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Cover Crop Options and Mixes for Upper Midwest Corn–Soybean Systems

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ABSTRACT

The use of cover crops can decrease soil erosion, weed density, and nitrate leaching while improving soil quality. We investigated nine cover crops, winter rye (*Secale cereale* L.), winter triticale (× *Triticosecale* Wittm. ex A. Camus), two winter canola (*Brassica napus* L.), winter camelina [*Camelina sativa* (L.) Crantz], spring barley (*Hordeum vulgare* L.), spring oat (*Avena sativa* L.), turnip (*B. rapa* L.), and hairy vetch (*Vicia villosa* Roth), as sole crops and selected binary and trinary mixtures and their influences on subsequent corn (*Zea mays* L.) productivity. A control treatment of no cover crop was included. Cover crops were no-till drilled immediately after soybean [*Glycine max* (L.) Merr] harvest. The study was a randomized complete block conducted in five environments over 2013–2014 and 2014–2015. Across environments, rye and rye mixtures produced the greatest spring aboveground biomass (758 kg ha^{-1}), C, and N accumulation, had some of the lowest spring soil nitrate concentrations, and generally produced the lowest corn leaf chlorophyll. Rye accounted for more than 79% of spring aboveground biomass accumulation in rye mixtures. Triticale and camelina monoculture produced approximately 50% less biomass than rye or mixtures with rye. Cover crops in monoculture and mixtures did not influence surface soil temperature, soil P or K concentrations, weed density, weed community, or corn yield. Cover crops had limited influence on volumetric soil water content. Cover crop mixtures had no advantages over monocultures except for increasing fall stand density. Turnip and vetch had limited winter survival while barley, oat, and canola winterkilled.

Core Ideas

- Cover crop mixtures did not provide benefits beyond cover crop monocultures.
- Cover crops did not influence soil temperature, soil P or K concentrations, or corn yield.
- Cover crops did not influence weed density or weed community in subsequent corn.

The corn–soybean cropping system dominates the Midwest and is one of the most productive cropping systems in the world. The Midwestern state of Iowa often leads the United States in hectares of corn and soybean, with an estimated 5.5 million hectares of corn and 3.8 million hectares of soybean planted in 2013 (USDA, 2014). Although corn and soybean are highly productive in Iowa, they are only grown for approximately 5 to 6 mo of the year. For the remainder of the year most of the cropland in Iowa does not have any actively growing plants. Soil residue cover is often low, especially in systems which use fall tillage. The lack of growing plants and limited ground cover can result in soil erosion, nitrate leaching, decreased soil microbial activity, decreased accumulation of soil organic C, and increased weed density. Iowa corn–soybean cropland is losing approximately 22 to 26 kg N ha^{-1} every year through nitrate leaching (Christianson et al., 2013) with the majority of this loss occurring because of a lack of actively growing plants in the late fall or early spring. Iowa cultivated cropland soil is currently being eroded at a rate of approximately 13.6 Mg ha^{-1} every year through sheet and rill erosion with no decrease in erosion having occurred since 1992 (USDA, 2015).

The addition of cover crops to an agricultural system has great potential to decrease soil erosion, weed density, and nitrate leaching while increasing soil organic C (Kaspar et al., 2001; Teasdale, 1996; Strock et al., 2004; Dinnes et al., 2002; Villamil et al., 2006; Kaspar and Singer, 2011). Despite these benefits, approximately 1.9% of Iowa farm ground was planted to cover crops in 2015 (Lenssen, 2015). Of this area, the majority of hectares were planted to winter rye. Winter rye is the most widely used cover crop in Iowa because it establishes easily, produces high quantities of biomass, germinates at approximately 1.1°C, produces vegetative growth above 3.3°C, is very winter hardy, and the seed is available and inexpensive (Snapp et al., 2005; Singer, 2008).

Establishment, overwintering, and growth of cover crops planted into standing corn/soybean or after corn/soybean harvest is a major limitation for the implementation of cover crops in the Aquic and Udic soils of the upper Midwest (Johnson et al., 1998; Wilson et al., 2013). Many cover crop species are effective in the 7a winterhardiness zone (USDA ARS, 2016)

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Abbreviations: FCCBM, fall cover crop biomass; SC, stand count; SCCBM, spring cover crop biomass; SGDD, soil growing degree days; VWC, volumetric water content.

of Aquic and Udic soils of mid-Atlantic (Clark et al., 1994), 6a to 7b winterhardiness zone of irrigated, Ustic or Xeric soils of Pacific Northwest (Weinert et al., 2002), 8a to 9a winterhardiness zones of Udic southeastern (Sainju et al., 2005), and 9a to 10a winterhardiness zones of the irrigated, Xeric western (reviewed in Snapp et al., 2005) United States. However, some of these cover crops would not survive the 5a winterhardiness zone that makes up the majority of Iowa (USDA, 2012), in part because of variable snow cover. Many of these cover crops would be far less productive in Iowa than in other areas of the country due to Iowa's corn–soybean cropping system, shorter cover crop growing season, and lower heat unit accumulation from harvest to planting. The colder climate in Iowa limits viable cover crop options and the potential for successful establishment and growth of cover crops.

Recently, many new cover crops for Iowa have been widely promoted by cover crop seed companies, farm journals, and other commercial sources. Iowa Natural Resource Conservation Service (NRCS) has produced literature with a vast assortment of new cover crop options for Iowa (NRCS, 2013). Despite this interest, limited research has been done on these new cover crops to test their effectiveness in Iowa or the Midwest. Winter rye has been heavily researched and is the predominant cover crop planted in Iowa, but winter rye can sometimes negatively affect corn establishment, growth, and yield possibly due to water use, immobilization of soil N, interference with planter performance, or fungal disease (Munawar et al., 1990; Tollenaar et al., 1993; Duiker and Curran, 2005; Krueger et al., 2011; Kaspar et al., 2015). Oat is a potential cover crop for Iowa when overseeded into standing soybean in August, but oat will not produce any spring growth because it does not overwinter in Iowa (Johnson et al., 1998).

Alternative cover crops such as hairy vetch, rapeseed (*B. napus* L.), and white mustard (*Sinapis alba* L.) have been effective in warmer regions of the United States (Clark et al., 1994; Wilke and Snapp, 2008; Villamil et al., 2006, Weinert et al., 2002), winterhardiness zones 6a to 8b. Brassicaceae are increasingly being utilized as cover crops and can reduce weed populations due to allelophathic breakdown products from glucosinolates (reviewed in Haramoto and Gallandt, 2004). Conventional, non-genetically modified canola (*Brassica napus* L.) and camelina [*Camelina sativa* (L.) Crantz], both small-seeded annual Brassicaceae can overwinter in Iowa (Martinez-Feria et al., 2016; Lenssen, personal observation, 2013). Recently, camelina was documented to be an effective fall seeded cash crop in west central Minnesota (Gesch and Cermak, 2011), a 3b winterhardiness zone. Camelina can survive harsh Minnesota and North Dakota (winterhardiness zone 4a) winters (Berti et al., 2015) and has been documented to produce the greatest seed yields when planted in early to mid-October and then harvested in mid-July (Gesch and Cermak, 2011). They also reported that earlier seeding dates in September produced lower camelina seed yields.

Hairy vetch has sparked interest as an Iowa cover crop due to its potential to increase N supply to the following crop, which has been documented in warmer climates than the Upper Midwest (Clark et al., 1994; Sainju and Singh, 2008). Harbur et al. (2009) planted hairy vetch into fallow ground in early September and documented hairy vetch winter survival rates of 0.0 to 73.0% for 12 different hairy vetch ecotypes grown in Udic, southern Minnesota, a 4b winterhardiness zone. Hairy vetch ecotypes, which were sourced from Minnesota, had superior survival rates to hairy vetch ecotypes sourced from warmer climate areas (Harbur et al., 2009), demonstrating that hairy vetch seed source selection is an important component of improving winter survival. Hairy vetch mean aboveground biomass accumulation across 2 yr and two locations was 1900 kg ha^{-1} (Harbur et al., 2009).

Along with new cover crops for Iowa, cover crop mixes have also been widely promoted. The Iowa NRCS has published recommendations for cover crop mixes (NRCS, 2013) with limited testing. Cover crop mixes have received a great deal of attention in response to the commonly held belief that increasing plant biodiversity in an environment is always beneficial. This reasoning is based on studies such as the work done by Tilman et al. (1997) who modeled plant interspecific competitive interactions and found that when plant diversity was increased, nutrient retention was greater and overall plant biomass productivity was 2- to10-fold greater in high diversity ecosystems as compared with monocultures. Few cover crop mixture studies have been conducted in the upper Midwest so it is uncertain if increasing cover crop diversity will increase biomass production or have other positive benefits. Some Midwestern studies have found that cover crop productivity did not increase with increasing cover crop diversity (Wortman et al., 2012a; Maloney et al., 1999). In areas warmer than Iowa, studies demonstrated that winter rye–hairy vetch mixtures can produce greater biomass than a winter rye monoculture, including winterhardiness zones 6ba to 7b (Clark et al., 1994), 8a and 8b (Sainju et al., 2005), and 7b and 8a (Parr et al., 2011).

Despite the interest in new cover crops and cover crop mixes for Iowa, few cover crops can survive the harsh Iowa winters, which limits their potential to accumulate biomass, prevent soil erosion, and nitrate losses. Cover crops, and especially winter rye, effectively decrease soil erosion and nitrate losses in many environments including Iowa (reviewed in Kaspar and Singer, 2011; Kaspar et al., 2001, 2012). The use of a winter cereal cover crop such as winter rye can provide excellent biomass production and decrease soil erosion (Kaspar et al., 2001; reviewed in Kaspar and Singer, 2011) but can also create management challenges as winter cereal cover crops often result in N immobilization and limit N supply to the following crop (reviewed in Snapp et al., 2005). Release of N from cover crop residues is greatly increased when cover crops are incorporated as opposed to being left on the soil surface (Kuo et al., 1997b). Incorporation of Brassicaceae cover crops in the fall leads to increased soil N loss compared to spring incorporation (Weinert et al., 2002; Haramoto and Gallandt, 2004). Cover crop residue C/N ratio has been documented to be a good predictor of N mineralization and N residue retention (Quemada and Cabrera, 1995). High C/N ratio residues mineralize N at a slower rate and retain more N throughout the growing season, limiting the supply of soil available N to the cash crop (Quemada and Cabrera, 1995).

