial Rotator roller mill (Mavco Industries, Inc., Science Hill, Kentucky). The soil samples (15-20 mg) were weighed on a Sartorius Cubis Ultra microbalance (Sartorius AG, Göttingen, Germany) and soil C and N concentrations were determined using a Costech-elemental combustion system (Model No. Costech ECS 4010, Costech Analytical Technologies Inc., Valencia, CA).

Procedure for determining permanganate oxidizable carbon (POXC) was conducted on 2014 and 2015 fall soil samples, after CC harvest. All POXC analyses were based on Weil et al. (2003) but modified slightly as described by Culman et al. (2012). Briefly, 2.5 g of air-dried soil were weighed into polypropylene 50-mL screw-top centrifuge tubes. To each tube, 18 mL of deionized water and 2 mL of 0.2 M KMnO4 stock solution were added and tubes were shaken for exactly 2 min (240 rpm), allowed to settle for exactly 10 min. After 10 min, 0.5 mL of the supernatant were transferred into a second 50-mL centrifuge tube and mixed with 49.5 mL of deionized water. An aliquot (200 μL) of each sample was loaded into a 96-well plate containing a set of internal standards, including a blank of deionized water, four standard stock solutions (0.00005, 0.0001, 0.00015, and 0.0002 mol L^{-1} $KMnO_4$), a soil standard and a solution standard. All standards and soil samples were replicated on a separate 96-well plate. Sample absorbance was read with a SpectraMax M5 spectrophotometer at 550 nm. Permanganate oxidizable C was determined following Weil et al. (2003) equation:

$$\text{POXC [mg kg}^{-1}\text{ soil]} = [0.02 \text{ mol L}^{-1} - (a + b + Abs)] x$$
$$(9000 \text{ mg C mol}^{-1})(0.02 \text{ L solution Wt}^{-1})$$

Where

0.02 mol L-1 is the concentration of the initial KMnO4 solution,

a is the intercept and b is the slope of the standard curve,

Abs is the absorbance of the unknown soil sample,

9000 mg is the amount of C oxidized by 1 mol of MnO4 changing from Mn7+ to Mn4+,

0.02 L is the volume of KMnO4 solution reacted, and

Wt is the mass of soil (kg) used in the reaction

Statistical Analysis

Data was analyzed using PROC MIXED in SAS Version 9.4 (SAS, Inc, Cary, NC). Fixed variables were CC and harvest treatments, and random variables were site-years (SY) and blocks. Means for CC and CC x harvest interactions were compared using single degree of freedom contrasts, with group contrasts constructed for legumes (LEG: RCL and OPmix), SUD and SDX (SUD/SDX), warm-season grasses (WSG: SUD, SDX, and Teff), and failed CC (FCC:

alfalfa, cowpea, and sunnhemp). Fallow treatment was compared to the RCL-NH, all other not harvested treatments, and all harvested treatments. Unless otherwise stated, a trend was declared at $P<0.10$, and significance was declared at $P<0.05$.

RESULTS

Weather

Mean air temperatures were cooler than normal from Jan. to Apr. in 2014 and 2015 while wheat crops were growing in the first phase of rotation for each site-year (Figure 1a). It was also unusually cool during July 2014 immediately before CC were planted. During the CC growth period from Aug. to Sept. in both site-years, precipitation was near or greater than normal (Figure 1b), and mean air temperature was near the 25-year average. During the corn rotation phases in 2015 and 2016, precipitation was slightly below normal in June and July 2015, and greatly below normal in June and July 2016. Mean air temperature was near normal throughout the corn growth period in both site years. While CC were growing between 1 August to 31 November, there were 1126 GDD in 2014 and 1407 GDD in 2015 (MAWN, 2016). For the corn rotation, there were 2705 GDD between 1 May and 31 October in 2014 and 2909 for the same period in 2015 (MAWN, 2016). The 20-year GDD averages (1995-2015) were 1233 GDD for the CC period and 2642 GDD for corn (MAWN, 2016).

Wheat Performance

Wheat grain yield averaged 4.09 and 6.21 Mg ha^{-1} in 2014 and 2015, respectively. Frost-seeded red clover did not affect wheat grain yield ($P > 0.05$) in either site-year.

Botanical Composition

Because some CC treatments failed to establish successfully, botanical composition of harvested CC (Figure 2a, 2b) is presented separately for each site-year to document our criteria for setting contrast comparisons among treatments. Successful CC were defined as achieving at least 20% of biomass DM in harvested plots. Red clover (RCL), oat/pea mix (OPmix), sudangrass (SUD), and sudex (SDX) were successful in achieving over 20% of biomass in both site-years. However, alfalfa, cowpea and sunn hemp failed to reach 20% of biomass in the first-year (Figure 2a) and alfalfa, cowpea, sunn hemp, radish, and teffgrass failed to reach it in the second-year (Figure 2b). Because alfalfa, cowpea, and sun hemp treatments failed in both site-years, they were grouped into a single contrast designated as failed CC (FCC) and presented as such for all subsequent discussions. The FCC treatment consisted primarily of volunteer wheat, which was present to some degree in most plots.

Botanical composition of harvested forage is presented in Figure 2. Botanical composition of harvested forage from RCL plots did not differ from OPmix for any component ($P > 0.10$). Botanical composition did not differ between SUD and SDX for any component (P > 0.10). Harvested biomass contained a greater ($P < 0.01$) proportion of CC for RCL (85%) than SUD/SDX (57%), FCC group (8%), or radish (31%). The LEG group contained a greater ($P < 0.01$) proportion of harvested CC biomass (79%) than the WSG group (45%). Harvested biomass of RCL (2%) contained less ($P < 0.01$) volunteer wheat than SUD/SDX (28%), FCC group (63%) or radish (43%). Harvested biomass percentage of the weed component did not differ among treatments ($P > 0.10$). The proportion of wheat straw in harvested biomass did not exceed 4% for any treatment.

Ground Cover

Ground cover percentages for botanical components at four key points in the rotation sequence are presented in Figure 3. Because the harvest treatment had not yet been applied, there were no harvest or CC x harvest effects 8 wk after CC planting ($P > 0.05$, Figure 3A). Across treatments, planted CC covered more ground ($P < 0.01$) for RCL (97%) than OPmix (49%), SUD/SDX (48%), Radish (51%) or the FCC group (21%). In contrast, volunteer wheat covered less ground ($P < 0.02$) in RCL treatments (2%) than OPmix (41%), SUD/SDX (40%), Radish (34%) or the FCC group (63%). CC covered more ground ($P < 0.01$) in the legume group (73%) than for the WSG group (39%), while volunteer wheat cover (21%) was less ($P < 0.05$) for legume then WSG (63%). Volunteer wheat covered less ground ($P < 0.01$) in the fallow treatment (6%) than in all other treatments (49%). Weed cover was less ($P < 0.01$) for RCL (1%) than the FCC group (6%). The sum of CC and VW was greater ($P < 0.05$) for RCL (98%) than SUD/SDX (88%), Radish (86%) and the FCC (92%) treatments. Live cover and total cover did not differ among treatments ($P > 0.05$)

Four weeks following CC harvest (Figure 3B), a CC x harvest interaction existed ($P < 0.05$) for all ground cover components except straw and live cover. The interaction ($P < 0.02$) indicated that ground cover of summed CC and VW was greater ($P < 0.02$) for RCL-NH (97%) than Radish-NH, Radish-H (74% and 55%, respectively) and FCC-NH, FCC-H (66% and 58%, respectively) treatments. Live cover did not differ among treatments ($P > 0.05$). Harvesting CC reduced residue cover across all treatments ($P < 0.01$).

Overwintering of CC and soil cover was assessed two weeks before corn planting (Figure 3C). There were CC x harvest interactions for CC, volunteer wheat, residue, and summed live plant components of ground cover ($P < 0.01$), but not for weeds or total ground cover of live plants plus residues ($P > 0.10$). The only CC that survived the winter was RCL regardless of harvest treatment and a few alfalfa plants in the FCC-H group. Volunteer wheat survived the winter on all CC treatments except RCL. Harvesting RCL the previous fall increased spring CC and live ground cover ($P < 0.01$) compared to not harvesting. Harvesting forage increased spring volunteer wheat cover for OPmix, teff, FCC group, and SUD/SDX plots ($P < 0.05$). Weed cover was less ($P < 0.01$) for RCL (10%) than for OPmix (18%), SUD/SDX (16%), Radish (16%) or the FCC group (16%). Weed cover was greater (*P* < 0.05) in the fallow treatment (27%) than in all NH (14%), harvested (16%) and RCL-NH (10%) treatments.

The only CC that survived to one month after corn planting (Figure 3D) was RCL (mean 26% ground cover) and a few alfalfa plants in the FCC group (< 1% ground cover). There were no CC x harvest interactions for any ground cover component at this time point (*P* > 0.05). Ground cover of the surviving CC was not affected by harvest (P >0.05). Across harvest treatments, live and total cover was greater while residue cover was less (*P* < 0.05) for RCL than OPmix, SUD/SDX, Radish or the FCC group. Residue cover was greater (*P* < 0.05) for fallow (45%) than for RCL-NH (38%), but less (*P* < 0.05) than all NH (53%) treatments.

Plant Canopy Height

Plant canopy height, is presented in Figure 4. Eight weeks after CC planting, SUD had the tallest plant canopy averaging 501 mm and was different from SDX at 389 mm (*P* < 0.01). Plant canopy height was taller (*P* < 0.01) for RCL (491 mm) than for radish (227 mm) and FCC (406 mm) treatments. Plant canopy height was lower (*P* < 0.02) for fallow compared with all CC plots that were not harvested CC (368 mm), all harvested CC (366 mm) and RCL-NH (490 mm) treatments. Four weeks after CC harvest, a CC x harvest interaction existed (*P* < 0.01). The treatment x harvest interaction (*P* < 0.01) indicated harvesting forages reduced plant canopy height in regrowth, but there were no differences between any CC (*P* > 0.10) in the harvested system. In the no harvested system, OPmix regrowth (573 mm) was taller than RCL (396 mm) and SUD (459 mm) was taller (P < 0.01) than SDX (385 mm). Corn plant canopy height, taken as part of the visual pre- and post- corn planting corn evaluations, did not differ among treatments (*P* > 0.10).

Harvested Forage Yield, Nutritive Value, and C, N Content

Forage dry matter yield, presented in Figure 5, was greatest ($P < 0.01$) for RCL (4.3 Mg ha^{-1}) than OPmix (2.5 Mg ha^{-1}), SUD/SDX (1.8 Mg ha^{-1}), Radish (1.2 Mg ha^{-1}) and the FCC (1.4 Mg ha^{-1}) treatments. The SUD and SDX yield was not significantly different ($P < 0.10$). Forage dry matter yield was greater ($P < 0.01$) for the legume group (3.4 Mg ha^{-1}) than the WSG group (1.6 Mg ha^{-1}). Average harvested yield over all CC treatments was 2.0 Mg ha^{-1}.

