

Corn Nitrogen Management Following Daikon Radish and Forage Oat Cover Crops

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Cover crops (CC) preceding corn (*Zea mays* L.) may influence subsequent nitrogen (N) availability, but it is not clear whether N strategies require adjustment. Field studies conducted in 2015 to 2016 evaluated the effects of a daikon radish [*Raphanus sativus* (L.)], forage oat [*Avena sativa* (L.)], and no CC following winter wheat [*Triticum aestivum* (L.)] on soil chemical properties, corn growth, grain yield, and profitability. Nitrogen management strategies were equalized to 179 kg N ha⁻¹ and included pre-plant incorporated (PPI) N, poultry litter (PL) PPI (61 kg N ha⁻¹) plus sidedress (SD) N V11, starter N (45 kg N ha⁻¹) subsurface banded (5 cm below and 5 cm beside the seed, 5×5) followed by V4, V11, or V4 plus V11 SD, and a zero N control. Cover crops reduced autumn soil NO₃-N levels 78 to 84% relative to no CC but occasionally reduced N during critical corn uptake periods. Cover crops did not increase soil base cation availability to the ensuing corn crop. When 5×5 starter was followed by full SD at V11, CCs reduced yield 3.2 to 3.9% and profitability 11.8 to 13.2% compared with no CC indicating reduced efficacy and possibly greater 5×5 requirements to maintain yield potential until SD time. In the zero N control, CCs reduced grain yield 11.8 to 14.2% and increased yield response to N 63 to 79% suggesting reduced N availability. Radish and oat CCs provided a trap crop for autumn residual N, but N management strategies may need to account for reduced N availability.

Abbreviations: CC, cover crop; SVREC, Saginaw Valley Research and Extension Center; SCRF, South Campus Research Farm; 5×5, subsurface banded; N, nitrogen; NDVI, normalized difference vegetation index; SD, sidedress; PPI, pre-plant incorporated; PL, poultry litter; UAN, urea ammonium nitrate; CM, chlorophyll meter; rel, relative.

Degradation of Great Lakes water quality may require improvements to corn N management strategies including increasing nitrogen use efficiency (NUE) and reducing opportunities for N losses (Dove and Chapra, 2015; USEPA, 2016). Michigan, located within the Great Lakes Basin and Northern Corn Belt, is characterized by a temperate, humid growing season. Climate variability has recently resulted in a prolonged period of autumn soil temperatures remaining above 10 °C, which may extend organic matter mineralization and increase soil NO₃-N availability (Schwartz et al., 2006; USEPA, 2016; Schultze et al., 2016). Winter wheat sometimes precedes corn in crop rotations leaving approx. a 90-d fallow period with no crop N uptake (Vyn et al., 2000). Residual soil NO₃-N combined with residue mineralization and no plant cover can increase N loss potential (Weinert et al., 2002; Derby et al., 2009). Cover crops are sometimes utilized between growing seasons to assimilate available N (i.e., post-harvest autumn residual N, inorganic N from soil organic matter [SOM] mineralization), and ameliorate N losses in humid climates (Shipley et al., 1992; Macdonald et al., 2005; Tonitto et al., 2006; McSwiney et al., 2010). Cover crop biomass production and ensuing N assimilation may improve N cycling and NUE in corn, maintain and support grain yield, and improve profitability (Decker et al., 1994; McSwiney et al., 2010; O'Reilly et al., 2012). Corn yields following non-leguminous CCs may be affected by the rate of residue decay and resulting N availability (Dapaah and Vyn,

Core Ideas

- Daikon radish and forage oat cover crops following winter wheat sequestered residual autumn soil NO₃-N levels.
- Nitrogen availability to the ensuing corn crop may be reduced when preceded by radish or oat cover crops.
- When using radish or oat cover crops, increased 5×5 starter rates (> 45 kg N ha⁻¹) may be required if full SD is delayed until V11.
- Radish and oat cover crops preceding corn did not provide a subsequent N fertilizer replacement value but may still be effectively utilized as soil conservation tools.

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1998; Vyn et al., 2000; O'Reilly et al., 2012; Gieske et al., 2016a). Corn yield gains and profitability may depend on the synchrony of CC N availability and N fertilizer strategy.