Cover crops have been documented to suppress weeds primarily through decreasing light transmittance to the soil (Teasdale, 1996). Teasdale et al. (1991) documented that when rye or hairy vetch cover crop residues covered more than 90%

of the soil, total weed density was decreased by 78% as compared to a no-cover crop control in a sweet corn crop 1 mo after sweet corn planting. In the same study Teasdale et al. (1991) also documented that increased cover crop biomass was positively correlated with decreased weed density and the relationship was linear. Other mechanisms for weed suppression, such as allelophathic effects from Brassicaceae cover crops, have been studied and are effective in the greenhouse (Haramoto and Gallandt, 2004), but show little evidence for being effective in the field (Haramoto and Gallandt, 2005). Teasdale (1996) reported that cover crop allelopathic effects are inconsistent and often difficult to document in field studies. When a cover crop produces adequate biomass and light interception, early season weed suppression in the crop can occur (reviewed in Teasdale, 1996). Spring terminated cover crops rarely provide complete weed control later in the season (reviewed in Teasdale, 1996). Cover crops provide limited weed suppression when they are tilled into the soil and cover crops residues are not allowed to remain on the soil surface (Teasdale, 1996; Wortman et al., 2013). Wortman et al. (2013) documented that increasing the number of species in a cover crop mix did not decrease weed density or weed biomass in an organic sunflower (*Helianthus annuus* L.)–soybean–corn rotation when cover crops were planted in late March, terminated in late May, and weed sampling occurred approximately 30 d after cash crop planting.

Cover crops might negatively impact crop development as a result of decreased spring soil temperatures due to light interception and soil shading. Corn emergence rate is highly correlated with the accumulation of growing degree days and soil temperature (Schneider and Gupta, 1985). Increases in soil cover from crop residue in the corn row at the time of planting has been documented as a strong detriment to corn growth rates from the time of planting to V6 stage corn (Swan et al., 1987). Corn row residue coverage of 87% was documented to require an additional 48 growing degree days for corn to reach V6 stage compared to 8% corn row residue coverage (Swan et al., 1987). Increasing cover crop biomass may increase soil cover and reduce soil solar interception, but little research has been published on this topic. Cover crops can have both positive and negative effects on soil available water (Munawar et al., 1990; Liebl et al., 1992; reviewed in Miguez and Bollero, 2005; Unger and Vigil, 1998; Krueger et al., 2011). Cover crops can decrease early season soil available water through transpiration losses but also increase available soil water due to increased soil coverage from cover crop residue remaining on the soil surface (Liebl et al., 1992; reviewed in Miguez and Bollero, 2005). Increased soil water loss through cover crop transpiration could be desirable in areas where heavy, wet spring soils and frequent rainfall limit early season field operations (reviewed in Kaspar and Singer, 2011). Alternately, areas with course-textured soils and limited rainfall may experience soil water deficits during the cropping season as a result of cover crop transpiration, if adequate rainfall does not occur after cover crop termination (Unger and Vigil, 1998; reviewed in Kaspar and Singer, 2011). The effect of cover crops on corn yield is highly variable and many contrasting results have been reported (Miguez and Bollero, 2005). Some studies documented that corn yield can be negatively influenced by certain cover crops in some years (Johnson et al., 1998; Krueger et al., 2011; Parr et al., 2011; Kaspar et al., 2012). Other studies documented that certain cover crops have no influence on corn yield in some years (Wortman et al., 2012b; Kaspar et al., 2012). Lastly, some studies documented that certain cover crops have a positive influence on corn yield in some years (Clark et al., 1994; Parr et al., 2011). A meta-analysis of 36 studies from the United States and Canada found on average a 21% increase in corn yield following a biculture winter cover crop, a 37% increase in corn yield following a legume winter cover crop, and no influence on yield of corn that followed a grass winter cover crop (Miguez and Bollero, 2005).

The objective of this study was to evaluate 16 potential cover crop treatments for Iowa, including two- and three-way mixtures. The effects of these 16 cover crops on (a) fall and spring cover crop aboveground biomass, C, and N accumulation, (b) spring soil temperature, (c) soil nutrients, (d) weed community and density, (e) corn population, (f) volumetric soil water content, (g) SPAD corn leaf chlorophyll, and (h) corn yield were examined.

MATERIALS AND METHODS

A field study was conducted at five sites in Iowa across two field years; two sites in 2013–2014 and three sites in 2014–2015. Sites were selected for the purpose of capturing a wide range of growing conditions across the state of Iowa. Sites included three major soil groups, as well as significant differences in precipitation, growing degree days, and winter temperatures, but all sites are considered 5a for winterhardiness.

Experimental site 1 (Ames), 2013–2014, was located 0.3 km South of Ames, IA (42°01′ N, 93°68′ W; altitude 307 m). Soil at the location was Nicollet loam (1–3% slope; fine-loamy, mixed, superactive, mesic Aquic Hapludoll) and half Canisteo clay loam (0–2% slope; fine-loamy, mixed, superactive, calcareous, mesic Typic Endoaquoll). Initial soil samples were not collected at this site. Experimental site 2 (Lewis1), 2013–2014, was located 7 km West of Lewis, IA (41°31′ N, 95°18′ W; altitude 387 m). Soil at the location was mapped as a predominantly 0 to 5% slope Ackmore–Colo–Judson complex (Ackmore: fine-silty, mixed, superactive, nonacid, mesic Mollic Fluvaquent; Colo: fine-silty, mixed, superactive, mesic Cumulic Endoaquoll; Judson: fine-silty, mixed, superactive, mesic Cumulic Hapludoll). Initial soil samples were not collected at this site. Experimental site 3 (Boone), 2014–2015, was located 10 km Southeast of Boone, IA (42°01′ N, 93°75′ W; altitude 324 m). Soil at the location was mapped as about half 2 to 6% slope Clarion loam (fine-loamy, mixed, superactive, mesic Typic Hapludoll) and half 0 to 2% slope Webster clay loam (fine-loamy, mixed, superactive, mesic Typic Endoaquoll). Initial soil samples showed pH of 6.35, Mehlich-3 P of 8 mg kg^{-1}, Mehlich-3 K of 128 mg kg^{-1}, and 3.2% organic matter at 0- to 15-cm depth. Experimental site 4 (Lewis2), 2014–2015, was located 7 km west of Lewis, IA (41°31′ N, 95°17′ W; altitude 396 m). Soil at the location was mapped as a 2 to 5% slope Marshall silty clay loam (fine-silty, mixed, superactive, mesic Typic Hapludoll). Initial soil samples showed pH of 6.35, Mehlich-3 P of 18 mg kg^{-1}, Mehlich-3 K of 244 mg kg^{-1}, and 3.7% organic matter at 0- to 15-cm depth. Experimental site 5 (Sutherland), 2014–2015, was located 5 km Southwest of Sutherland, IA (42°93′ N, 95°54′ W; altitude 444 m). Soil at the location was mapped as a 0 to 2% slope Marcus silty clay loam (fine-silty, mixed, superactive, mesic Typic Endoaquoll). Initial soil samples from 0- to 15-cm depth showed pH of 5.95, Mehlich-3 P of 18 mg kg^{-1}, Mehlich-3 K of 154 mg kg^{-1}, and 4.8% organic matter.

The experimental design was a randomized complete block with four blocks at each of the five research sites. Each block contained 17 different treatments and 18 plots, resulting in 72 individual plots at each site. Nine different cover crop monocultures and seven different cover crop mixture treatments were randomly assigned to the plots in each block (Table 1). Two control plots were also included in each block. The control plots were not planted with a cover crop, but were otherwise managed the same as the cover crop plots. Individual plot size was 7.62 by 6.10 m at Ames and Lewis1 (2013–2014) and 6.10 by 6.10 m at Boone, Lewis2, and Sutherland (2014–2015).

All five sites were in a corn–soybean rotation for over 20 yr, but past tillage systems differed. Ames and Boone were conventionally tilled for at least a decade while Lewis1, Lewis2, and Sutherland had been in a no-till system for 7 yr or longer. For this study, fall or spring tillage was not conducted at any of the sites.

Initial soil samples were collected at Boone, Lewis2, and Sutherland in the fall of 2014. Samples consisted of four soil cores, taken at 0- to 15-cm depth and aggregated into one sample. Core sampling locations were randomly selected from the alleys between the plots. Soil pH was measured using the 1:1 soil/water method. Initial soil samples were not taken at Ames and Lewis1 in fall of 2013.

Soil P and K levels were optimum (16–20 mg kg^{-1} Mehlich-3 P and 86–120 mg kg^{-1} Mehlich-3 K) or above optimum at every site except Boone. Triple super phosphate (0–46–0) and muriate of potash (0–0–62) were applied at 90 kg P_2O_5 ha^{-1} and 123 kg K_2O ha^{-1} with a Befco (Befco, Inc., Rocky Mount, NC) broadcast spreader in the spring of 2015 at Boone. Although soil tests did not indicate it necessary, Sutherland was fertilized with diammonium phosphate (18–46–0) and muriate of potash (0–0–60) at 83 kg P_2O_5 ha^{-1} and 108 kg K_2O ha^{-1}. The fertilizer was broadcast applied with a Gandy drop spreader (Gandy Co., Owatonna, MN) in late fall of 2015. All other sites did not receive any P or K additions. Spring N was applied at all locations in two events with split applications (Table 2). The first application occurred within a week of corn planting and the second was applied when corn was in the V6 to V8 stage (Table 2). All N applications were applied as urea ammonium nitrate (UAN) with a side-dress applicator, except the V6–V8 N application at Sutherland, which was applied as dry urea with a Y-Drop system (360 Yield Center, LLC, Morton, IL). Ames site did not receive an initial spring N application due to a product application error. The N application rate at the four other research sites was 202 to 212 kg N ha^{-1}, which is greater than the Iowa State University recommended corn fertilizer rate of 168 kg N ha^{-1}. The higher N rates were selected as a result of assumed nitrate leaching due to heavy spring rains which occurred at the research sites.

Cover crop treatments were planted at all five sites immediately following soybean harvest in mid- to late October (Table 2). No tillage occurred after soybean harvest. Soybean, which preceded cover crops, was adapted varieties with high yield potential. Soybean was harvested at the time of maturity and as soon as field conditions and farm crew scheduling allowed. Cover crops were no-till drilled with a Tye Pasture Pleaser with row spacing of 20.3 cm and at a seeding depth of 1.3 cm. Because the 10-row Tye drill had a total planting width of 182.7 cm, three passes were made through each plot to plant the entire width of the plot. The Tye drill had two hoppers; a large hopper for large seeded crops such as rye and a small hopper for small seeded crops such as camelina. When two-way mixtures were planted, both the large and small hoppers were used at the same time. When three-way mixtures were planted

Table 1. Cover crop treatments and pure live seed (PLS) seeding rate for five environments in Iowa.