Nutritive composition of harvested CC is presented in Table 2. The CC species differed ($P < 0.01$) in moisture concentration at harvest. The RCL treatment (754 g kg^{-1}) had a greater ($P < 0.01$) moisture concentration than the FCC (631 g kg^{-1}) group. Moisture concentration at harvest was greatest for the Legume group (763 g kg^{-1}) than the WSG group (687 g kg^{-1}). Concentrations of NDF were least ($P < 0.02$) for RCL (586 g kg^{-1}) than for SUD/SDX (675 g kg^{-1}) and the FCC (645 g kg^{-1}) treatments. Concentrations of ADF and ash did not differ among any treatments ($P > 0.10$). Concentration of CP was greater ($P < 0.04$) for RCL (144 g kg^{-1}) than OPmix (107 g kg^{-1}), SUD/SDX (85 g kg^{-1}), Radish (108 g kg^{-1}), and the FCC (100 g kg^{-1}) treatments. The legume group had a greater ($P < 0.01$) concentration of CP (126 g kg^{-1}) than the WSG group (92 g kg^{-1}). The C:N ratio was lowest ($P < 0.06$) for RCL (19); SUD/SDX was 33, radish 32, and FCC 22. Nitrogen (N) concentrations mirrored the CP results presented in Table 2.

Corn Performance

Corn grain and stover yields are presented in Table 3. Corn grain yield averaged 12.7 Mg ha^{-1} and were not affected by harvesting CC as forage ($P > 0.05$). Corn stover biomass averaged 13. 6 Mg/ha^{-1} and was not affected by CC or harvest treatments ($P > 0.10$). Results for N concentration of corn ear leaf are presented in Table 4. Corn ear leaf N concentration were affected by CC harvest ($P < 0.06$), but contrasts found no differences between treatments ($P > 0.10$).

Results for N concentration and C:N ratio of corn grain and stover are presented in Table 4. Corn grain N concentration was greatest ($P < 0.04$) for RCL (18 g kg^{-1}) than OPmix (15 g kg^{-1}), SUD/SDX (16 g kg^{-1}), Radish (15 g kg^{-1}), and the FCC (15 g kg^{-1}) treatments. Legume and WSG corn grain N concentration did not differ ($P > 0.10$). Corn grain N concentration was less ($P < 0.05$) for the fallow (13 g kg^{-1}) treatment than for all not harvested (16 g kg^{-1}) and harvested (15 g kg^{-1}) CC and RCL-NH (20 g kg^{-1}). Corn stover N concentration was greatest ($P < 0.01$) for RCL (11 g kg^{-1}) than OPmix (8 g kg^{-1}), SUD/SDX (9 g kg^{-1}), Radish (9 g kg^{-1}), and the FCC (10 g kg^{-1}) treatments. Corn stover N concentration was less ($P < 0.05$) for the fallow (9 g kg^{-1}) treatment than for RCL-NH (11 g kg^{-1}). Corn stover C:N ratio was less ($P < 0.01$) for RCL (43) than OPmix (54), SUD/SDX (53), Radish (48), and the FCC (49) treatments. The fallow treatment did not differ from any other treatments ($P > 0.10$).

Total N removed (TNR) in corn grain and stover results are presented in Table 4. The treatment x harvest interaction ($P < 0.01$) indicated that harvesting forage reduced total N removal in the subsequent corn for RCL but not for OPmix, SUD/SDX, radish and the FCC treatments. In the harvested system, TNR did not differ ($P > 0.05$) between RCL (297 kg N/ha^{-1}) and OPmix (284 kg N/ha^{-1}), but unharvested RCL (374 kg N/ha^{-1}) had greater ($P < 0.01$) TNR than OPmix (338 kg N/ha^{-1}), but not greater ($P > 0.10$) than SUD/SDX (349 kg N/ha^{-1}) and the FCC (349 kg N/ha^{-1}) treatments.

Photosynthetic data collected using the PhotosynQ system did not reveal useful data, possibly because of the beta-testing status of the instrument. Data are included in Appendix B.

Soil Assessment

There were no main effect or interactions for POXC (Figure 6, $P > 0.05$) or for concentration of soil C, soil N concentration, and soil C:N ratio (Table 5, $P > 0.05$). There was a trend ($P < 0.10$) for an interaction in POXC between Radish and RCL, whereby harvesting forage increased POXC under Radish but decreased it under RCL.

DISCUSSION

In 2013 to 2014 winter months, the air temperature was much colder than usual, resulting in winter kill and yield reduction of wheat in 2014. Though air temperature and precipitation followed the 25-year norms, growing degree days (GDD) were low in the summer of 2014. The first-year had 1126 GDD versus the following year, which had 1407 GDD (MAWN 2016). The first-year GDD days were 107 GDD lower than the 20-year norms, whereas the second-year GDD had 174 more than the norm. This 281 GDD difference could help explain why alfalfa and especially the warm season CCs cowpea, sunn hemp, and teff, didn't perform as well as expected the first-year. Fick (1984) reported that 720 GDD were required, in a perennial cropping system, for alfalfa (average of nine cultivars) to reach first flower at the first cutting in Ithaca, NY. 'Hi Nitro' alfalfa has been tested and shown to give high quality feed and useful yields in 60 days (Pfarr, 1988; Sheaffer et at., 1988; Sheaffer et al., 1989; Sheaffer et al., 1992). However, we found that the 'Hi Nitro' alfalfa did not establish well when planted after wheat harvest, even when there was sufficient GDD. Additionally, sunn hemp, cowpea, and teff did not establish well in one of two years. Possible reasons for this occurrence, despite adequate GDD, could be attributed to volunteer wheat competition, especially in the second site-year, or perhaps the lack of ideal growing conditions, such as high competition from volunteer wheat, for the alfalfa.

Additionally, we looked at precipitation to see if moisture was adequate for cover crop establishment 28 d and 14 d before and 14 and 28 d after cover crop planting. We found that precipitation during these critical time periods was less in the second-year than in the first year of this study. Precipitation averaged >1 mm and 10 mm 28 d and 14 d before cover crop planting, respectively, and averaged 30 mm at both 14 and 28 d after cover crop planting (MAWN 2016). While the second-year precipitation 28 d and 14 d before cover crop planting was higher than the first-year, averaging at 2 mm and 31 mm respectively while 14 d and 28 d after cover crop planting averaged 68 mm and 34 mm respectively (MAWN 2016). Adequate precipitation and soil moisture is needed for plant establishment (Veihmeyer and Hendrickson, 1950; Stanhill, 1957; Denmead and Shaw, 1962; Lipiec et al., 2013) In our study the low GDD in the first-year combined with the low precipitation before and after cover crop planting, potentially leading to a lower soil moisture content, could have contributed to poor cover crop establishment.

The first-year corn had adequate precipitation and temperatures (2705 GDD). Corn requires about 2700 GDD to reach full maturity (Neild and Newman, 1987), depending on the hybrid, while our hybrid only needed 2350 GDD (Monsanto 2016). Both site-years had sufficient GDD and were above the 20-year GDD norm. The second-year of corn had adequate temperatures and 2909 GDD, but precipitation was much lower than the 25-year norm, putting the site in moderate drought conditions (US Drought Monitor, 2016) and leading to lower overall corn yields. The recommended 84 kg ha-1 of N placed on corn at the V4 stage, was decided because this was the minimum amount to still have adequate corn growth and reach a desired corn yield while also hoping to see cover crop differences on corn grain and stover yield.

Volunteer wheat presented an unanticipated challenge to the experiment, especially in the second-year where greater wheat yields and delayed harvest due to slow grain drying led to considerable shattering of overripe wheat at harvest. Applying glyphosate before CC planting did not control volunteer wheat because it germinated after CC were planted. Volunteer wheat competed with the CC and appeared to limit their growth (Figure 2b). While part of CC success is defined by the ability to suppress weeds (Lal et al., 1991; Reeves, 1994; Smeda et al., 1996; Dabney et al., 2001), wheat can itself be used as a CC (Tyler et al., 1987; Holderbaum et al., 1990; Worsham 1991; Stivers-Young and Tucker, 1999) and makes excellent forage

(Christiansen et al., 1998; Redmon et al., 1995; Pinchak et al., 1996; Ralphs et al., 1997; Epplin et al. 2000; Giunta et al., 2017). Therefore, in this study we simply consider the volunteer wheat to be an additional, unplanned CC grown in mixtures with the planned CC.

Ground cover evaluations were used to determine canopy closure and CC treatment establishment. Most CC treatments reached 80% canopy closure by the time of harvest eight weeks after CC planting; frost-seeded red clover had greater than 95% ground cover at this time (Figure 3A). Creamer et. al (1997) reported 30% canopy closure for thirteen different covers (mainly legumes) by four weeks after planting and 100% by 16 weeks after planting. In our study, volunteer wheat, weeds, and CC all contributed to canopy closure, but the proportion of weed species was relatively low. Plots designated as pure volunteer wheat due to CC failure had canopy closures of 30% eight weeks after CC planting and 60% four weeks after CC harvest (Figures 3A and 3B).

Results provide insight on the ability of different CC to establish after wheat harvest in Michigan and compete with volunteer wheat. Frost-seeded red clover was very competitive with volunteer wheat because of earlier establishment and a longer growth period compared to the other cover crops seeded after wheat harvest (Figure 3). Mutch et al. (2003) and Blaser et al. (2006) reported few weeds in frost-seeded red clover. Teffgrass was not competitive with volunteer wheat in our production system, contradicting research by Aberra (1992), where teffgrass was competitive when nonselective herbicides were applied before sowing. However, the Aberra (1992) study was in a conventional tillage system with different ploughing methods while our study was a no-till system. Volunteer wheat seed would have been buried below the germination zone and then teffgrass seeded shallow after tillage. Habtegebrial et al. (2007) and

Tulema et al. (2008) reported that teffgrass yield was suppressed in reduced tillage systems if weeds were not controlled by herbicide or handweeding.

Suppression of weeds by wheat, alfalfa, oats, sudangrass and red clover CC was reported in New York by vegetable growers (Stivers-Young and Tucker, 1999), and sorghum-sudangrass and oats CC suppressed weeds at a vegetable research station in Arizona (Burgos and Talbert, 1996). In a North Carolina study, sudangrass and sorghum-sudangrass not only suppressed weeds, but produced more biomass than most of the eight CC studied (Creamer and Baldwin, 2000). In our study, sudangrass, sorghum-sudangrass and oat/pea mix treatments as well as the unplanned volunteer wheat "cover crop" suppressed weeds. Additionally, wheat straw residues could have potentially contributed to weed suppression (Putnam and DeFrank, 1983; Barnes and Putnam, 1983; Shilling et al.,1985; Akemo et al., 2000), though this is not always the case (Teasdale and Daughtry, 1993; Akemo et al, 2000). In our study, we saw an increase in weeds after cover crop harvest which could be due to the opening of the plant canopy (Ballaré and Casal, 2000)

Oilseed radish competed successfully with weeds until forage harvest in October, but radish was not competitive with weeds in late October through November because there was little no regrowth from crowns after forage harvest. In our study, the weed cover in oilseed radish averaged 10% and fall weed cover consisted of 11%, which was not a significant change. Stivers-Young (1998) found that oilseed radish was most competitive with weed populations in the fall when planted in early spring due to early canopy development and closure. Stivers-Young (1998) study also showed that spring planted oil seed radish reduced weeds by 40% in the fall compared to other brassicas, kale and turnip, which reduced weeds by 55-65%. In this study, they disked the soil first before seeding CC, thus allowing for quicker radish establishment and canopy development and the spring planting allowed for a longer growth period, differing from our study. In other field experiments (Lawley et al., 2011) had almost complete weed suppression observed in all 4 site-years in early spring following forage radish, however suppression began to decline by mid-spring, although weed cover was still lower than that in the no cover control. Similarly, in another study, Lawley et al. (2012) found that oilseed radish is most competitive in the fall, when planted and fertilized in late summer. Similarly to the Stivers-Young (1998), Lawley et al., (2011) and Lawley et al. (2012) experiments, we found that oilseed radish, along with volunteer wheat, could suppress weeds sufficiently in the fall before CC harvest but less suppression was observed as the growing season continued into late fall and after CC harvest. The discrepancy between our results and the literature, could be that our study is a no-till cropping system and the radish seeds may not have had optimal conditions for quick growth and establishment (i.e. cooler, darker under the residue, lower soil-seed contact). We found volunteer radish in both site-years of corn plots. This could be related to the lack of optimal growing conditions, high residues, and that radish has a hard seed coat which protects it from germinating in poor conditions. Overall, oilseed radish did not compete as well as other annual CC in our study.