Radish (*Raphanus sativus* L.) is an annual, nonleguminous *Brassicaceae* CC utilized to sequester nutrients including available soil $\text{NO}_3\text{-N}$ (Mutch and Thelen, 2003; Warncke et al., 2009). Radish is characterized as having a taproot that may reduce soil compaction, and increase nutrient levels in soil surface layers (Fageria et al., 2005; Wang et al., 2008; White and Weil, 2011). In addition, a radish cover crop may help suppress winter annual weeds, and winterkills at air temperatures below -4°C , eliminating the need for chemical termination (Williams and Weil, 2004; Clark, 2007; Lawley et al., 2011; Thomas et al., 2017). In the Northern Corn Belt, autumn radish biomass production (herbage and roots) ranged from 2.9 to 6.1 Mg ha^{-1} after two to three months of growth while soil inorganic N was reduced 24 to 42% compared with no CC (Hill et al., 2016). However, dry autumn soils can limit radish growth and reduce N uptake (Gieske et al., 2016b). Compared with no CC, corn grain yields following radish have been unaffected (Vyn et al., 2000; Gieske et al., 2016a, 2016b), reduced (Ruark et al., 2018), or increased (Dapaah and Vyn, 1998; Vyn et al., 1999; O'Reilly et al., 2012). Variable corn yield response may be due to differences in radish biomass, chemical composition, detrimental soil moisture use, or residue decomposition rates and subsequent impacts on N availability. Cover crop residue decomposition, N mineralization, and N immobilization are dependent on the carbon (C)/nitrogen ratio (C/N) and lignin concentration (Wagger et al., 1998; Jahanzad et al., 2016). The reduced C/N associated with radish (14 to 31:1) (Hill et al., 2016) relative to a grass (15 to 38:1) (e.g., oats [*Avena sativa* L.], triticale [*Triticosecale* spp.], or cereal rye [*Secale cereale* L.]) (Andraski and Bundy, 2005) help explain increased soil $\text{NO}_3\text{-N}$ concentrations (24–43%) observed following radish in Ontario, mid-May to mid-June (Vyn et al., 1999). However, when compared with no CC, radish may increase risk of N loss (i.e., leaching or denitrification) during winter freeze–thaw cycles (Dean and Weil, 2009; Thomas et al., 2017) and may not increase N availability to a subsequent corn crop (Vyn et al., 2000; Gieske et al., 2016a). Adjusting N fertilizer strategies may be needed to account for radish N assimilation and corn N uptake.

Oat is a non-leguminous CC used to sequester residual soil N and prevent wind and water erosion (Warncke et al., 2009). Oat is an annual CC that winterkills (Johnson et al., 1998; Snapp et al., 2005), but unlike radish oat has a dense, fibrous root system and may contain more lignin and cellulose thus affecting decomposition rates and N release compared with radish (Thorup-Kristensen, 2001; Jahanzad et al., 2016). Slower decay of cereal residues can affect the synchrony between N availability and corn uptake (Wagger, 1989). The C to N ratio of oat can exceed 30:1 immobilizing soil N and reducing corn uptake (Andraski and Bundy, 2005; Dean and Weil, 2009). Corn yields decreased or were unaffected following oat in non-irrigated conditions (Johnson et al., 1998; Vyn et al., 2000; O'Reilly et al., 2012). However, Andraski and Bundy (2005) suggested increased irrigated corn yield follow-

ing oat was due to rotation and not N contributions as evidenced by similar May soil $\text{NO}_3\text{-N}$ concentrations. Vyn et al. (2000) suggested oat reduced corn N availability as indicated by greater corn yield response to fertilizer N. Reduced corn yield following oat corresponded to reduced soil $\text{NO}_3\text{-N}$ concentrations at corn planting (36%) and at mid-June sidedress (20%) (Vyn et al., 2000). Cereal CCs also increased gaseous N_2O emissions 76% relative to no CC during the non-growing season and may also explain reduced N availability to the subsequent corn crop (Thomas et al., 2017).