Treatment	Grass	Brassicaceae	Vetch	Grass	Brassicaceae	Vetch
	kg ha^{-1}			PLS m^{-2}		
Control	0	0	0	0	0	0
Sole crops						
Cultivar Spooner winter rye	67			225		
Cultivar Trical102 winter triticale	67			300		
Cultivar Bison camelina		6			640	
Cultivar Purple Top turnip		6			510	
Hairy vetch (VNS)†			17			54
Cultivar Sitro canola		6			390	
Cultivar Claremore canola		6			390	
Cultivar Tradition spring barley	84			225		
Spring oat (VNS)	84			225		
Rye mixtures						
Rye–cultivar Claremore canola	45	6		150	390	
Rye–camelina	45	6		150	640	
Rye–vetch	45		11	150		35
Rye–camelina–vetch	45	6	11	150	640	35
Triticale mixtures						
Triticale–camelina	45	6		200	640	
Triticale–vetch	45		11	200		35
Triticale–camelina–vetch	45	6	11	200	640	35

† VNS = variety not stated.

rye or triticale was mixed with vetch at the correct seeding ratio and loaded in the large hopper while camelina was loaded in the small hopper. Cover crop treatments and seeding rates are described in Table 1.

Fall cover crop biomass sampling occurred the second week of November, immediately following a hard killing frost (Table 2). Lewis1 cover crop biomass harvest was not done due to minimal growth. Boone fall cover crop biomass harvest was not completed because the cover crops had not emerged. Cover crop biomass harvest was completed at Ames, Lewis2, and Sutherland with three of four blocks sampled at each site.

Cover crop stand counts were taken over a randomly selected area of 0.41 m^{-2}. Aboveground biomass of 20 randomly selected cover crop plants was hand clipped from each plot. When cover crop mixtures were sampled, the cover crops were separated by species. The biomass of the 20 plants was dried in a forced air oven for 7 d at 60°C and weighed. Fall cover crop biomass (FCCBM) was calculated as:

$$\mathrm{FCCBM} = (\mathrm{SC} \times ((\mathrm{Mass}/20) \times 2.4606)) \times 10 \qquad [1]$$

where FCCBM is fall cover crop biomass (kg ha^{-1}), SC is stand count, Mass/20 is the mass of 1 plant (g), 2.4606 is a conversion factor (0.4064–1 m^{-2}), and 10 is a conversion factor (g m^{-2} to kg ha^{-1}).

Spring cover crop biomass harvest occurred in late April to early May (Table 2), the optimal time period for corn planting in Iowa. Aboveground cover crop biomass was hand clipped from one randomly selected 0.5 m^{-2} area of every plot. The harvested biomass was dried in a forced air oven for 7 d at 60°C and weighed. Spring cover crop biomass was calculated as:

$$\mathrm{SCCBM} = (\mathrm{Mass} \times 2) \times 10 \qquad [2]$$

where SCCBM is spring cover crop biomass (kg ha^{-1}), Mass is cover crop mass (g 0.5 m^{-2}), 2 is a conversion factor (0.5 to 1 m^{-2}), and 10 is a conversion factor (g m^{-2} to kg ha^{-1}).

For both fall and spring cover crop biomass samples, species within cover crop mixtures were separated at harvest. All samples were weighed and then most samples were ground to pass a 1.0-mm sieve with either a UDY Cyclone Lab Sample Mill or a Thomas Wiley Mill (UDY Corporation, Fort Collins, CO; Thomas Scientific, Swedesboro, NJ). Some samples with limited amounts of biomass were ground with a coffee grinder and/or a mortar and pestle. Biomass samples were analyzed for total C and N concentrations by elemental combustion analysis at Iowa State University Soil and Plant Analysis Laboratory. The combustion procedure used a Leco Truspec CN Analyzer (Leco Corporation, St. Joseph, MI). Results from the analysis were used to calculate C and N concentration of every species, determine the contribution of each species to the mixture C and N accumulations, and calculate C/N ratios.

Spring soil sampling occurred the same day or 1 d after spring cover crop biomass harvest (Table 2). Three soil cores of 0- to 30-cm depth were sampled from a random location, directly between cover crop rows, in every plot. These three samples were composited for each plot prior to analysis for soil nitrate.

Determination of weed community in cover crops occurred 2 wk before spring cover crop biomass harvest at Ames and Lewis1 and the same day as spring cover crop biomass harvest at Boone, Lewis2, and Sutherland. Ames and Sutherland data were not included in the analysis due to very low weed density at these sites. Any plant that was not a cover crop was

Table 2. Field operation dates, corn variety, and N fertilizer rates and forms for five Iowa research sites. Ames, Lewis 1; 2013-2014. Boone, Lewis2, Sutherland; 2014-2015.

Field operation	Ames	Lewis1	Boone	Lewis2	Sutherland
Cover crop planting	10,11 Oct.	17,18 Oct.	29 Oct.	21 Oct.	14,15 Oct.
Fall cover crop biomass harvest	9,10 Nov.	na†	na‡	12 Nov.	13 Nov.
Spring weeds in cover crop	21 Apr.	21 Apr.	12 May	22 Apr.	28 Apr.
Spring cover crop biomass harvest	5 May	6 May	12 May	22 Apr.	28 Apr.
Spring soil sample	5 May	6 May	13 May	22 Apr.	28 Apr.
Cover crop termination	6 May	6 May	13 May	23 Apr.	30 Apr.
Corn planting	19 May	9 May	13 May	29 Apr.	30 Apr.
Initial N application	na§	6 May	21 May	29 Apr.	6 May
Corn population sample	9 June	10 June	10 June	21 May	21 May
Weeds in corn	3 June	10 June	1 June	21 May	21 May
Post emergence herbicide	13 June	10 June	1 June	21 May	16 June
In corn N application	26 June	16 June	2 July	18 June	2 July
Corn harvest	na¶	16 Oct.	16 Oct.	22 Oct.	20 Oct.
Corn variety	Pioneer P0453AM	Wyffels 6626	Pioneer P0453AM	Pioneer P0937	Pioneer P0297
Initial N application rate#	0	156	135	135	135
Initial N application form		32% UAN††	28% UAN	32% UAN	28% UAN
In corn N application rate	80	56	67	67	67
In corn N application form	32% UAN	32% UAN	32% UAN	32% UAN	Dry Urea

† na = not applicable; negligible cover crop emergence, no data collected.
‡ na = not applicable; cover crops did not emerge.
§ na = not applicable; initial N application never occurred.
¶ na = not applicable; site abandoned in July, frequent ponding and lack of N fertilizer.
# All N rates are kg N ha^{-1}.
†† UAN = urea ammonium nitrate.

considered a weed. Weed populations were sampled using five 0.1 m^{-2} hoops per plot. Hoops were randomly placed in every plot and weeds counted by species within each hoop. Weed species density and total weed density were calculated as:

$$\text{Weed density} = \text{Count} \times 2 \quad [3]$$

where weed density (weeds m^{-2}) count is sum of weeds in five hoops (weeds 0.5 m^{-2}), and 2 is conversion factor (0.5 m^{-2} to m^{-2}).

Cover crops were chemically terminated within 3 d of spring cover crop biomass harvest through application of 1.9, 2.3, 3.1, 3.1, and 2.9 L ha^{-1} of glyphosate [*N*-(phosphonomethyl) glycine] at Ames, Lewis1, Boone, Lewis2, and Sutherland, respectively. Boone site was also treated with 1.2 L ha^{-1} of 2,4-D [(2,4-dichlorophenoxy)acetic acid]. Cover crop termination also served as the initial burndown spray practiced in the no-till systems. A residual herbicide was intentionally omitted from the first spray for subsequent determination of weed community in corn prior to the first in-crop herbicide application.

Corn planting occurred in late April to early May (Table 2). Corn planting occurred 13, 3, 1, 6, and 0 d after cover crop termination at Ames, Lewis1, Boone, Lewis 2, and Sutherland, respectively (Table 2). Corn was planted with a no-till Kinze (Kinze Manufacturing, Williamsburg, IA) planter at all sites. Row spacing was 76.2 cm and planting depth was 3.8- to 5.1-cm deep. Each plot contained eight corn rows 6.1-m in length. Corn planting population was 79,100 seeds ha^{-1} at all sites except Boone, which was planted at 83,400 seeds ha^{-1}. Full season, glyphosate-tolerant corn varieties were planted at all locations (Table 2).

Soil temperature probes were deployed at corn planting at Experimental site 3 (Boone) in eight selected plots. HOBO Pro v2 external temperature data loggers were used (Onset Computer Corporation, Bourne, MA) for soil temperature data to determine if rye or rye mixes influenced soil temperature in comparison to a no-cover crop control. Loggers were placed in the soil at corn planting depth (5 cm) in two plots for each of the four following treatments: control, rye, rye–camelina, and rye–camelina–vetch. Loggers were placed at a depth of 5 cm by digging a small trench into the planted corn row at a 45° angle. Soil that was removed for digging of the trench was carefully held together and original soil structure was preserved. Data loggers were installed in the soil, and the removed soil slice was replaced to its original position within 1 min of extraction. Cover crop residue and aboveground crop residue were not disturbed in this process. Data were collected for 34 d starting the day after corn planting. HOBOware Pro software was used to calculate accumulated soil growing degree days (SGDD) which was based on the formula:

$$\text{SGDD} = ((T_{\max} + T_{\min})/2) - 5°\text{C} \quad [4]$$

where SGDD is soil growing degree days in °C, $T_{\max}$ is the maximum daily soil temperature with an upper limit of 41°C, $T_{\min}$ is the minimum daily soil temperature with a lower limit of 5°C, 2 is to calculate the daily mean soil temperature, and 5°C is the lower limit below which corn development is limited (Mark Westgate, Iowa State University, personal communication, 2015).

Corn population was determined at all five sites at approximately V2 stage corn. The number of plants in the two center rows within 5.31 m was counted. The number of plants ha^{-1} was calculated as:

$$\text{Population} = \text{Plants}/2 \times 2471.05 \quad [5]$$

where Population is corn plants ha^{-1}, Plants/2 is mean number of corn plants across two rows, and 2471.05 is a conversion factor (4.05 $m^{-2}$to 1 ha).

Weed community was determined at all sites from late May to early June before any post emergence herbicides were applied (Table 2). Weeds were sampled as previously described. A postemergence herbicide was applied to all five sites in late May to early June. Standard and appropriate labeled herbicides were tank mixed with a residual herbicide and applied to control grass and broadleaf weeds (Table 2).

Soil volumetric water content (VWC) measurements were taken at corn planting, V6 corn, and R1 corn. Measurements were taken at all sites for all three corn stages except at the time of corn planting at Lewis1 due to a miscommunication with the farm manager. All VWC measurements from Ames were not included in the analysis due to four ponding events during the growing season and poor corn growth due to no initial N application. Soil volumetric water was measured with a FieldScout TDR 300 Soil Moisture Meter (Spectrum Technologies, Inc., Aurora, IL). The meter was calibrated prior to use at each site. Measurements were collected immediately next to the corn row in a single random location in each plot. The VWC was sampled for the 0 to 7.6 cm and 0- to 20-cm depth layers.