In our research, alfalfa (non-winter-hardy variety), cowpea, and sunn hemp failed to establish enough biomass to be useful as a CC in this system. Several factors may have contributed to this failure, including the unexpectedly cool temperatures, potentially low soil moisture and low GDD in late summer, lack of starter fertilizer at CC planting, large amounts of wheat residue that may have interfered with CC seed placement at planting, and competition from volunteer wheat. We chose not to apply starter fertilizer to CC because we felt farmers would be unlikely to pay to fertilize CC and because we wanted to encourage the N fixation benefit from our legume covers. However, small amounts of fertilizer can be beneficial to improving CC establishment and growth (Lawley et al., 2012).

We chose to leave wheat straw residue in the field because it could potentially increase SOM, water holding potential, and decrease soil erosion (Mannering and Meyer, 1963; Unger, 1975; Crutchfield et al., 1986); however, large amounts of residue can also decrease successful seed planting and germination (Day, 1968; Crutchfield et al., 1986; Hicks et al., 1989). In our study, CC established successfully on the edges of the plot where straw residues and competition from volunteer wheat was lower--this was noticeable in all treatments except for red clover. Farmers will often remove straw from the field for uses such as roughage in feed, compost, or bedding (Ashfield, 1978; Rynk et al. 1992; Wang et al., 2004). If the straw was removed, it could potentially solve the problem of CC establishment in high residue situations while also providing additional value from the system. Another possible solution is to minimal till or strip-till to create a more suitable seedbed for the CC.

Some degree of volunteer wheat establishment is inevitable after a commercial wheat harvest due to shatter of grain during harvest. Because wheat can be used as a CC (Mannering and Meyer, 1963; Unger, 1975; Crutchfield et al., 1986; Decker et al., 1994), this is not necessarily a negative when a CC is desired. However, the seeding rate of such volunteer plants is not controlled by the farmer and therefore may prove to be too competitive when a deliberately seeded CC is also being planted. In our study, an unusually high rate of shatter occurred during harvest because of plot combine design and weather that delayed harvest of the grain.

Overwintering planted CC in our study consisted of red clover and alfalfa. Additionally, there was also overwintering of volunteer wheat (Figure 3). Volunteer wheat survival ranged from 1% volunteer wheat cover in the red clover plots to about 40% in SUD/SDX. The positive side of volunteer wheat was weed suppression. Most treatments with volunteer wheat kept weed cover below 16%. The CC control weeds through competition, increasing water holding capacity and aeration (Creamer et al. 1996; Conklin et al., 2002). Weed suppression can reduce herbicide use resulting in lower production costs; however, the overwintering of red clover, alfalfa, and volunteer wheat as well as the presence of spring weeds still requires herbicide applications to remove living plants and prevent undue competition with corn (Van Heemst, 1985; Hall et al., 1992; Murphy et al., 1996; Liu et al., 2009; Otto et al., 2009; Tursen et al. 2016). One month after corn was planted, red clover and alfalfa were still the only CC to survive, with few weeds or volunteer wheat. Most plots had 90% of greater of the soil surface covered by the combination of surviving CC, weeds, volunteer wheat, corn, and straw/residue. In a crop management experiment with simulated rainfall applications in southwestern Brazil, Panachuki et al. (2011) reported higher runoff and soil loss under no-till system without residue, significantly less runoff under a no-till system with 2 tons/ ha^{-1} of surface soybean residue, and no runoff or soil loss under a no-till system with 4 ton/ha^{-1} of surface soybean residue. Water infiltration rates were likewise higher in no-till system with surface residue (Tisdall and Oades, 1982). The high degree of soil cover and residue in our study can potentially help reduce soil erosion, increase water infiltration and soil nutrients and recycling (Laflen and Colvin, 1981; Aulakh et al., 1991; Zibilske et al., 2002; Roldán et al., 2003; Govaerts et al., 2006; Bertol et al., 2007).

The CC with the largest accumulation of biomass was red clover (Figure 5) which agrees with Decker et al. (1994) who found that clover was the highest yielding of hairy vetch (*Vicia villosa* Roth.), winter pea and winter wheat. Red clover is planted 5 months earlier than the other CCs, as an undersown CC, which provides a unique advantage for this CC system (add something along this line). In addition, oat/pea mix, sudangrass, and sorghum-sudangrass produced enough yield to potentially cover the cost of harvest (Figure 5). Akemo et al. (2000a) in Ohio found that a pea/rye mix yielded > 4 Mg ha^{-1} of biomass which shows that peas can be high yielding when grown with a cereal. Akemo et al. (2000b) also found that pea-rye yields were greatest when soil moisture was between 80-100 mm of moisture. In the Akemo et al. (2000) study, cold and wet weather prevailed in 1996 and 1997 from April through June, which could have contributed to the greater yields of the pea/oat mix during the first site-year because of possible soil moisture retention with high residues and adequate precipitation. Both site-years of our study showed adequate moisture for pea establishment, but as discussed previously several other factors could have effected pea establishment and growth (i.e. volunteer wheat competition, high residues, etc.). Andraski and Bundy (2005) had a similar study, looking at oats, rye and triticale, and found that CC dry matter yielded 1.16 ± 0.86 Mg ha^{-1}, which is equal or lower to what we found in our experiment.

Sudex and sorghum are reported to have very high forage dry matter yields in some cases > 8 Mg ha^{-1} (Finney et al., 1988; Creamer and Baldwin, 2000). However, the Creamer and Baldwin (2000) study was conducted in the southern region of the US and therefore had more favorable growing conditions for these warm season grasses, when compared to the northern region's cooler and wetter growing conditions, particularly in Michigan. Due to unfavorable growing conditions and the excessive competition with volunteer wheat in our study, harvested forage yields were very low for teff, radish and VW (Figure 5), and farmers might not profit from harvesting low-yielding CC as double crops in Michigan due to seed, labor, and machinery costs (Teasdale, 1996). As a rule of thumb, forage harvests yielding less than about 1 Mg ha^{-1} may not produce enough value to cover the mechanical and labor cost of harvest in Michigan (Cassida, personal communication).

In addition to yield, nutritive value of harvested forage is important. Red clover had the highest CP content with oat/pea mix and radish being the next highest CP content, averaging 144 g kg^{-1}, 107 g kg^{-1} and 108 g kg^{-1} respectively (Table 2). This was an expected result since typically legumes have a greater CP content than grasses (Balde et al., 1993; Dewhurst et al., 2003), however, we would expect a 30-200g kg^{-1} greater CP concentration in the legumes than what our study showed. Typical CP concentration range for most legumes are 130 g kg^{-1} to 300 g kg^{-1} (Buxton et al., 1985; McGraw and Marten, 1986). The CP content for the grasses in this study were consistent with the literature (Robinson, 1969; Cherney et al., 1991; Pedersen and Toy, 1997; Ghanbari-Bonjar and Lee 2002; McCrown et al., 2012). Cassida et al. (2000) reported that alfalfa and red clover had high CP content during summer growth averaging 215 g kg^{-1} and 192 g kg^{-1}, respectively in a perennial forage cutting system. Average CP was lower in this study then what Cassida et al. (2000) found, which can be explained by the different management and cropping systems as well as the presence of volunteer wheat in all treatments (Table 2). The harvested volunteer wheat in the plots potentially reduced CP in forages because no additional N fertilized was added. This lack of fertilizer combined with the higher plant densities, the volunteer wheat was most likely unable to find adequate amounts N (about 100 kg N ha^{-1}) for wheat growth and higher N content (Evans, 1983; Valenti and Wicks, 1992; Delogu et al., 1998; Staggenborg et al., 2003). One indicator of the volunteer wheat N deficiency we noticed in our study was the tops to middle of the volunteer wheat leaves were yellow (Evans, 1983; Valenti and Wicks, 1992; Stone et al., 1996; Staggenborg et al., 2003). Roseberg et al., (2006) reported that teffgrass CP was responsive to N fertilizer and water with CP content ranging from 119 to 166 g kg^{-1}, while McCrown et al., (2012) reported teffgrass CP content between 89 to 100 g kg^{-1}. The CP content of teffgrass in our study agreed more with the

McCrown et al., (2012) study which is surprising since there was so much volunteer wheat in our teffgrass plots and the McCrown et al. (2012) study had mostly pure stands of teffgrass.

Cell wall content is measured by NDF and ADF and is considered a negative nutritive value component (Collins and Fritz, 2003). The NDF content was greatest for SUD/SDX and the FCC group, 675 g kg^{-1} and 645 g kg^{-1} respectively, while the legumes, red clover and the oat/pea mix, 586 g kg^{-1} and 628 g kg^{-1} respectively, had the lowest NDF content. Legumes, RCL and the OPmix, and the warm season grasses group, which included sudangrass, sudex and teffgrass, were significantly different from each other which was an expected result, since legumes have typically a lower NDF content than grasses (Balde et al., 1993; Dewhurst et al., 2003), depending on the growth stages of the grasses (Paterson et al., 1994; Balasko and Nelson, 2003). The reason for such high NDF content in all treatments in our study could be the volunteer wheat and straw contamination in all the plots. Wheat straw is almost pure cell wall with high NDF content and therefore increases the NDF of a forage mix containing straw (Leng, 1990; Poore et al., 1991; Moore et al., 1999).

Chapko et al. (1991) conducted a study with 4 different treatments consisting of oat, oat-pea, barley, and barley-pea. Looking at forage yield and forage quality of these treatments and found that the addition of pea to oat decreased NDF content by 7.1 percentage units and increased CP by 4.4 percentage units. Chapko et al. (1991) compared the oat-pea mix with all other treatments and found that the oat-pea mix had superior forage quality, though it was lower yielding compared to the other treatments. In the Chapko et al. (1991) study the forage quality of their oat/pea mix, CP, ADF and NDF values, were similar to our study, with very little difference. There was no difference in the ADF content for any treatments in the study, which could be explained by volunteer wheat contamination in all treatments (how did the average

ADF compare to recommended values for different livestock systems? Add some more context here). We did not examine digestibility of the harvested forage, which is another potential area of research for forages grown in this type of management (Yun et al., 1999).