Nitrogen placement and timing are important factors to consider when synchronizing corn N fertilizer application and availability (Rutan and Steinke, 2018). Pre-plant incorporated (PPI) N applications in the spring are considered a best management practice in conventional-till, poorly drained, medium- to fine-textured soils of the Northern Corn Belt, but single-pass N application systems made prior to or within one to three days after spring planting can sometimes reduce corn yield in fine-textured soils (Vetsch and Randall, 2004; Franzen, 2017). Multiple-pass N application systems can improve N recovery (Vetsch and Randall, 2004; Warncke et al., 2009) and may involve starter N (up to 67 kg N ha^{-1}) applied in a subsurface band 5 cm below and 5 cm laterally (5×5) relative to the seed furrow followed by sidedress (SD) N at V4 corn. Banding N below surface mulches may reduce N immobilization and increase grain yield (Mengel et al., 1982). In a cereal rye–hairy vetch (*Vicia villosa* Roth) mixture, subsurface banding N below the residue increased N uptake 72% relative to broadcast and incorporated N with the residue (Poffenbarger et al., 2015). Recent studies suggest maximum rates of corn N uptake occurred between V10 and V14 (Bender et al., 2013). Corn N uptake between V10 to V14 suggest delaying in-season N SD applications to improve synchrony between N availability and uptake while simultaneously reducing early-applied N losses (Binder et al., 2000; Scharf et al., 2002). Although V6 total corn N uptake approaches 15%, deficiencies at this time reduce corn yield potential and emphasize the importance for N management strategies to maintain yield potential until SD application (Binder et al., 2000; Bender et al., 2013). Variable CC decomposition rates may require adjusting N management to account for residue N mineralization or soil N immobilization. Radish and oat can serve as a trap crop by sequestering autumn soil N, but more evidence is needed to provide data on N availability to a subsequent corn crop and corn response to multiple N placement and timing combinations. The objective of this study was to i) quantify biomass and $\text{NO}_3\text{-N}$ uptake of actively growing radish and oat CCs, ii) evaluate impact of radish and oat CCs on soil P, K, Mg, Ca, and $\text{NO}_3\text{-N}$, and iii) evaluate N placement and timing strategies on corn growth, grain yield, and response to N following radish or oat.

MATERIALS AND METHODS

Site Characteristics and Cultural Practices

Field studies were conducted (2014–2016) in Lansing, MI on a Capac loam (fine-loamy, mixed, active, mesic Aquic Glossudalf). Soil samples (20-cm depth) were collected prior to August CC establishment, air-dried, and ground to pass through

a 2-mm sieve. Soil characteristics were 5.8 to 6.0 pH (1:1 soil/water) (Peters et al., 2015), 24 to 55 mg kg⁻¹ phosphorus (P) (Bray-P1) (Frank et al., 2015), 122 to 136 mg kg⁻¹ potassium (K) (ammonium acetate method [AAM]), 138 to 194 mg kg⁻¹ magnesium (Mg) (AAM), 985 to 1037 mg kg⁻¹ calcium (Ca) (AAM) (Warncke and Brown, 2015), and 24 to 34 g kg⁻¹ soil organic matter (loss-on-ignition) (Combs and Nathan, 2015). Fields were chisel plowed following wheat harvest and disk harrowed (10-cm depth) prior to seeding CCs. Calcitic lime was applied at 2.2 Mg ha⁻¹ prior to corn planting for a target pH of 6.5. Prior to corn planting fields received disk tillage (10-cm depth) followed by a one-pass disc cultivator (10-cm depth). Broadcast P and K fertilizer were applied PPI (10-cm depth) prior to planting as triple super phosphate (0–45–0 N-P-K) and muriate of potash (0–0–62) based on soil tests (Warncke et al., 2009). Weed control consisted of acetochlor [2-chloro-N-ethoxymethyl-N-(2-ethyl-6-methylphenyl) acetamide] and glyphosate [N-(phosphonomethyl) glycine] followed by a second application of glyphosate 17 to 24 d later. Environmental data were collected throughout the year using the Michigan Automated Weather Network (<http://www.agweather.geo.msu.edu/mawn/>, Michigan State University, East Lansing, MI; verified 11 Jul. 2018) from an on-site weather station.

Experimental Design and Treatment Application

Eighteen treatments were arranged in a split-plot, randomized complete block design with four replications. The main plot factor was CC while the subplot factor was N management. The CC treatments were ‘The Buster’ daikon radish, ‘Magnum’ spring forage oat (Weaver Seed of Oregon, Crabtree, OR), and no CC. Whole plots measured 27.4 m in length by 12.2 m wide. Radish was drill-planted at 11.2 kg ha⁻¹ and oat at 28.0 kg ha⁻¹ in the August prior to corn planting using a Gandy Orbit-Air Seeder coupled with John Deere double disk openers in 19-cm rows (Table S1). The no CC treatment received a single glyphosate application in autumn to remain free of vegetative ground cover. To ensure winterkill, CCs were terminated with glyphosate in November after 79 to 83 d of growth.