Corn leaf chlorophyll measurements were taken at V6 and R1 stage corn at all sites except Ames due to the frequent ponding and no initial N application. Corn leaf chlorophyll was measured with a nondestructive SPAD-502 chlorophyll meter (Konica Minolta, Inc., Osaka, Japan). The uppermost collared leaf was sampled from one randomly selected corn plant in each of the six center corn rows of each eight-row plot. The mean of the six values was used to represent the plot chlorophyll reading. Each sample was taken from the center of the corn leaf (halfway between the stalk and the tip) and just slightly offset from the leaf midrib. During the V6 sampling each corn plant sampled was marked with brightly colored ribbon so that identical plants could be resampled at R1.

Corn harvest occurred in mid- to late October (Table 2). Corn yield data were collected with a self-propelled combine equipped with a calibrated yield monitor from the center four rows of every plot. Corn yield data were adjusted to 155 g kg^{-1} moisture. In early June of 2014, an intense 76 mm rain event occurred at Lewis1 resulting in severe soil erosion within the test area. All plots affected by gully formation or corn row washouts were eliminated from subsequent data collection except in corn weeds data collection.

Data were analyzed with PC-SAS v9.4 using the GLIMMIX procedure. The GLIMMIX procedure was selected due to the missing values discussed in the previous paragraph. Cover crop treatment was considered a fixed effect and was the response variable. Year and location were combined into one factor of "environment" and environment was considered a random effect. Environment, block, and the environment × block interaction were considered random effects. The LSMEANS statement was used to calculate treatment least squares means and the LINES statement was used to determine approximate *t* groupings for the treatment least squares means. Differences between means were reported as significant at a *P* value of 0.05.

RESULTS AND DISCUSSION

Fall Cover Crop Aboveground Biomass

When fall cover crop stand counts and aboveground biomass harvest were determined at Ames, Lewis2, and Sutherland; the grasses were at two-leaf stage, the Brassicaceae cover crops were at early cotyledon stage, and vetch shoot length was approximately 5 cm. Biomass harvest was taken in late fall, at the time of the first killing frost. Biomass harvest did not occur at Boone because the cover crops did not emerge until the following spring. Biomass harvest did not occur at Lewis1 because biomass accumulation was negligible with grasses barely emerged. Soybean harvest occurred approximately 1 to 2 wk later than in most years due to wet field conditions, which limited available growing degree days for cover crop development due to later planting. Despite cover crops being planted at each site 1 or 2 d after combine harvest of soybean, postharvest heat unit accumulation was limited, resulting in poor fall cover crop biomass accumulation at all sites (Table 3). Cover crops had at most 3 to 4 wk to germinate, emerge, and grow before the first hard killing frost (Table 2). Johnson et al. (1998) documented a mean of 440 kg ha^{-1} of fall aboveground biomass when oat and winter rye cover crops were overseeded into soybeans in August in Iowa. The most productive cover crop in our study produced 15% of the fall cover crop biomass of the Johnson et al. (1998) study. Early maturity soybean cultivars which can be harvested earlier, or intercrop cover crop seeding by either aerial application or a high-clearance tractor with drop tubes, may allow cover crops to achieve significantly more biomass accumulation and improved winter survival of canola and hairy vetch cover crops.

Cover crops differed for fall biomass accumulation with rye–camelina mix producing the greatest amount of aboveground biomass, 68 kg ha^{-1} (Table 3). Rye monoculture and rye mixtures did not differ in biomass production. Triticale associated cover crops produced slightly less biomass than rye-associated cover crops. Triticale monoculture and triticale mixtures did not differ in biomass production. These results would lead to the conclusion that fall biomass production was not greater in mixtures than in a monoculture under the conditions and cropping systems of this study. In general, the treatments that included a grass accumulated at least twice as much biomass as the sole crop Brassicaceae treatments (Table 3). Hairy vetch monoculture accumulated 5 kg ha^{-1}, the least biomass of all cover crops and cover crop mixtures, producing 90.1% less biomass than monoculture rye (Table 3). Apparently, hairy vetch must be planted earlier in the fall to allow the accumulation of more growing degree days to increase potential winter survival (Samarappuli et al., 2014). It is also possible that the hairy vetch genotype used in this study may not have sufficient winter hardiness to tolerate harsh Iowa winters with limited snow cover, as occurred in this study.

Table 3. Fall aboveground biomass cover crop associated response variables. Cover crop biomass accumulation, cover crop C accumulation, cover crop N accumulation, cover crop C/N ratio for three Iowa sites 2013–2014.

Treatment	Biomass	Carbon	Nitrogen	C/N ratio
	kg ha^{-1}			
Sole crops				
Winter rye	56ab†	25a	2.3ab	10.7a
Winter triticale	42abcd	19abc	1.9abc	10.0abc
Camelina	20cdefg	7bcde	0.8cdef	9.3cde
Cultivar Purple Top turnip	18 defg	7cde	0.8cdef	8.8fe
Hairy vetch	5g	2e	0.3f	8.2f
Cultivar Sitro canola	12fg	5e	0.5ef	9.0def
Cultivar Claremore canola	13efg	5de	0.6def	8.3f
Spring barley	61ab	26a	3.1a	8.1f
Spring oat	42abcde	18abc	1.8abcd	9.6cde
Rye mixtures				
Rye–cultivar Claremore canola	52ab	23a	2.3ab	10.2abc
Rye–camelina	68a	29a	2.8ab	10.5ab
Rye–vetch	61ab	27a	2.7ab	9.9abc
Rye–camelina–vetch	48abc	20a	2.0abc	10.1abc
Triticale mixtures				
Triticale–camelina	46abcd	19abc	1.8bcde	10.6ab
Triticale–vetch	39bcdef	17abcd	1.7bcde	9.7abcd
Triticale–camelina–vetch	47abcd	19ab	2.0abc	9.9abcd
Significance				
Treatment	***	***	***	***
P Value	0.0007	0.0005	0.0011	0.0001

*** Significant at $P \leq 0.001$.

† Means followed by different lower case letter within a column in a set are significantly different at $P \leq 0.05$ by the least square means test.

Fall Cover Crop Stand Density

Cover crop entries differed significantly in their stand densities and rye–camelina had the greatest stand density (Fig. 1). Monoculture rye and monoculture camelina produced stand densities that were 43 and 63% of the stand density of rye–camelina mixture (Fig. 1). Rye mixtures and triticale mixtures which included camelina produced the greatest stand densities (Fig. 1). These results lead to the conclusion that fall cover crop stand densities can be significantly greater in a mixture than in a monoculture when two productive monoculture cover crops are planted as a mix, as long as seeding rates of either are not greatly decreased (Fig. 1).

Fall Cover Crop Carbon and Nitrogen Accumulation and Carbon/Nitrogen Ratio

Cover crop entries differed in their aboveground C and N accumulation and C/N ratio (Table 3). Entries that included a grass accumulated the most C and N (Table 3). Among entries, the C/N ratio was generally lowest for the Brassicaceae and vetch sole crops (Table 3). Cover crop residues that remain on the soil surface and have a high C/N ratio decompose and release accumulated N more slowly than low C/N ratio cover crop residues (Quemada and Cabrera, 1995). Despite the statistical significance among species for fall cover crop biomass, and C and N accumulation, cover crop growth was nominal compared to other areas of the United States, different cropping systems, or earlier cover crop planting dates that accumulate more heat units following cover crop planting and the onset of winter (Kuo et al., 1997a,1997b; Sainju et al., 2005; Sainju and Singh, 2008; Poffenbarger et al., 2105). The most productive cover crop in our study produced 2 to 10% of the fall cover crop biomass of six different cereal forage crops, which were seeded in August in winterhardiness zones 4b and 5a in Wisconsin (Maloney et al., 1999). Finney et al. (2016) documented that when cover crops were seeded after oat harvest in August in Pennsylvania (winterhardiness zone 6b) fall cover crop biomass accumulations of winter rye and winter rye mixtures all produced at least 10 times greater biomass accumulation than the most productive cover crop in our study.

Spring Cover Crop Aboveground Biomass

The majority of turnip and vetch plants winterkilled and the spring turnip and vetch biomass collected probably came from hard seed, which did not emerge in the previous fall. In southern Minnesota (winterhardiness zone 4b), hairy vetch planted into fallow ground in early to mid-September had survival rates of 0 to 73% across 12 ecotypes sourced from differing locations in the United States (Harbur et al., 2009). They also documented that all 12 hairy vetch ecotypes winterkilled at one out of six locations across 3 yr of the study, and the average hairy vetch survival rate was approximately 50% (Harbur et al., 2009). Our study had lower hairy vetch survival rates and was planted much later than the Harbur et al. (2009) study. We are not aware of optimal fall developmental growth stage for winter survival of hairy vetch.

Sitro canola, Claremore canola, barley, and oat all winterkilled and produced no spring growth. Oat does not survive the winter in Iowa (Johnson et al., 1998), so it was expected it would winterkill. Gusta and O'Connor (1987) documented that barley at the two leaf stage does not survive temperatures below −10°C. In our study the barley had just reached two leaf stage in the fall and winter temperatures were far below −10°C. Rife and Zeinali (2003) documented that canola rarely survives temperatures below −12°C. Canola generally does not survive winter unless it has reached rosette stage or has at least six fully developed leaves (Great Lakes Canola Association, 2016). In this study, canola plants only reached cotyledon stage and none survived the harsh winters. Temperatures dropped below −20°C on multiple occasions at all sites during the 2013–2014 and 2014–2015 winters, with no snow cover during several of these events. It should be noted that the rye–canola mix contained no canola biomass in the spring due the winterkill