Covers with the greatest moisture concentration at harvest were OPmix and RCL, 772 g kg^{-1} and 754 g kg^{-1} respectively and would therefore require the most wilting before ensiling, while the FCC group contained the least moisture at 631 g kg^{-1}. Recommended moisture for ensiling alfalfa and similar forage crops is 65-70% moisture (Jones et al., 2004), which compared to the 77% moisture content in RCL and 75% in OPmix treatments would require at least a 5-7% moisture decrease. Small grains, such as wheat and oats require a moisture content of 60-70% before ensiling (Jones et al., 2004), showing that the FCC group was in the range for direct chopping or baling, and the oats in the OPmix needed to dry about another 5% before ensiling. The other grass treatments in our study were in the recommended range for ensiling grasses, between 60-70% (Jones et al., 2004).

Corn grain or stover yields were not affected by a preceding CC (Table 3), therefore CC can potentially be used as a double crop in Michigan, though competition from a biannual CC such as red clover could potentially reduce corn yields if not managed (Kasper et al., 1990; Drury et al., 1999; Zemenchik et al., 2000). Andraski and Bundy (2005) found that corn yields were not affected by CC treatment if it was winterkilled. Dyke and Liebman (1995) also found that corn yields did not change in a study with red clover and oat residues incorporated into the soil before corn planting. Griffin et al. (2000) conducted a study in Maine looking at biomass and N accumulation of alfalfa, winter rye (*Secale cereale* L.), and hairy vetch (*Vicia villosa* Roth subsp. *Villosa*) plus rye. They found that the legumes accumulated more N than the rye cover grown alone, though biomass was similar for all covers. Both legumes accumulated more N than rye grown alone, although total biomass was similar. Several researchers have shown greater corn N uptake and/or yield following a clover CC compared with no cover (Torbert and Reeves, 1991; Dapaah and Vyn, 1998; Vyn et al., 2000; Gentry et al., 2013). In the Griffin et al. (2000) study, sweet corn yields were affected by CC red clover, oats, and N fertilizer rates. Similarly, the unharvested RCL treatment in our study had the greatest corn grain N concentration among all treatment combinations, but corn grain N concentration was reduced by 25% when RCL was harvested (20 to 15 g kg^{-1}, for unharvested and harvested, respectively) (Table 4). Harvesting RCL also reduced ear leaf N by 17% compared to unharvested RCL (23 vs. 19 g kg^{-1}). These reductions in ear leaf and corn grain N concentrations were not reflected in corn grain yields. The difference in the corn yields found in the Griffin et al (2000) study compared to the no difference in corn yields in our study could be due to the different crop (sweet corn versus field corn) and management of plots. We fertilized all our corn plots at the minimum required N for corn growth based on the MRTN (2016) rates for Michigan.

Total N removed by our corn crop showed a CC x harvest interaction. The harvesting of forage led to greatest reduction of corn crop TNR for the RCL, and had a lesser effect on OPmix, SUD/SDX, and radish treatments. The RCL and OP in the harvested system did not differ by TNR by corn, but RCL in the unharvested system had a greater TNR, though there was still no significant effect on corn yield. This finding potentially shows a quantifiable N removal rate of corn grown after CCs, especially for the RCL and OPmix treatments. This could help farmers better understand the benefits and negatives of harvesting a CC for forage and where to adjust for fertilizer rates, if needed. However, more research is needed to look at TNR of harvesting CC and its effect on corn.

Corn ear leaf N concentration was reduced for all harvested treatments except for radish, where forage harvest increased ear leaf N to 22 g kg^{-1} in corn the following year compared to 20 g kg^{-1} for ear leaf N when radish was not unharvested (Table 4). The same treatment pattern occurred for N content of corn grain after a radish CC (16 vs. 13 g kg^{-1} in the harvested vs not harvested plots, respectively). This could potentially be explained by Smith and Collins (2003) study, which found that broadleaf and brassica crops residues degrade quickly and therefore do not impede corn establishment and growth if weed competition is reduced or removed. A study by Jani et al. (2016) conducted in the Southeastern USA found that pea, clover and vetch roots decompose and release N rapidly and that termination by disking or roller-crimping does not affect these processes. Additional studies showed similar results of legumes CC shoots decompose and release N rapidly following termination, because of their low C:N ratio and percent lignin which favors fast rates of decomposition and N release (Buchanan and King, 1993; Sainju et al., 2005). Conversely, legume cover-crop roots have higher C:N ratios, elevated lignin content, and are often protected from microbial decomposition within the soil (Buchanan and King, 1993; Puget and Drinkwater, 2001; Schmidt et al., 2011; Dungait et al., 2012), all of which lead to slower rates of legume root decomposition and N release relative to shoots. Although legume cover-crop root decomposition and N release is relatively slow, roots can account for about 30% of total legume biomass (Sainju et al., 2005).

As discussed above, most harvested treatments saw a reduction in corn grain N, however, RCL and OPmix had the greatest decrease in corn grain N content. Rajcan and Tollenaar (1999) compared two corn hybrids and found that a higher N uptake during grain filling was related to a higher dry matter accumulation. This differs from some of the CC treatments in our study, when compared to stover biomass at harvest, oat/pea mix, sudex and FCC treatments had a higher corn grain N content with a lower corn stover biomass. Many of the studies are based on N uptake compared to other corn hybrids (Rajcan and Tollenaar, 1999) or C and N in the soil (Elliott, 1986; Utomo et al., 1990; Drinkwater et al, 1998; Dabney et al., 2001; Wilhelm et al., 2007) not the direct effects of CC on corn tissue, which makes evaluation difficult and leaves this an area open for more research for better comparisons.

Soil organic matter (SOM) did not respond to CC treatments. This is not surprising since it typically takes multiple years to detect changes in SOM (Sainju et al. 2002). Total C and N tests showed that overall, total soil N and C was similar among CC treatments (Table 5). This could be due to sampling error and/or change in bulk density over time (Logsdon et al., 2008). However, POXC results have shown to be good indicators of changes in a short period (Culman et al., 2012; Culman et al., 2013). There was a similar trend for POXC in red clover, oat/pea mix and the warm season grasses (Figure 6). These treatments had a lower POXC value for the harvested treatments compared to the not harvested treatments. Teffgrass was the only warm season grass that was the opposite, having a lower POXC value for the no harvest treatment. Culman et al. (2013) saw a significant difference in POXC values comparing three management systems including conventional till, an integrated system including CCs such as red clover, and compost. However, POXC in Culman et al. (2013) was measured over time both short-term and long-term, in comparison to our study which only looked at one point in a period. In the Culman et al. (2013) short-term study, POXC values were significantly lower for the conventional fertilizer management systems versus compost and cover crop alternative management. In three studies previously conducted in Michigan, red clover interseeded with wheat found increased soil C and N mineralization (Mutch and Martin 1998; Sanchez et al., 2001; Snapp et al., 2003), which is another potential area for further research.

CONCLUSIONS

Seeding CCs after winter wheat harvest in Michigan and then harvesting the CC for forage eight weeks later can provide harvestable forage. Red clover, oat/pea mix and sudangrass could be potential forage crops for double-cropping with acceptable nutritive value for some classes of livestock, such as dry cows and heifers, and they yielded the most forage and were best at competing with the weeds and volunteer wheat in Michigan. Sunn hemp, cowpea, teffgrass, and alfalfa did not establish following wheat harvest in our research and were not successful as cover crops or as forage crops. Seeding rates were a recommended seeding rate for cover crop establishment, however the high volunteer wheat and straw could have prevented cover crops to be no-till drilled in successfully. The removal of straw, which can provide on farm use such as bedding and as a roughage feed, and potentially a minimal or strip till could help with cover crop establishment. Therefore, allowing the cover crops to better compete with weeds and volunteer wheat and potentially increasing forage yield and quality, though more research of the effect on weed and volunteer wheat competition with these cover crops will need to be researched. Volunteer wheat can function as a CC and was accounted for in cover evaluations including canopy closure and height. Volunteer wheat was not the desired CC in this specific study and could have caused differences, or lack of differences, in quality and nutritional value in the desired CCs. There were no negative consequences of partial removal of CC biomass for forage on corn grain or stover yield. If a grower does not get red clover frost-seeded or does not want a perennial cover crop to terminate in the spring, an alternative cover crop is an oat/pea mixture following wheat harvest which will winter kill and still provide N and adequate forage yields. However, harvesting CCs such as frost-seeded red clover, oat/pea mix and volunteer wheat following wheat harvest in a Michigan wheat-corn rotation could potentially decrease available N during corn uptake, effecting corn quality and lower CP in corn grain. Measures of soil quality including SOM and POXC did not differ among CC treatments during this study, though more research should be done to quantify SOM and POXC for a longer term. Soil nutrient, C and N concentrations and C:N showed no differences because our study was not long enough to detect changes and should be done in a longer term study to see more accurate changes.

APPENDICES

APPENDIX A

Results

TABLES

Table 1. Variety and pure live seeding rates for cover crops grown after wheat harvest at East Lansing, MI. in 2014 and 2015.

Cover crop	Cover Crop Variety	Seeding Rate (kg ha^{-1})	Seed cost (per kg)	Cost kg/ha^{-1}
red clover	variety not stated	14.6	$4.27	$62.34
alfalfa	'Hi Nitro'	17.9	$9.68	$173.27
cowpea	variety not stated	56.0	$2.28	$127.68
sunn hemp	'Tillage Sunn'	22.4	$4.07	$91.17
oil seed radish	'CSS Tillage Radish'	20.2	$6.01	$121.40
oats	'Jerry'	33.6	$0.91	$30.01
field pea	'LC64040'	44.8	$1.32	$59.14
BMR sudangrass	'Piper'	22.4	$1.98	$44.35
BMR sudex	'GW 300 BMR'	33.6	$1.98	$66.53
teffgrass	2014-'Reprieve' 2015-'Dessie'	11.2	$6.42	$71.90

Seeding rates were recommendations found on the Midwest cover crop council (MCCC) website: http://mccc.msu.edu/ and seed cost were obtained from the individual seed companies where seed was obtained from and costs at that specific point in time (seed costs may differ).

Table 2. Nutritive value and carbon and nitrogen concentration and ratio of forage in cover crops harvested eight weeks after seeding following July 2014 and 2015 wheat harvest at East Lansing, MI.

	NDF†	ADF	CP	Ash	Harvest moisture	C	N	C: N Ratio
	----------	----------	----------	----------	g kg^{-1}	----------	----------	----------
RCL‡	586	374	144	91	754	448	23	19
OPmix	628	363	107	90	772	440	17	26
SUD	682	375	89	92	717	441	14	30
SUX	668	380	81	111	689	445	13	36
Teff	634	366	107	97	655	439	17	27
Radish	638	376	108	108	691	432	14	32
FCC	645	382	100	93	635	438	16	22
SE	1.6	1.2	0.7	0.8	1.6	0.5	0.1	2.1
	----------	----------	----------	----------	*P* <	----------	----------	----------
Model								
Cover crop	0.01	NS§	0.07	NS	0.04	0.01	0.07	NS
Contrasts								
RCL vs. FCC	0.02	NS	0.01	NS	0.01	0.04	0.01	0.06
RCL vs. OPmix	NS	NS	0.04	NS	NS	0.01	NS	NS
RCL vs. Radish	NS	NS	0.01	NS	NS	0.01	0.01	0.05
RCL vs. SUD/SDX	0.01	NS	0.01	NS	NS	0.07	0.01	0.02
SUD vs. SDX	NS	NS	NS	NS	NS	0.04	NS	NS
LEG vs. WSG	0.01	NS	0.01	NS	0.02	†NS	0.02	0.04

† NDF, neutral detergent fiber; ADF, acid detergent fiber; CP, crude protein; FCC, failed cover crop; LEG, legume group: RCL and OPmix; OPmix, oat/pea mix; N, nitrogen; RCL, frost-seeded red clover; SUD, sudangrass; SDX, sorghum x sudangrass; Teff, teffgrass; WSG, warm-season grass group: SUD, SDX, teffgrass.