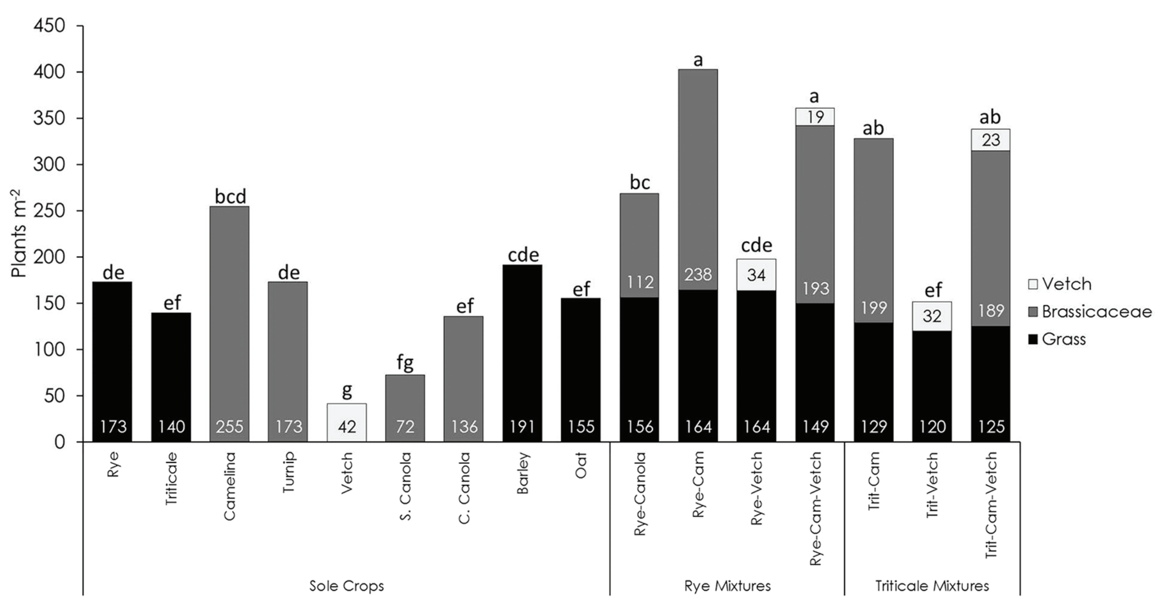

Fig. 1. Fall cover crop stand density (plants m^{-2}) of 16 cover crop treatments at three sites sampled in early November of 2013 and 2014. Mean species plant density presented in every bar. Sum of the species means in each bar = total cover crop treatment plant density. Means with different lowercase letters above the bar are significantly different at $P \leq 0.05$ by the least square means test. Cover crop treatment significant at P value = <0.0001.

of canola (Fig. 2). Camelina survived winter well in our study, similar to other reports from winterhardiness zones 3b and 4a in the upper Midwest (Gesch and Cermak, 2011; Gesch and Archer, 2013; Gesch et al., 2014).

Cover crop entries influenced spring cover crop aboveground biomass accumulation (Fig. 2). Rye–vetch mixture was composed of 97% rye biomass and produced the most biomass of all cover crops, but it was not significantly different from any other rye-associated treatment or the three-species mixture of triticale–camelina–vetch (Fig. 2). Rye and mixtures with rye accumulated the most biomass with a mean of 758 kg ha^{-1} across the five rye treatments. Spring winter rye biomass accumulation was very similar to another recent Iowa study in which cultivar Wheeler winter rye produced 720 kg ha^{-1} of biomass over a 3-yr study (Pantoja et al., 2015). Conversely, Kaspar and Bakker (2015) reported mean aboveground biomass yield of 2230 kg ha^{-1} from six winter rye cultivars grown in Iowa over a different 4-yr period, 2006 to 2009, a period with greater growing degree days (GDD) accumulation than observed during the period of our study. In a 5-yr study from 2005 to 2009, Kaspar et al. (2012) reported average spring biomass accumulation of 1310 kg ha^{-1} for winter rye. As for other annual crops, winter rye biomass accumulation is influenced by environment, cultivar, date of termination, and numerous other factors.

At cover crop termination, rye and triticale mixtures had produced similar biomass to their corresponding monocultures (Fig. 2). Both rye and triticale were highly competitive with the intercropped Brassicaceae and vetch (Fig. 2). Rye production was >79% and triticale production was >58% of the total biomass in two- and three-way mixtures (Fig. 2). These findings are consistent with other studies which have found that cover crop mixes do not produce more biomass than the most productive cover crop monocultures (Finney et al., 2016; Poffenbarger et al., 2015; Wortman et al., 2012a). Other studies have confirmed that rye often dominates biomass production in a mixture (Clark et al., 1994; Finney et al., 2016; Poffenbarger et al., 2015). Poffenbarger et al. (2015) examined cover crop planting ratios for hairy vetch–winter rye mixtures and recommended a hairy vetch/winter rye seeding rate of 27:34 kg ha^{-1} to maximize N content of the cover crop and maintain a relatively low C/N ratio for a cover crop, which was planted in mid-September to mid-October in Maryland after a soybean cover crop that was terminated in late August. In the same study, if rye was proportionally greater than a seeding rate of 27:34 kg ha^{-1} hairy vetch/winter rye, rye biomass dominated the mix for 3 out of 4 site-years (Poffenbarger et al., 2015). Winter rye/hairy vetch seeding ratio in our study was 45:11 kg ha^{-1}, which would give a strong advantage to the winter rye.

Triticale monoculture produced 50% as much biomass as the mean of the rye-associated cover crops (Fig. 2). It should be noted that our study only included a single cultivar of winter rye, winter triticale, camelina, hairy vetch, turnip, spring barley, and spring oat so our results may not be representative of each species. Camelina monoculture produced 41% as much biomass as the mean of rye-associated cover crops (Fig. 2). Camelina and vetch produced less biomass in a mix than when grown as a monoculture (Fig. 2). Turnip and vetch produced 15 and 10% as much biomass as rye-associated cover crops, respectively, and had sparse stand density due to lack of overwintering.

Spring Cover Crop Carbon and Nitrogen Accumulation and Carbon/Nitrogen Ratio

Rye-associated cover crops accumulated the most aboveground C and N with a mean of 315 kg C ha^{-1} and 21 kg N ha^{-1} across the five rye-associated treatments (Fig. 3). Rye mixes did not accumulate more C or N than a rye monoculture (Fig. 3). Due to their increased biomass production, winter rye cover crops have the potential to contribute more soil organic C and accumulate more soil N than the other cover crop treatments included in this study. Kuo et al. (1997a) also documented similar results to our study, demonstrating that winter rye had

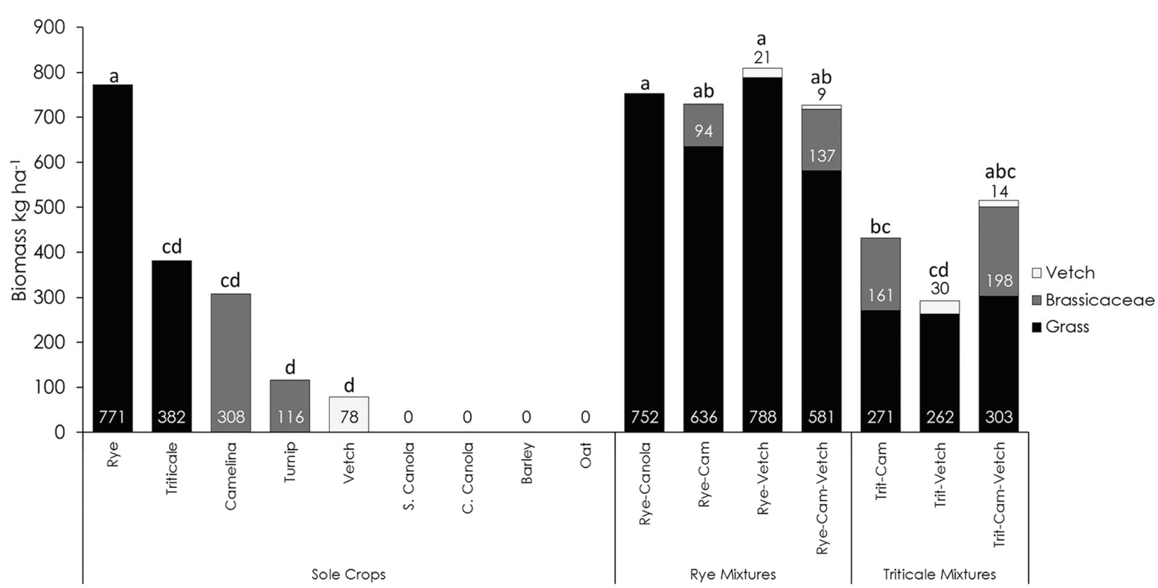

Fig. 2. Spring cover crop aboveground biomass accumulation (kg ha^{-1}) at five sites sampled at cover crop termination; late April–early May of 2014 and 2015. Mean species biomass presented in every bar. Sum of the species means in each bar = total cover crop treatment biomass. Means with different lower case letters above the bar are significantly different at $P \leq 0.05$ by the least square means test. Cover crop treatment significant at P value = <0.0001.

greater potential to increase soil organic C than hairy vetch, canola, or Austrian winter pea [*Pisum sativum* L. ssp. *arvense* (L.) Poir.]. On average, approximately 22 to 26 kg N ha^{-1} N is lost from Iowa corn–soybean farm ground every year through nitrate leaching (Christianson et al., 2013). Nitrogen fertilizer recommendations in Iowa assume that nitrate which is present in fall soil samples is lost via leaching or denitrification (Sawyer, 2013). In our study, the five treatments which included a winter rye cover crop accumulated a mean of 21 kg N ha^{-1} in aboveground biomass (Fig. 3b), which should reduce the N being lost from Iowa farm ground in the months of October to April when crops are otherwise not growing in Iowa fields. In a 3-yr field study at four Iowa locations, Pantoja et al. (2015) documented that winter rye cover crops accumulated 21 kg N ha^{-1}, which is identical to what we report. Camelina and vetch accumulated 36 and 10% as much C and 60 and 13% as much N, respectively, as the mean of the five rye-associated treatments. Camelina and vetch accumulated much less C and N when grown in a mix compared to a monoculture (Fig. 3), likely due to competition from rye and triticale.

The C/N ratio of rye-associated cover crops was greater than for all other cover crops and cover crop mixtures, except for triticale monoculture and triticale–vetch (Fig. 4). The C/N ratio did not differ between rye monoculture and rye mixtures (Fig. 4). Two out of three triticale mixtures had significantly lower C/N ratios than all of the rye-associated cover crops. Camelina monoculture had a lower C/N ratio than all rye and triticale-associated cover crops (Fig. 4). Turnip had the lowest C/N ratio (Fig. 4), but this was comparatively unimportant as turnip produced limited biomass from seeds that germinated in the spring (Fig. 2).

The C/N ratio for rye mixtures were somewhat surprising as we expected rye mixtures to have lower C/N ratios than rye monoculture as previously documented by Sainju et al. (2005).