‡ All values are dry matter basis except harvest moisture.

§ NS, not significant (*P* >0.10).

Table 3. ANOVA results and planned contrasts for corn grain and stover yields after cover crops were harvested or not harvested the previous October 2014 and 2015 at East Lansing, MI.

Treatment	Harvest Treatment	Grain, Mg/ha^{-1}	Stover, Mg/ha^{-1}
Fallow	fallow	14	13
RCL[‡]	NH[†]	12	13
RCL	H	11	13
OPmix	NH	13	15
OPmix	H	13	14
SUD	NH	13	14
SUD	H	13	13
SDX	NH	12	14
SDX	H	13	14
Teff	NH	13	14
Teff	H	13	15
Radish	NH	13	13
Radish	H	13	13
FCC	NH	13	14
FCC	H	13	13
SE		0.7	0.5
		------------------------ $P <$	--------------------------
Model			
Cover crop (CC)		NS[§]	NS
Harvest (harv)		NS	NS
CC t*harv		NS	NS
Contrasts			
RCL vs. FCC		NS	NS
RCL vs. OPMix		NS	NS
RCL vs. Radish		NS	NS
RCL vs. SUD/SDX		NS	NS
SUD vs. SDX		NS	NS
LEG vs. WSG		NS	NS
Interaction Contrasts			
RCL vs FCC for harv		NS	NS
RCL vs. OPmix for harv		NS	NS
RCL vs. Radish for harv		NS	NS
RCL vs. SUD/SDX for harv		NS	NS
SUD vs. SDX for harv		NS	NS
LEG vs. WSG for harv		NS	NS

Table 3. (cont'd)

Fallow vs. all not harvested CC	NS	NS
Fallow vs. all harvested CC	NS	NS
Fallow vs. RCL-NH	0.06	NS

† NH, Not Harvested; FCC, failed cover crop; H, Harvested; LEG, legume group: RCL and OPmix; OPmix, oat/pea mix; N, nitrogen; RCL, frost-seeded red clover; SUD, sudangrass; SDX, sorghum x sudangrass; Teff, teffgrass; WSG, warm-season grass group: SUD, SDX, teffgrass.

‡ All values are dry matter basis except harvest moisture.

§ NS, not significant (*P* >0.10).

Table 4. Nitrogen concentration, carbon/nitrogen ratio, and total nitrogen removed in V-12 stage corn ear leaves, grain and stover harvested after cover crops were harvested or not harvested the previous October 2014 and 2015 at East Lansing, MI.

		Corn Ear Leaf	Corn Grain		Corn Stover		Total N removed, kg/ha-1
Treatment	Harvested	N, g kg^{-1}	N, g kg^{-1}	C:N	N, g kg^{-1}	C:N	
Fallow	fallow	19	13	29	9	49	308
RCL[‡]	NH[†]	23	20	23	11	42	374
RCL	H	19	15	27	10	44	297
OPmix	NH	18	16	27	8	52	338
OPmix	H	18	13	30	8	55	284
SUD	NH	19	17	25	9	50	343
SUD	H	18	15	27	9	52	366
SDX	NH	20	14	28	8	56	293
SDX	H	19	15	28	8	55	304
Teff	NH	20	16	26	9	50	339
Teff	H	19	14	28	9	51	327
Radish	NH	20	13	30	9	48	291
Radish	H	22	16	26	9	47	335
FCC	NH	19	16	28	10	49	349
FCC	H	19	15	28	9	50	316
SE		0.6	0.1	1.0	0.1	3.9	21.3
		-------------------------	$P <$	-------------------------			
Model							
Cover Crop (CC)		NS[§]	0.10	NS	0.08	NS	NS
Harvest (harv)		0.06	NS	NS	NS	NS	0.01
CC*harv		NS	NS	NS	NS	NS	0.03
Contrasts							
RCL vs. FCC		NS	0.03	NS	0.01	0.01	NS
RCL vs. OPMix		NS	0.02	NS	0.01	0.01	NS
RCL vs Radish		NS	0.04	NS	0.01	0.01	NS
RCL vs. SUD/SDX		NS	0.03	NS	0.01	0.01	NS
SUD vs. SDX		NS	NS	NS	NS	NS	NS
LEG vs. WSG		NS	NS	NS	0.04	0.08	NS
Interaction Contrasts							
RCL vs FCC for harv		NS	NS	NS	NS	NS	0.01
RCL vs. OPmix for harv		NS	NS	NS	NS	NS	0.01
RCL vs. Radish for harv		NS	0.02	NS	NS	NS	0.01

Table 4. (cont'd)

RCL vs. SUD/SDX for harv	NS	0.10	NS	NS	NS	0.01
SUD vs. SDX for harv	NS	NS	NS	NS	NS	0.07
LEG vs. WSG for harv	NS	NS	NS	NS	NS	0.02
Fallow vs. all not harvested CC	NS	0.5	NS	NS	NS	NS
Fallow vs. all harvested CC	0.07	0.05	NS	NS	NS	NS
Fallow vs. RCL-NH	NS	0.01	NS	0.05	NS	0.01

† NH, Not Harvested; FCC, failed cover crop; H, Harvested; LEG, legume group: RCL and OPmix; OPmix, oat/pea mix; N, nitrogen; RCL, frost-seeded red clover; SUD, sudangrass; SDX, sorghum x sudangrass; Teff, teffgrass; WSG, warm-season grass group: SUD, SDX, Teff.

‡ All values are dry matter basis except harvest moisture.

§ NS, not significant (P >0.10).

FIGURES

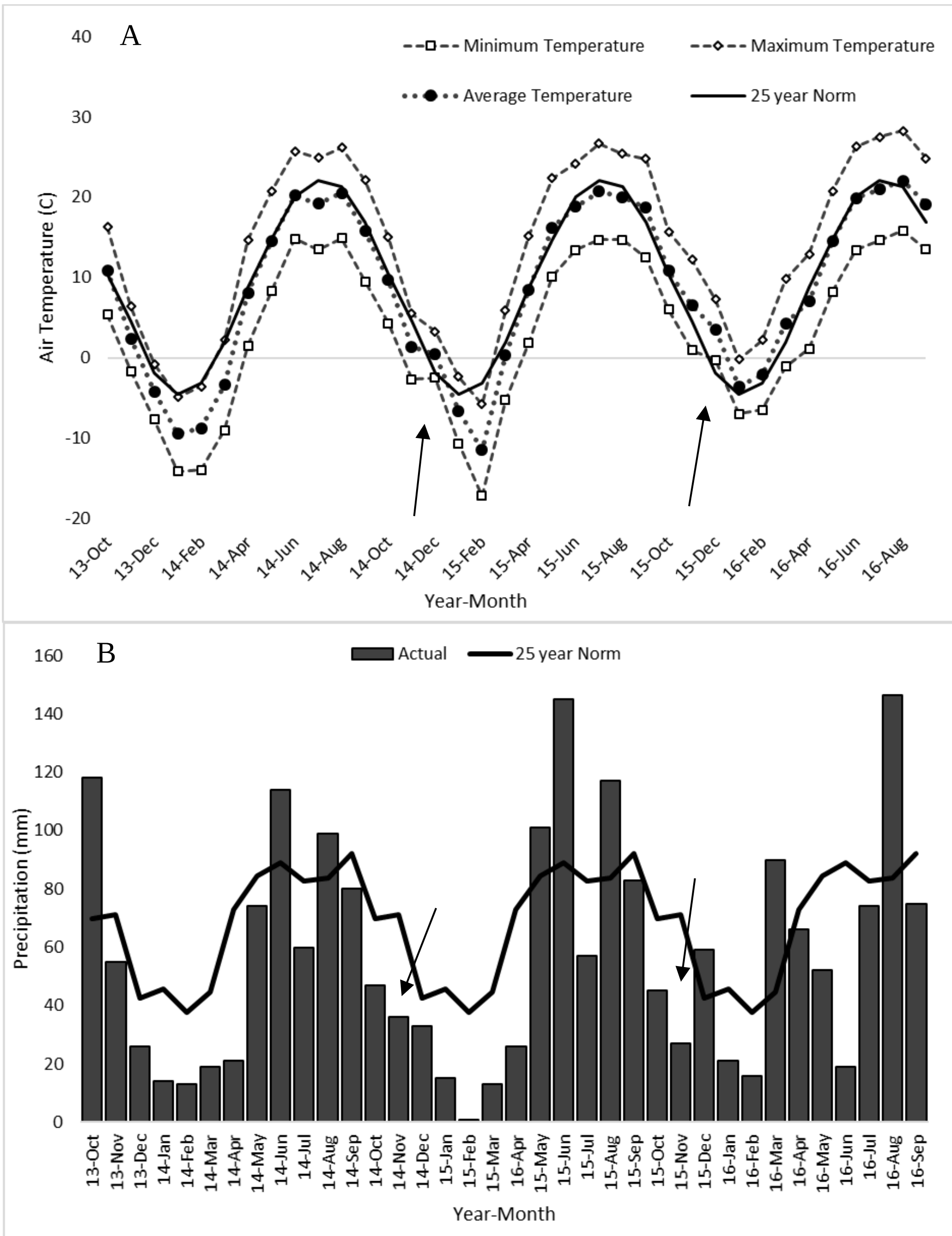

Figure 1. (A) Maximum, minimum, and average monthly air temperature, (B) cumulative monthly precipitation, and 25-year norms at East Lansing, MI., from October 2013 to September 2016. Arrows indicate when soil samples were obtained.

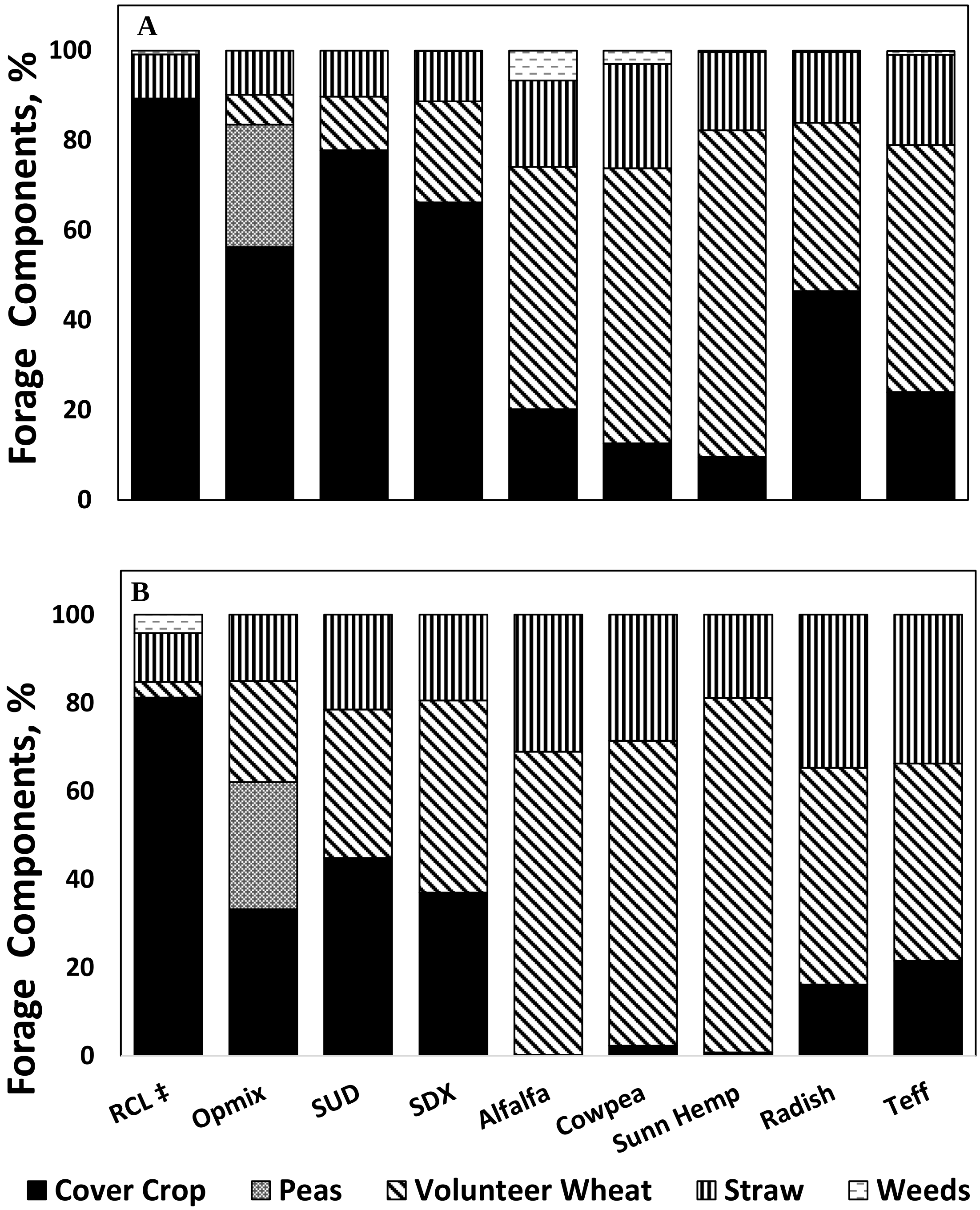

Figure 2. Percentage (dry matter basis) of cover crop, volunteer wheat, wheat straw, and weed components in biomass harvested in October in 2014 (A) and 2015 (B) from cover crop plots in East Lansing, MI. (‡ RCL, frost-seeded red clover; OPmix, oat/pea mix, SUD, sudangrass; SDX, sorghum x sudangrass; Teff, teffgrass)

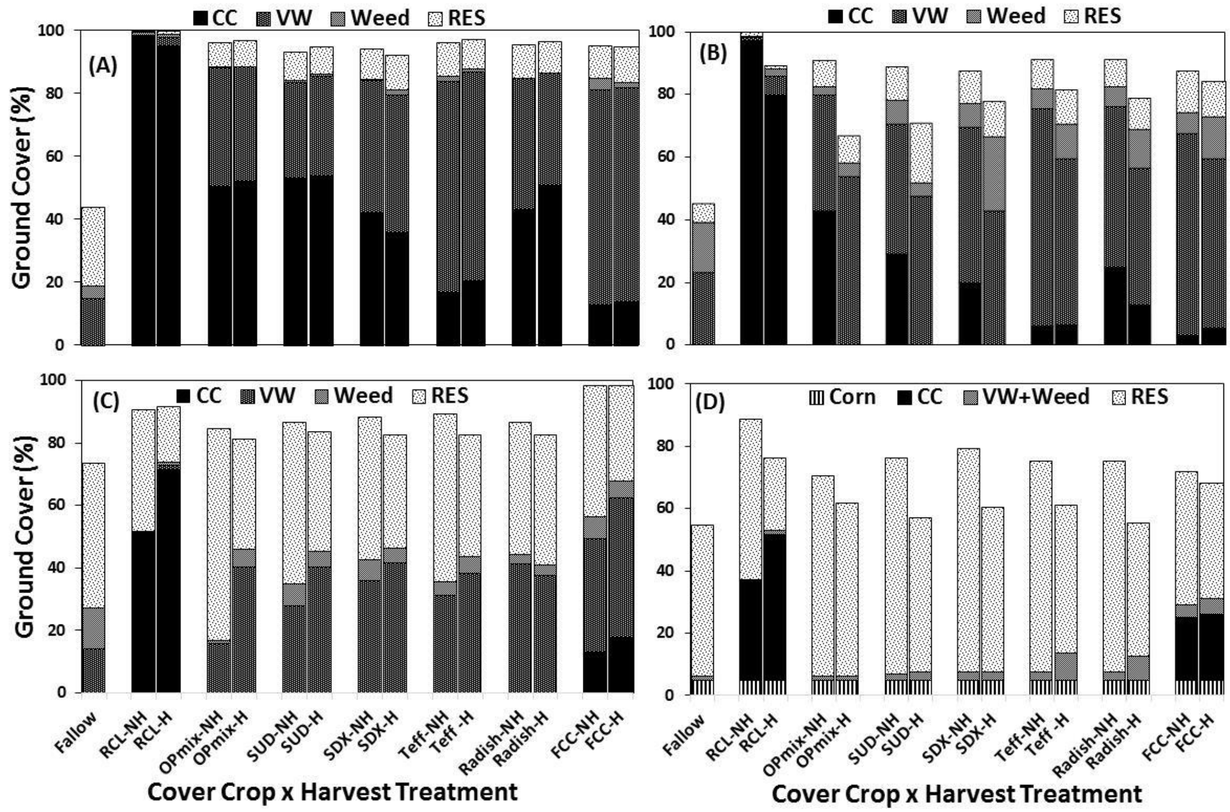

Figure 3. Cover crop (CC), volunteer wheat (VW), weed, crop residue (RES), and corn components of ground cover when measured: (A) eight weeks after CC planting following wheat harvest, (B) four weeks after Oct. CC harvest, (C) four weeks before May corn planting the following year, and (D) four weeks after May corn planting. Values are means from two site-years (2014-2015 and 2015-2016) at East Lansing, MI. (RCL = red clover, OPmix = oat/pea mix, SUD= sudangrass, SDX = sorghum x sudangrass, FCC = failed cover crop, NH = no CC harvest, H = CC harvested)

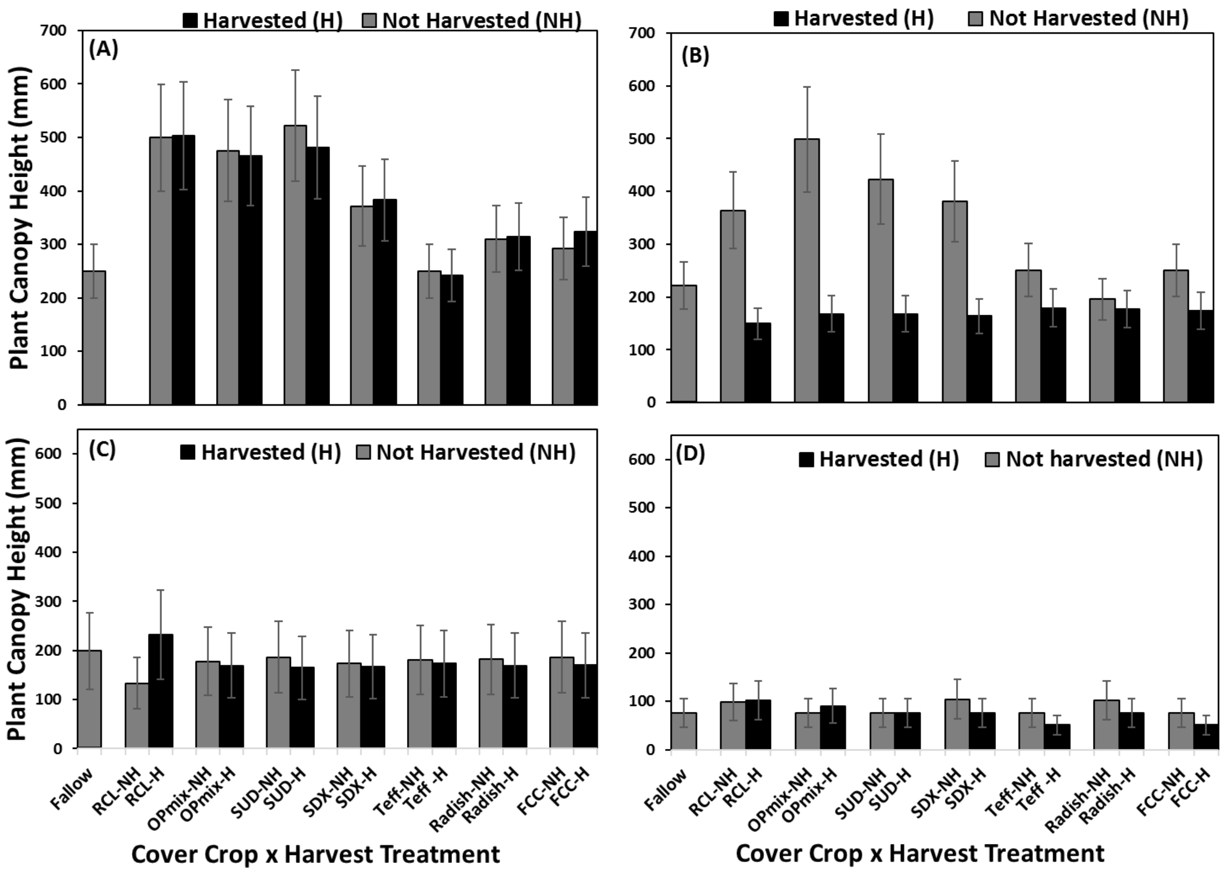

Figure 4. Plant canopy height when measured: (A) eight weeks after CC planting following wheat harvest, (B) four weeks after Oct. CC harvest, (C) four weeks before May corn planting the following year, and (D) four weeks after May corn planting. Values are means from two site-years (2014-2015 and 2015-2016) at East Lansing, MI. Error bars are SEM. (RCL = red clover, OPmix = oat/pea mix, SUD= sudangrass, SDX = sorghum x sudangrass, FCC = failed cover crop, NH = no CC harvest, H = CC harvested)