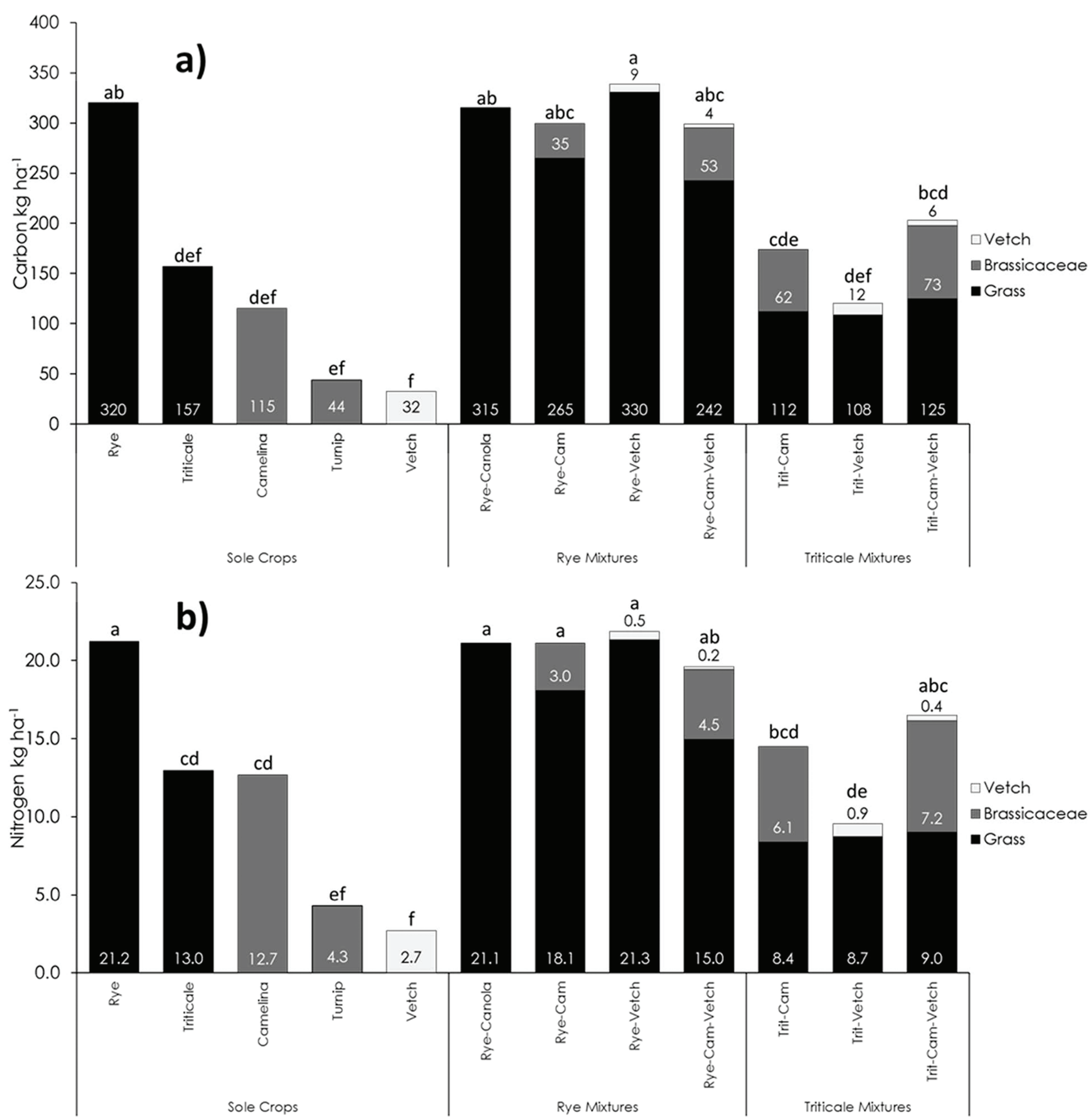

Fig. 3. Spring cover crop aboveground (a) C and (b) N accumulation (kg ha^{-1}) at five sites at cover crop termination; late April–early May of 2014 and 2015. Mean species C or N accumulated biomass presented in every bar. Sum of the species means in each bar = total cover crop treatment C or N accumulation. Means with different lower case letters above the bar are significantly different at $P \leq 0.05$ by the least square means test. Cover crop treatment significant at P value = <0.0001.

Sainju et al. (2005) planted a fall-seeded rye and hairy vetch biculture in Georgia at 50% of the rye and 68% of the hairy vetch monoculture rates. Sainju et al. (2005) documented rye monoculture C/N ratios of 29, 57, and 40 and rye–hairy vetch mixture C/N ratios of 10, 32, and 11 across a 3-yr study. We had assumed the presence of camelina and vetch with low C/N ratios, would decrease the C/N ratio of the mix. But this was not the case; probably due to the fact that rye accounted for 79% or more of the biomass in rye mixtures, and triticale accounted for 58% or more of the biomass in triticale mixtures. Our results may have been different if seeding ratios would have been adjusted to greatly decrease the seeding rate of rye and triticale, while increasing the seeding rate of hairy vetch and camelina.

The C/N ratio is often a major factor in determining cover crop rate decomposition and N release (reviewed in Blanco-Canqui et al., 2015). All cover crop entries included in this study had C/N ratios less than 14:1, in large part because their growth and development was low due to lack of accumulated heat units prior to their termination for planting corn. Weinert et al. (2002) documented that cover crops with C/N ratios below 16:1 were unlikely to cause N immobilization; therefore, we can assume that although C/N ratio probably affected decomposition rates, cover crop entries in our study did not immobilize soil N. Due to differences in cover crop C/N ratio, cover crop residue N release may have been slower for the rye-associated cover crops, intermediate for the triticale-associated cover crops as well as the vetch, fast in the camelina and turnip, and very fast in the cover crops which did not overwinter. The assumption that winterkilled cover crops released N very fast is supported by Weinert et al. (2002), who documented that cover crops which winterkill release and leach N more quickly than cover crops which overwinter.

Quemada and Cabrera (1995) documented that winter rye residue had C/N ratios of 98.9 for stems and 28.9 for leaves which was higher than the C/N ratios for clover, wheat, or oat leaves and stems (Quemada and Cabrera, 1995). In the same study, the leaf C/N ratio in rye was greater than twice as much as the leaf C/N ratio for clover, wheat, or oat cover crops (Quemada and Cabrera, 1995). They also reported that rye residue retained 26% or more N than clover, oat, or wheat cover crops after 160 d of incubation on the soil surface (Quemada and Cabrera, 1995). The C/N ratios in our study were far below those in the Quemada and Cabrera (1995) study, but the assumption that cover crops with high C/N ratio release N more slowly is still supported by our results which document that higher C/N ratio cover crops appear to have decreased corn N accumulation as discussed below in the Corn Leaf Chlorophyll section.

Soil Growing Degree Days

Over the 34-d period following corn planting, accumulated soil growing degree days were similar at corn seeding depth for rye (508 GDD), rye–camelina (504 GDD), rye–camelina–vetch (506 GDD), and the no-cover crop control (500 GDD)). A high percentage of the accumulated rye biomass present at cover crop termination remained on the soil surface, but this did not influence soil growing degree days. Other studies have found that cover crop residues can reduce spring soil temperatures, total seed germination, and negatively influence crop establishment in no-till systems while moderating temperature extremes by decreasing day time high temperatures and increasing night time low temperatures (reviewed in Blanco-Canqui et al., 2015). None of these effects were observed in this study, perhaps due to limited biomass production or relatively high soil residue cover in the no cover crop treatment. Biomass accumulation may have been insufficient to impact radiation interception. It is also possible that rye transpired increased levels of soil water and created a drier soil than the control. Dry soil has the potential to heat and cool more quickly than wet soil (Licht and Al-Kaisi, 2005). Drier soil in the rye treatment may have compensated for decreased solar interception caused by the rye residues shading the soil surface.

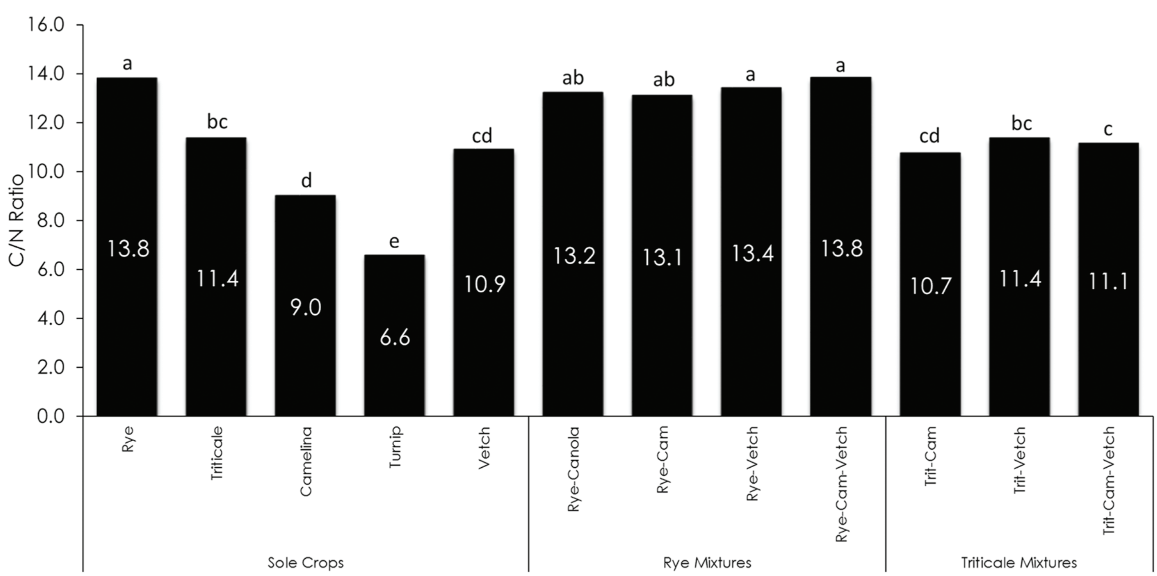

Fig. 4. Spring cover crop aboveground biomass C/N ratio at five sites at cover crop termination; late April–early May of 2014 and 2015. Mean cover crop treatment C/N ratio presented in every bar. Means with different lower case letters above the bar are significantly different at $P \leq 0.05$ by the least square means test. Cover crop treatment significant at P value = <0.0001.

Spring Soil Nutrients

Cover crops did not influence soil extractable Mehlich-3 P and K concentrations from 0 to 30 cm at the time of cover crop termination and had similar P and K concentrations to the no cover crop control (results not presented). Mean (min.–max.) soil P and K concentration was 18 (15.4–21.9) and 147 (140–151) mg kg^{-1}, respectively. However, cover crops differed in their effect on soil nitrate concentration (Fig. 5). Rye, rye mixtures, triticale–camelina, and triticale–camelina–vetch cover crops produced greater biomass than the other cover crop treatments and consequently, soil at 0 to 30 cm had significantly lower soil nitrate concentrations than soil in the no cover crop control (Fig. 5). Conversely, soil nitrate concentrations where cover crops produced limited or no spring growth did not have significantly different soil nitrate concentrations from the control (Fig. 5). At the time of cover crop termination increased cover crop biomass was negatively correlated with soil nitrate concentration in this study (results not presented). In another study conducted in Iowa, Pantoja et al. (2015) documented similar results, finding that a winter rye cover crop decreased soil nitrate levels at the time of spring cover crop termination.