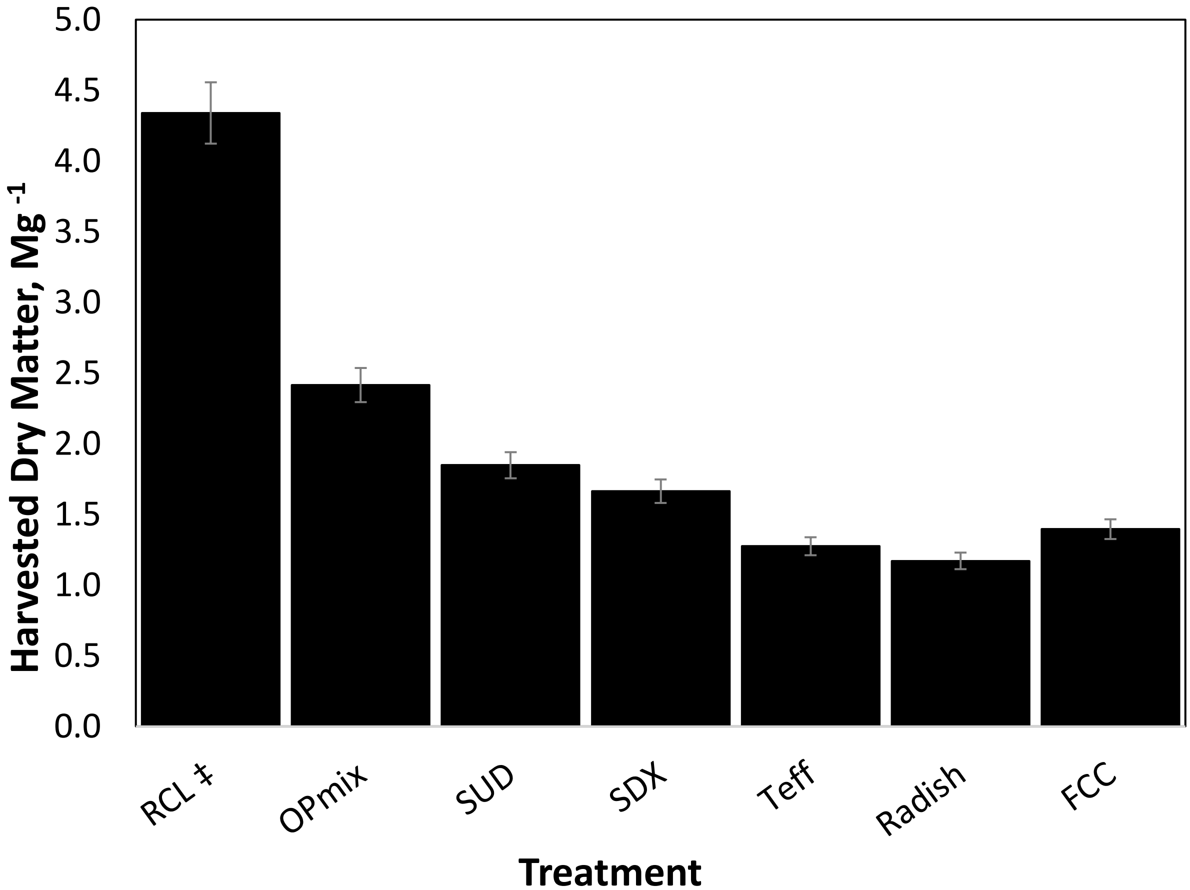

Figure 5. Forage dry matter harvested in October 2014 and 2015 from red clover and annual cover crops planted after wheat harvest in July, at East Lansing, MI. The error bars show statistically different results based on SE. (‡ RCL, frost-seeded red clover; FCC, failed cover crop; OPmix, oat/pea mix, SUD, sudangrass; SDX, sorghum x sudangrass; Teff, teffgrass)

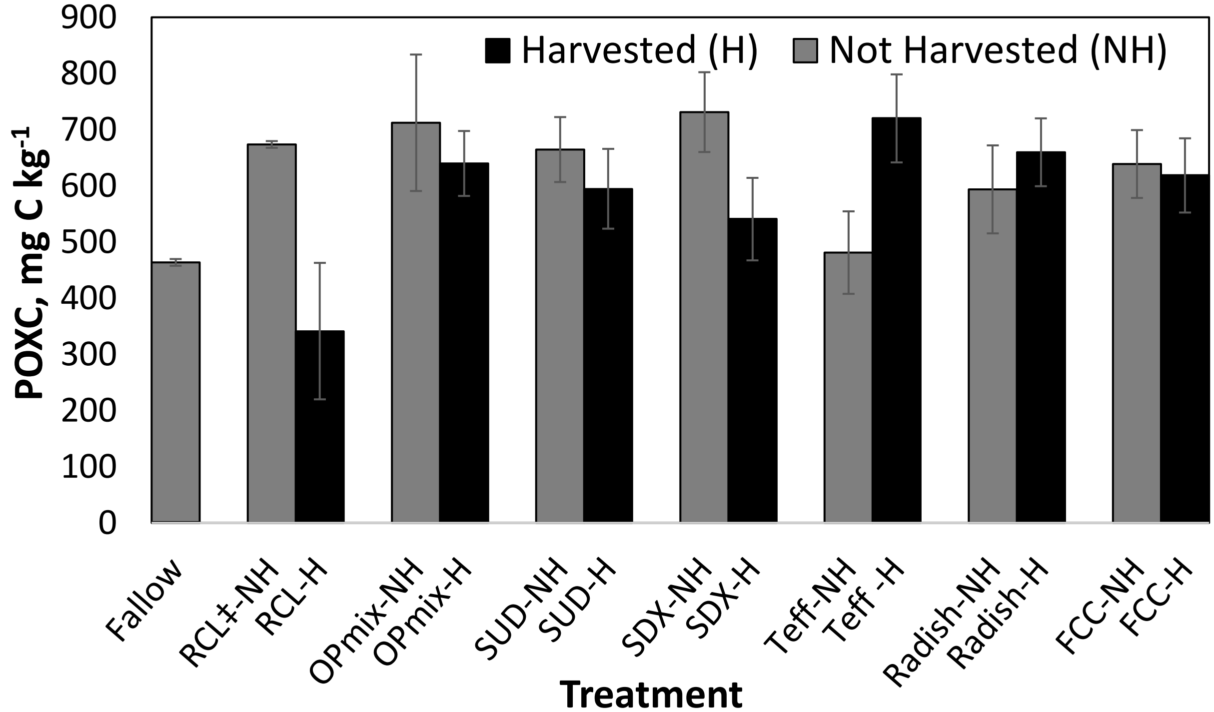

Figure 6. Analysis of variance for labile organic matter for 2014 and 2015 fall soil sampling after cover crop harvest. Cover crops were harvested in October 2014 and 2015 from red clover and annual cover crops planted after wheat harvest in July. Cover crops were harvested in October 2014 at East Lansing, MI. The error bars show statistically different results based on SE. (‡ RCL, frost-seeded red clover; FCC, failed cover crop; OPmix, oat/pea mix, SUD, sudangrass; SDX, sorghum x sudangrass; Teff, teffgrass)

APPENDIX B

ANOVA Tables for Figures

Table A1. ANOVA table for cover evaluations taken bi-weekly from red clover and annual cover crops planted after wheat harvest approximately, (A) eight weeks after cover crop planting (B) four weeks after cover crop harvest, (C) four weeks before corn planting (D) four weeks after planting. Cover crops were harvested in October 2014 and 2015 and corn was planted in May 2015 and 2016 at East Lansing, MI.

--*P* < ---										
	Eight weeks after cover crop planting					Four weeks after cover crop harvest				
Response Variable	Volunteer Wheat	Cover Crop	Weed	Bare Ground	Straw	Voluntee r Wheat	Cover Crop	Weed	Bare Ground	Straw
Model										
Cover crop (CC)	0.01	0.01	NS[§]	NS	NS	0.01	0.01	0.01	NS	NS
Harvest (harv)	NS	NS	NS	NS	NS	NS	0.01	0.01	0.07	0.01
CC *Harv	NS	NS	NS	NS	NS	0.01	0.01	0.01	NS	NS
SE	4.04	1.03	1.99	1.81	3.94	3.52	0.41	2.61	1.65	4.02
Contrasts										
RCL[†] vs. FCC	0.01	0.01	0.03	NS	0.05	0.01	0.01	0.01	NS	0.03
RCL vs. OPMix	0.01	0.01	NS	NS	NS	0.01	0.01	0.01	NS	NS
RCL vs. Radish	0.02	0.01	NS	NS	0.08	0.01	0.01	0.01	NS	NS
RCL vs. SUD/SDX	0.01	0.01	NS	NS	NS	0.01	0.01	0.01	NS	0.05
SUD vs. SDX	NS	NS	NS	NS	NS	NS	NS	0.04	NS	NS
LEG vs. WSG	0.01	0.01	0.01	NS	NS	0.01	0.01	0.04	NS	0.06
Interaction Contrasts										
RCL vs FCC for harv	NS	NS	NS	NS	NS	0.01	0.01	NS	NS	0.06
RCL vs. OPmix for harv	NS	NS	NS	NS	NS	NS	0.03	NS	NS	NS

Table A1. (cont'd)

RCL vs. SUD/SDX	NS	NS	NS	NS	NS	0.05	0.01	NS	NS	NS
SUD vs. SDX for harv	NS	NS	NS	NS	NS	NS	NS	0.01	NS	NS
LEG vs. WSG for harv	NS	NS	NS	NS	NS	0.01	0.01	NS	NS	NS
Fallow vs. all not harv CC	0.01	0.01	NS	NS	0.01	0.01	0.03	NS	0.01	0.01
Fallow vs. all harv CC	0.01	0.01	NS	NS	NS	0.01	NS	NS	NS	NS
Fallow vs. RCL-NH†	NS	0.01	0.01	0.01	0.01	0.03	0.01	NS	0.01	0.01

	-------------------- *P* < --------------------									
	Pre-Corn Planting					Post-Corn Planting				
Response Variable	Volunteer Wheat	Cover Crop	Weed	Bare Ground	Straw	Corn	Cover Crop	Weed	Bare Ground	Straw
Model										
Cover crop (CC)	0.01	0.01	0.10	NS§	0.08	NS	0.01	NS	NS	0.03
Harvest (harv)	0.01	0.01	0.01	0.01	0.01	0.01	NS	0.01	NS	0.01
CC *Harv	0.01	0.01	NS	NS	0.01	NS	NS	NS	NS	NS
SE	4.04	1.03	1.99	1.81	3.94	3.52	0.41	2.61	1.65	4.02
Contrasts										
RCL† vs. FCC	0.01	0.01	0.01	0.01	0.10	NS	0.01	0.04	0.05	0.01
RCL vs. OPMix	0.01	0.01	0.01	0.07	0.01	NS	0.01	0.03	NS	0.01
RCL vs. Radish	0.01	0.01	0.01	0.06	0.01	NS	0.01	NS	0.01	0.01

Table A1. (cont'd)

RCL vs. SUD/SDX	0.01	0.01	0.01	0.01	0.01	NS	0.01	0.05	0.01	0.01
SUD vs. SDX	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
LEG vs. WSG	0.01	0.01	NS	0.01	NS	NS	0.01	NS	0.05	0.01
Interaction Contrasts										
RCL vs FCC for harv	0.05	0.01	NS	NS	0.01	NS	0.03	NS	NS	NS
RCL vs. OPmix for harv	0.01	0.01	NS	0.04	0.03	NS	NS	NS	NS	NS
RCL vs. Radish for harv	NS	0.01	NS	NS	0.01	NS	NS	NS	NS	NS
RCL vs. SUD/SDX for harv	0.05	0.01	0.10	0.08	0.01	NS	0.08	NS	NS	NS
SUD vs. SDX for harv	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
LEG vs. WSG for harv	NS	0.01	NS	NS	0.01	NS	NS	NS	NS	NS
Fallow vs. all not harv CC	0.01	0.01	0.02	0.01	NS	0.03	0.09	0.04	NS	0.03
Fallow vs. all harv CC	NS	0.01	0.01	NS	0.01	NS	0.08	NS	NS	0.07
Fallow vs. RCL-NH†	0.02	0.01	0.01	0.01	NS	NS	0.01	0.01	NS	NS

† NH, Not Harvested; FCC, failed cover crop; H, Harvested; LEG, legume group: RCL and OPmix; OPmix, oat/pea mix; N, nitrogen; RCL, frost-seeded red clover; SUD, sudangrass; SDX, sorghum x sudangrass; Teff, teffgrass; WSG, warm-season grass group: SUD, SDX, Teff.
§ NS, not significant (P >0.10).