Weed Community

Weed density and weed community associated with cover crops before cover crop termination was similar among cover crop entries and the control (results not presented). Mean (min.–max.) weed density taken at the time of cover crop termination was 59.6 (35–85) weeds m^{-2}. Weed community at the time of cover crop termination across all site-years contained 42.4% shepherd's purse [*Capsella bursa-pastoris* (L.) Medik], 31.0% clover (*Trifolium* spp.), 7.9% neckweed (*Veronica peregrina* L.), 6.7% field pennycress (*Thlaspi arvense* L.), 2.7% West Indian black nightshade (*Solanum ptycanthum* Dunal), and 9.3% composed of 12 other species.

Weed density and weed community associated with corn was taken approximately 22 d after corn planting and results were similar among cover crop entries and the control (results not presented). Mean (min.–max.) weed density associated with corn was 90.0 (68–133) weeds m^{-2}. Weed community associated with corn was 83.6% tall waterhemp [*Amaranthus tuberculatus* (Moq.) Sauer], 5.0% shepherd's purse [*Capsella bursa-pastoris* (L.) Medik], 2.3% velvetleaf (*Abutilon theophrasti* Medik), and 9.1% composed of 24 other species.

Weed suppression by cover crops is often determined by the quantity of cover crop biomass produced (Teasdale, 1996; Finney et al., 2016; Smith et al., 2015), which is highly dependent on the accumulation of heat units. Few heat units were accumulated between soybean harvest in the fall and corn planting in the subsequent spring, resulting in limited biomass accumulation of cover crops. Finney et al. (2016) reported that cover crop biomass production which exceeded 4625 ± 509 kg ha^{-1} was the plateau at which nearly 100% weed suppression occurred. The cover crops included in our study achieved far less biomass production than the Finney et al. (2016) study, which is a probable explanation for why cover crops had limited influence on weed density or weed community. Smith et al. (2015) documented that different functional or family classifications of cover crops did not serve as directional filters, increasing or decreasing certain weed species, and that cover crop mixtures did not provide better weed suppression than cover crop monocultures. We had hoped to test our cover crops in a similar fashion as the Smith et al. (2015) study, but the cover crops in our study did not significantly influence weed community.

Cover crops have a great deal of variation in their influence on weed suppression (Teasdale, 1996; Blanco-Canqui et al., 2015). Brassicaceae cover crops have been reported to suppress weed emergence in greenhouse settings due to the production of toxic glucosinolate breakdown products, (Haramoto and Gallandt, 2004) but these breakdown products show little evidence for being effective in the field (Haramoto and Gallandt, 2005; Teasdale, 1996). Monoculture Brassicaceae cover crop biomass accumulation in the Haramoto and Gallandt (2005)

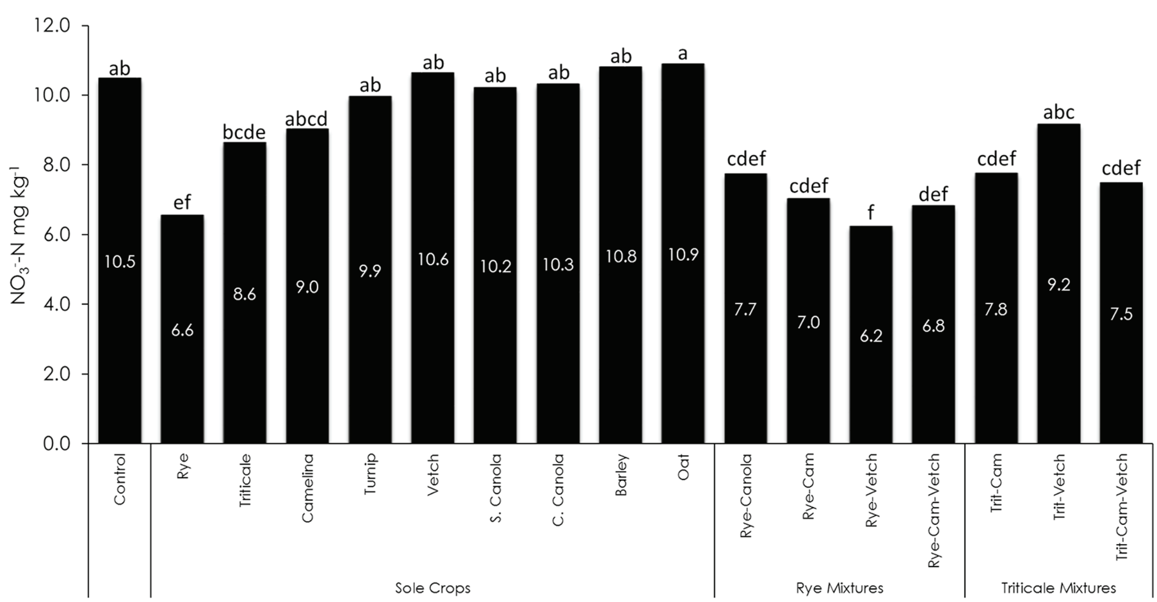

Fig. 5. Spring soil nitrate (NO_3^-) concentration (mg kg^{-1}) at 0 to 30 cm at five sites at cover crop termination; late April–early May of 2014 and 2015. Mean species NO_3^- concentration presented in every bar. Means with different lower case letters above the bar are significantly different at $P \leq 0.05$ by the least square means test. Cover crop treatment significant at P value = <0.0001.

study was 218 to 439 kg ha^{-1} which is similar to our study in which camelina monoculture accumulated 308 kg ha^{-1} of biomass. They reported that incorporation of Brassicaceae cover crops suppressed weed emergence at the same rate as non-Brassicaceae cover crops (Haramoto and Gallandt, 2005). Camelina monoculture and camelina mixtures included in our study did not suppress weed emergence (results not presented). Our results support the hypothesis that glucosinolate breakdown products do not suppress weeds in the field, at least for the amount of biomass and glucosinolates accumulated.

Corn Population

Cover crops did not influence corn population as measured in V2–V3 corn; mean (min.–max.) corn population was 75,334 (73,800–76,800) plants ha^{-1} (results not presented). Pantoja et al. (2015) documented a 5% reduction in corn population following a winter rye cover crop with similar biomass production as our study. Pantoja et al. (2015) reported that the corn population reduction may have been due to incomplete rye residue removal from the corn row and early season insect feeding on corn plants. These problems did not occur in our study. Mean days between cover crop termination and corn planting was 7.3 d for Pantoja et al. (2015) and 4.4 d for our study. These intervals are very close so it is unlikely they influenced corn stand density. Many climatic factors including soil moisture, soil temperature, and growing degree days contribute to early season corn development so it is difficult to determine exactly why these two studies report different results for the influence of cover crops on corn stand density.

Volumetric Soil Water Content

Cover crops did not influence soil VWC at 0- to 7.6-cm depth at corn planting, 0- to 7.6-cm depth at V6, 0- to 20-cm depth at V6, 0- to 7.6-cm depth at R1, or 0- to 20-cm depth at R1 stage corn (results not presented). Cover crops influenced VWC at 0- to 20-cm depth at corn planting (Fig. 6). Although VWC at 0- to 20-cm depth at corn planting did not differ between most cover crop entries (rye–vetch mixture was the only entry which was significantly different from the control), a generalization can be made that the cover crops with higher levels of spring biomass accumulation resulted in lower VWC in comparison to the other cover crops and the no-cover crop control (Fig. 6). Rye-associated cover crops and triticale mixtures generally had lower VWC than the control at 0- to 20-cm depth at corn planting (Fig. 6). Rye monoculture and rye mixes were similar for VWC (Fig. 6). Monoculture triticale had significantly greater VWC than triticale mixtures at 0- to 20-cm depth at corn planting (Fig. 6) and it is unclear why this occurred. Gesch and Johnson (2015) reported that camelina used less water than soybean in Minnesota. Nielsen et al. (2015) documented that cover crop monocultures and mixtures used similar amounts of soil water and were similar for water use efficiency (Nielsen et al., 2015). Daigh et al. (2014) documented that even during drought in 2012, rye cover crops either did not affect or increased soil VWC. It should be noted that although VWC was reduced at 0 to 20 cm at corn planting, is it unlikely corn was limited by water availability. All sites received average or above average spring precipitation. Differences in VWC between treatments could generally be described as wet vs. very wet soils at four out of five research sites at the time of corn planting.

Decreased VWC at 0- to 20-cm depth at corn planting following rye and rye mixtures could be beneficial for initial herbicide application and corn planting as Iowa field operations are often slowed by wet soils in early spring. Our study would suggest that precipitation events between corn planting and V6 stage corn erased cover crop effects on soil water reduction, resulting in similar VWC in all treatments at V6 and R1. Rainfall in Iowa typically is sufficient to replenish water, which is removed by cover crops. Semiarid regions face a greater risk of soil water depletion as high biomass production cover crops have been documented to reduce soil water and subsequent wheat (Unger and Vigil, 1998) and corn yields (Reese et al., 2014).

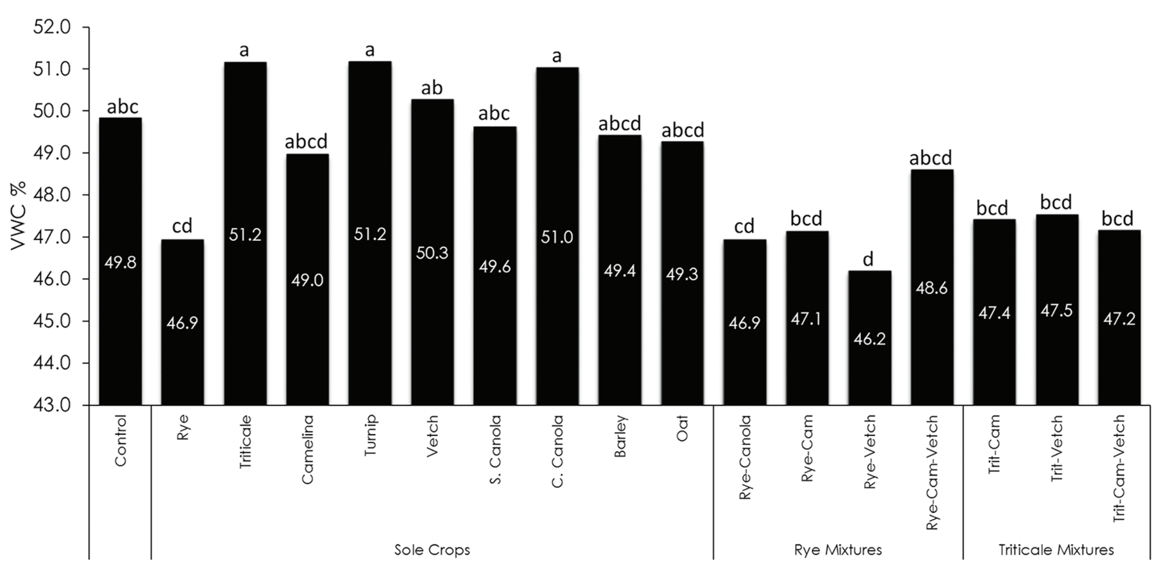

Fig. 6. Soil volumetric water content (VWC) at three sites at corn planting at 0- to 20-cm depth; late April–early May of 2014 and 2015. Soil VWC sampled with FieldScout TDR 300 Soil Moisture Meter (Spectrum Technologies, Inc., Aurora, IL). Mean species VWC presented in every bar. Means with different lower case letters above the bar are significantly different at $P \leq 0.05$ by the least square means test. Cover crop treatment significant at P value = 0.0378.

Corn Leaf Chlorophyll

Cover crops influenced corn leaf chlorophyll content at both V6 and R1 stage corn (Fig. 7). At V6, chlorophyll content for rye-associated cover crops was significantly lower than the no-cover crop control (Fig. 7a). Corn following the triticale–camelina–vetch mixture was the only other treatment which had significantly lower chlorophyll content than the control. SPAD chlorophyll readings indicate leaf greenness and N content (Costa et al., 2001) so it might be concluded that rye cover crops decreased corn N accumulation. This is reasonable to assume as rye-associated cover crops had the highest N accumulation and C/N ratios, leading to slower N release, and lowest soil nitrate concentrations in soil (Fig. 4 and 5). We observed that corn leaves were visibly less green in some plots which followed a rye cover crop. This would suggest that soil N, which was originally taken up by the rye, may not yet have been returned to the soil in an available form by stage V6. The N was probably retained in slowly decomposing rye residue on the soil surface, a phenomenon that has been observed in previous research (Quemada and Cabrera, 1995).

At R1 stage corn, corn leaf chlorophyll content was lower when following rye–canola, rye–camelina, rye–camelina–vetch, and triticale–camelina–vetch cover crops than corn that followed the no-cover crop control (Fig. 7b). Corn, which followed these four cover crops, also had lower corn leaf chlorophyll content than corn, which followed the no-cover crop control at V6. Lower chlorophyll content throughout the growing season in the aforementioned cover crops was probably a result of increased cover crop uptake of soil N, higher C/N ratios of cover crop residues, and a slow release of N from cover crop residues which limited corn N accumulation through R1 stage corn. These results indicate that reduced corn leaf N content may occur as a result of increased cover crop growth even when N application rates of 168 kg N ha^{-1} are exceeded. Alternately, rye may have had an allelopathic effect on corn due to benzoxazinones (Schulz et al., 2013).

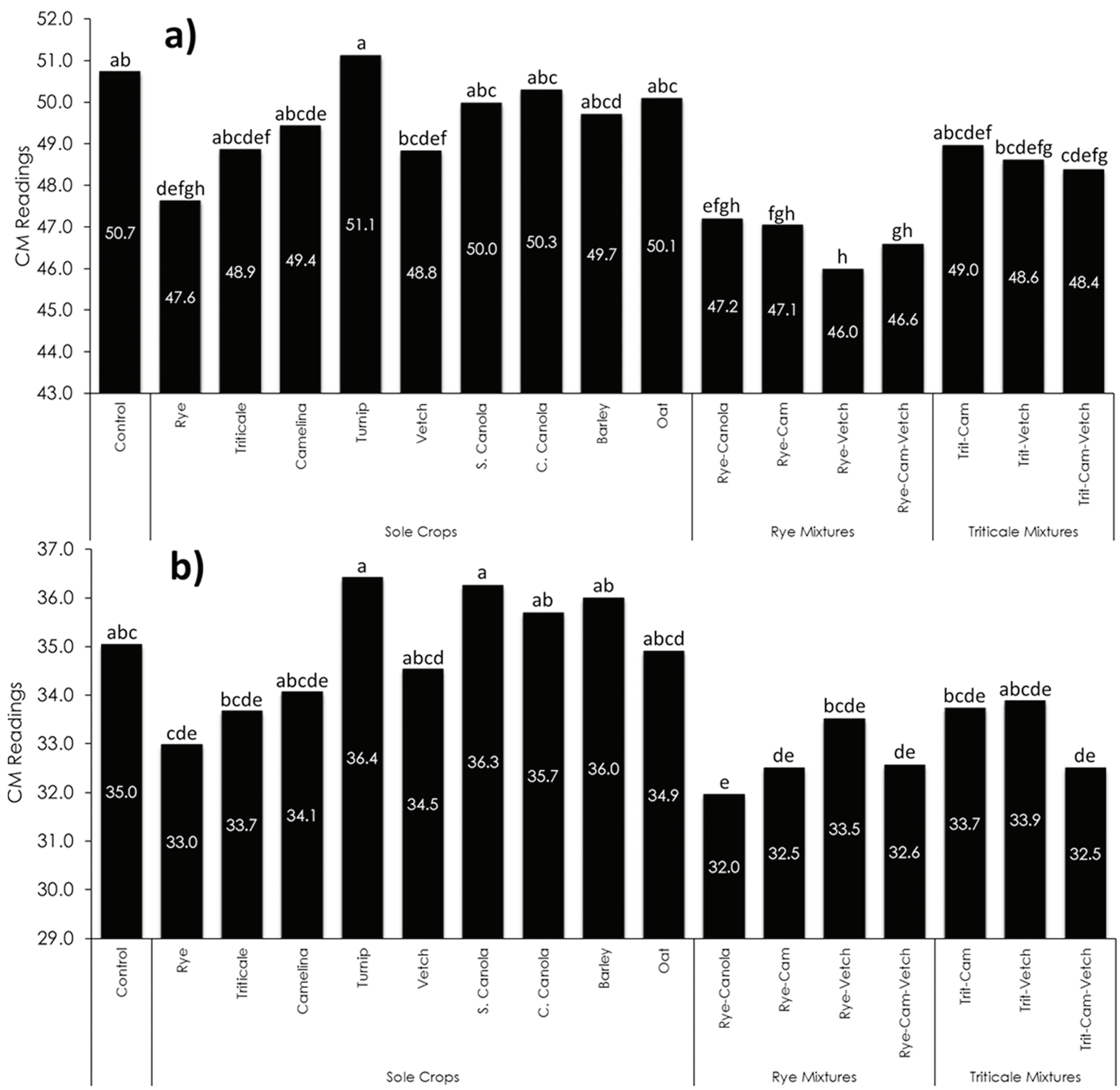

Fig. 7. Corn leaf chlorophyll content (CM Readings = chlorophyll meter readings) at (a) V6 and (b) R1 stage corn in 2014 and 2015. Corn leaf chlorophyll content measured with SPAD-502 chlorophyll meter (Konica Minolta, Inc., Osaka, Japan). Mean species CM reading presented in every bar. Means with different lower case letters above the bar are significantly different at $P \leq 0.05$ by the least square means test. Cover crop treatment significant at P value = (a) <0.0001 and (b) 0.0062.

One possible alternative explanation to the lower leaf greenness readings in this study would be to attribute the N deficiencies to corn root fungal disease damage, which may have occurred in corn which followed a rye cover crop (Bakker et al., 2016; Kaspar et al., 2015; Acharya et al., 2017). They determined that corn seedlings which followed a winter rye cover crop sometimes exhibited visible fungal disease symptoms on the primary and seminal roots. If corn root pathogens more readily infect seedling roots following a rye cover crop, they could potentially decrease the plants' N uptake capability regardless of the N fertilizer rate applied. In this study we did not investigate fungal disease symptoms on corn roots.

Corn Grain Yield

Cover crops did not influence corn grain yield; mean (min.–max.) corn grain yield was 14.2 (13.7–14.8) Mg ha^{-1} across all site years and treatments (results not presented. Additionally, although the differences were not significant the winter rye and rye–canola cover crop treatments had an average corn yield of 14.2 and 14.4 Mg ha^{-1}, respectively, compared with 14.0 Mg ha^{-1} for the no cover crop control. This is somewhat surprising as both V6 and R1 chlorophyll readings suggested that corn was consistently N limited following rye–canola, rye–camelina, rye–camelina–vetch, and triticale–camelina–vetch cover crops (Fig. 7). The R1 corn SPAD readings have been documented to be highly positively correlated with corn yield (Rorie et al., 2011). This lack of N limitation expressing itself in reduced corn yield may be due to late season cover crop decomposition and release of N, which was previously tied up in cover crop biomass. It is possible that cover crop decomposition between R1 and corn harvest released adequate corn available N to reduce the severity of original N limitation at V6 and R1 stage corn. However, alternate explanations are that the variability of the yield measurements was large enough that small differences in yield could not be detected or that factors other than N affected yield.

CONCLUSIONS

Cover crop biomass accumulation was limited in this study due to late planting dates, poor winter survival, a lack of thermal units, and a very short growing season. Winter rye was the most productive cover crop species included in this study. Rye accounted for more than 79% of the spring aboveground biomass accumulation in rye mixtures. Cover crop entries which included winter rye produced the most fall aboveground biomass, C, and N accumulation (other than barley); the most spring aboveground biomass, C, and N accumulation; had the highest C/N ratios; resulted in some of the lowest soil nitrate concentrations; generally produced the lowest SPAD corn leaf chlorophyll readings; and had no effect on corn yield.

Sitro canola, Claremore canola, barley, and oat are not good cover crop options when drilled in late fall following soybean harvest in Iowa. All four species produced limited fall biomass, winterkilled, and thus produced no spring growth. Turnip and vetch have very limited potential as late fall planted Iowa cover crop as these two species produced negligible amounts of fall biomass, suffered high rates of winterkill, and spring biomass accumulation was minimal. Triticale and camelina have limited potential as late fall planted Iowa cover crops. Triticale and camelina monoculture produced 50 and 41% as much spring aboveground biomass respectively as the rye-associated cover crops.

Cover crops did not influence soil temperature, soil P or K concentrations, weed density or weed community, or corn yield. Cover crops had a limited influence on volumetric soil water content at a depth of 0 to 20 cm, but only at the time of corn planting.

Cover crop mixtures did not produce results which were significantly different from the most productive cover crop monocultures. Two exceptions to this statement exist: triticale–camelina mixes had greater fall cover crop stand density than triticale or camelina monocultures, and triticale monoculture had higher soil VWC at corn planting at 0- to 20-cm depth than triticale mixtures. Cover crop mixtures were similar to the most productive cover crop monocultures for fall and spring biomass, N, and C accumulation, fall and spring C/N ratio of cover crop residues, soil N, P, and K concentrations, weed community and weed density, SPAD corn leaf chlorophyll readings, and corn yield. This study does not support the hypothesis that increased cover crop diversity will result in increased productivity, decreased weed density, and increased nutrient retention. Future cover crop research for Iowa and the upper Midwest should focus on selecting and testing cover crops which are very winter hardy. Research should include early seeding methods before harvest to increase fall cover crop growth which should increase the overwintering ability of the cover crops.

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