Table A2. ANOVA table for Plant canopy height taken bi-weekly from red clover and annual cover crops planted after wheat harvest approximately, (A) eight weeks after planting (B) four weeks after harvest (C) four weeks before corn planting (D) four weeks after corn planting. Cover crops were harvested in October 2014 and 2015 and Corn was planted in May 2015 and 2016 at East Lansing, MI.

	----------------------------------*P* <	---------------------------------		
	Eight weeks after cover crop planting	Four weeks after cover crop harvest	Pre-Corn Planting	Post-Corn Planting
Model				
Cover crop (CC)	0.01	0.01	NS§	NS
Harvest (harv)	NS	0.01	NS	NS
CC*Harv	NS	0.01	NS	NS
Contrasts				
RCL† vs. FCC	0.01	0.03	NS	NS
RCL vs. OPMix	NS	0.01	NS	NS
RCL vs. Radish	0.01	0.02	NS	NS
RCL vs. SUD/SDX	0.09	NS	NS	NS
SUD vs. SDX	0.01	NS	NS	NS
LEG vs WSG	0.01	0.04	NS	NS
Interaction Contrasts				
RCL vs FCC for harvest	NS	0.01	NS	NS
RCL vs. OPmix for harv	NS	0.01	NS	NS
RCL vs. Radish for harv	NS	0.01	NS	NS
RCL vs. SUD/SDX for harv	NS	NS	NS	NS
SUD vs. SDX for harv	NS	0.01	NS	NS
LEG vs. WSG for harv	NS	0.01	NS	NS
Fallow vs. all not harv CC	0.01	0.01	NS	NS
Fallow vs. all harv CC	0.02	0.02	NS	NS
Fallow vs. RCL-NH†	0.01	0.01	NS	NS

† NH, Not Harvested; FCC, failed cover crop; H, Harvested; LEG, legume group: RCL and OPmix; OPmix, oat/pea mix; N, nitrogen; RCL, frost-seeded red clover; SUD, sudangrass; SDX, sorghum x sudangrass; Teff, teffgrass; WSG, warm-season grass group: SUD, SDX, Teff.
§ NS, not significant (*P* >0.10).

Table A3. ANOVA table for Figure 5 forage dry matter harvested in October 2014 and 2015 from red clover and annual cover crops planted after wheat harvest in July, at East Lansing, MI.

Model	
	---- P < ----
Cover crop	0.02
Contrasts	
RCL‡ vs. FCC†	0.01
RCL vs. OPMix	0.01
RCL vs. Radish	0.01
RCL vs. SUD/SDX	0.01
SUD vs. SDX	NS§
LEG vs. WSG	0.01

† FCC, failed cover crop; LEG, legume group: RCL and OPmix; OPmix, oat/pea mix; N, nitrogen; RCL, frost-seeded red clover; SUD, sudangrass; SDX, sorghum x sudangrass; Teff, teffgrass; WSG, warm-season grass group: SUD, SDX, Teff.

‡ All values are dry matter basis except harvest moisture.

§ NS, not significant (P >0.10).

Table A4. ANOVA table for Figure 6 analysis of variance for labile organic matter for November 2014 and October 2015 fall soil sampling after cover crop harvest. Cover crops were harvested in October 2015 from red clover and annual cover crops planted after wheat harvest in July. Cover crops were harvested in October 2014 at East Lansing, MI.

Model	
	------*P* < --------
Cover Crop (CC)	NS§
Harvest (harv)	NS
CC*harv	NS
Contrasts	
RCL‡ vs. FCC†	NS
RCL vs. OPMix	NS
RCL vs. Radish	NS
RCL vs. SUD/SDX	NS
SUD vs. SDX	NS
LEG vs WSG	NS
Interaction Contrasts	
RCL vs FCC for harv	NS
RCL vs. OPmix for harv	NS
RCL vs. Radish for harv	0.09
RCL vs. SUD/SDX for harv	NS
SUD vs. SDX for harv	NS
LEG vs. WSG for harv	NS
Fallow vs. all not harv CC	NS
Fallow vs. all harv CC	NS
Fallow vs. RCL-NH	NS

† NH, Not Harvested; FCC, failed cover crop; H, Harvested; LEG, legume group: RCL and OPmix; OPmix, oat/pea mix; N, nitrogen; RCL, frost-seeded red clover; SUD, sudangrass; SDX, sorghum x sudangrass; Teff, teffgrass; WSG, warm-season grass group: SUD, SDX, Teff.

‡ All values are dry matter basis except harvest moisture.

§ NS, not significant (*P* >0.10).

Table A5. Carbon and nitrogen concentration in soil from the 12 cm depth sampled in November after cover crop were harvested or not harvested in October 2014 and 2015 at East Lansing, MI.

Treatment	Harvested	C g kg^{-1}	N g kg^{-1}
Fallow	Fallow	20.1	2.3
RCL[‡]	NH[†]	19.4	2.1
RCL	H	19.9	1.8
OPmix	NH	19.8	2
OPmix	H	20.4	2
SUD	NH	18.2	2
SUD	H	20.8	2
SDX	NH	18.5	2
SDX	H	20.7	2
Teff	NH	19.6	2
Teff	H	21.1	2
Radish	NH	18.2	1.8
Radish	H	18.5	1.8
FCC	NH	20.5	2
FCC	H	19.4	2
		0.2	1.5
SE			
	--------------	*P* <	--------------------
Model			
Cover crop (CC)		NS[§]	NS
Harvest (harv)		NS	NS
CC *harv		NS	NS
Contrasts			
RCL vs. FCC		NS	NS
RCL vs. OPMix		NS	NS
RCL vs. Radish		NS	NS
RCL vs. SUD/SDX		NS	NS
SUD vs. SDX		NS	NS
LEG vs WSG		NS	NS
Interaction Contrasts			
RCL vs FCC for harv		NS	NS
RCL vs. OPmix for harv		0.08	NS
RCL vs. Radish for harv		NS	NS
RCL vs. SUD/SDX for harv		NS	NS
SUD vs. SDX for harv		NS	NS

Table A5. (cont'd)

LEG vs. WSG for harv	NS	NS
Fallow vs. all not harv CC	NS	NS
Fallow vs. all harv CC	NS	NS
Fallow vs. RCL-NH	NS	NS

† NH, Not Harvested; FCC, failed cover crop; H, Harvested; LEG, legume group: RCL and OPmix; OPmix, oat/pea mix; N, nitrogen; RCL, frost-seeded red clover; SUD, sudangrass; SDX, sorghum x sudangrass; Teff, teffgrass; WSG, warm-season grass group: SUD, SDX, Teff.

‡ All values are dry matter basis except harvest moisture.

§ NS, not significant (*P* >0.10).

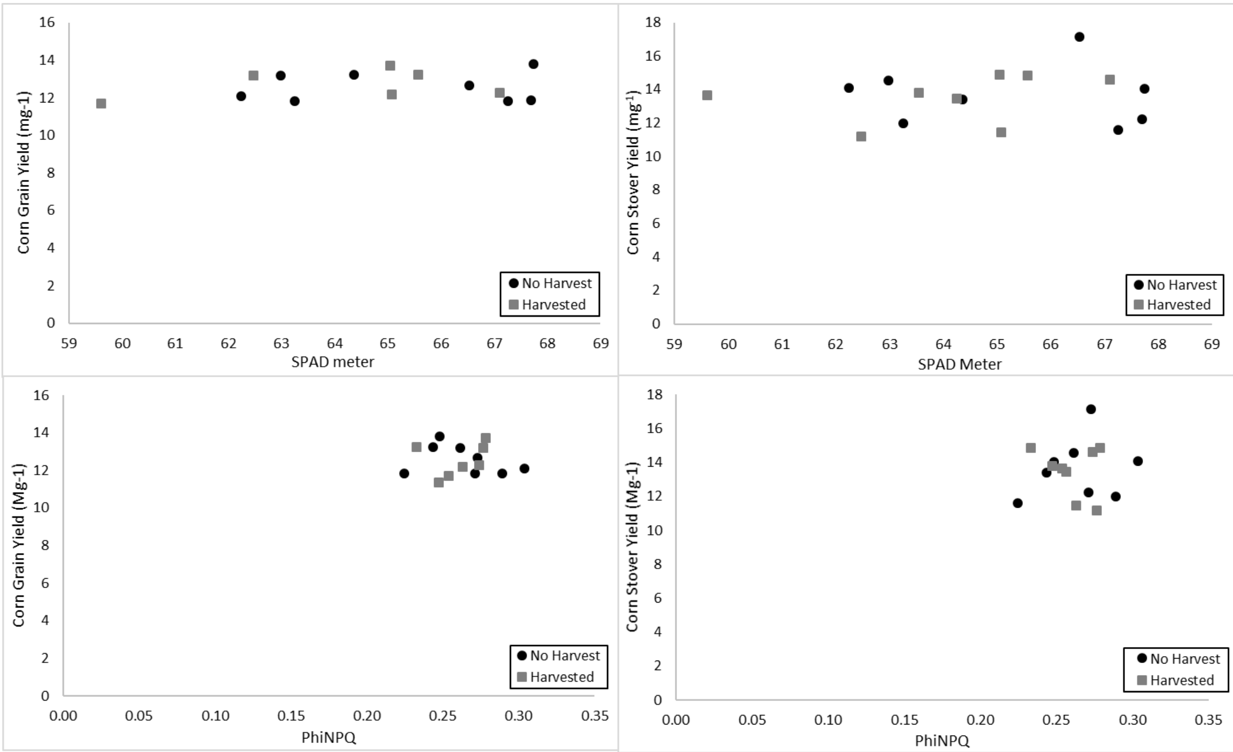

Figure A1. Corn SPAD (Soil Plant Analytical Division value) meter and PhiNPQ readings at V-12 stage in ear leaves of corn grown after cover crops were harvested or not harvested the previous October at East Lansing, MI. SPAD measures active regulation of energy towards photosynthesis and should be positively correlated with grain yield. PhiNPQ is the measurement of active regulation of energy away from photosynthesis and should be correlated with reduced grain yields

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