Subplots were N management and consisted of five corn N strategies and a zero-N control. Subplots measured 4.6 m wide by 12.2 m in length. Nitrogen strategies were urea–N PPI (46–0–0), dried poultry litter (4–3–2) PPI at 2.2 Mg ha⁻¹ plus V11 SD N (61 kg ha⁻¹ first year available N), and starter N applied 5 cm below and 5 cm beside the furrow (5×5) (45 kg N ha⁻¹ urea ammonium nitrate [UAN, 28–0–0]) followed by SD N at V4, V11, or split 50:50 at V4 and V11. The V4 application was UAN coulters injected 12 cm deep and 38 cm to one side of each row. The V11 SD was UAN–mixed with a urease inhibitor [N-(n-butyl) thiophosphoric triamide] (NBPT) (Koch Agronomic Services, LLC, Wichita, KS) to prevent N volatilization and banded 10 to 15 cm to the side of each row on the soil surface. Total N rates were equalized to the site-specific maximum return to nitrogen rate (179 kg N ha⁻¹) (Sawyer et al., 2006). Corn seeding and starter N application utilized a Monosem planter (Monosem

Inc., Kansas City, KS) equipped with Yetter floating planter-unit mounted row cleaners (Yetter Manufacturing, Colchester, IL) and liquid fertilizer applicators. Corn was seeded in 76-cm rows at 84,510 seeds ha⁻¹ using Dekalb DKC48–12 RIB (98 d relative maturity) (Monsanto Co., St. Louis, MO) (Table S1).

Data Collection and Statistical Analysis

Soil Chemical Properties

Soils were sampled for NO₃–N (cadmium reduction) (0–30 cm) (Huffman and Barbarick, 1981), and P, K, Mg, and Ca (0–20 cm) (previously described). Ten soil cores were collected from each whole plot replication in autumn simultaneous to CC biomass sampling and at corn planting (Table S1). After corn planting two (0–30 cm) soil samples were collected monthly (May through October) from subplots of the zero N control for NO₃–N analysis.

Cover Crop Measurements

Cover crop measurements included biomass production and total N tissue concentration (Table S1). Within each whole-plot replicate radish (shoots and roots) and oat (shoots only) CC samples were collected within five days of termination in autumn and again in mid-March (oats only) using three 0.25 m² quadrats. At sampling, radish roots were excavated and washed with water. Fresh weights of CC subsamples were recorded and tissues dried at 60 °C and ground using a 1-mm mesh screen. Nitrogen uptake was calculated as the product of N concentration and biomass (dry basis).

Corn Growth

Active canopy sensing was conducted to determine normalized difference vegetation index (NDVI) at V6 using a GreenSeeker Model 505 handheld red-band optical sensor (Trimble Agriculture Div., Westminster, CO) (Table S1). Corn plant height was measured at V6 as an average of 20 randomly selected plants plot⁻¹. Measurements were taken from the soil surface to the top of the newest fully developed leaf (height of leaf curve apex) with visible collar (V6) (Yin and McClure, 2013). Chlorophyll content was assessed at R1 to indicate ear-leaf N status using a Minolta SPAD 502 chlorophyll meter (SPAD) (Konica Minolta, Tokyo, Japan) (Scharf et al., 2006).

The center two rows of each plot were harvested with a research plot combine to determine grain yield, moisture, and test weight. Yield data were reported at 155 g kg⁻¹ moisture. Treatment profitability was calculated as net return = gross return from yield–input costs (Table S2). Grain prices and input costs were determined each year using spring N prices (USDA–AMS 2015, 2016), and autumn grain prices (USDA–NASS 2015, 2016).

Data were analyzed in SAS (9.4; SAS Institute, 2011) using the GLIMMIX procedure. Corn measurements assumed fixed effects of year, CC, and N management, and random effects of block and block × CC. Cover crop influence on soil inorganic N data were analyzed at the whole-plot level, assumed block as a random effect, and were compared within each sample time and not over time. Normality and homoscedasticity assumptions

were validated with the UNIVARIATE procedure and Levene's test, respectively, using residuals ($P \leq 0.05$). The LINES option was used to separate least square treatment means ($P \leq 0.10$) with interactions analyzed using the sliceby subroutine of the slice statement when ANOVA was significant ($P \leq 0.10$). Pearson's correlation coefficients were used to investigate linear relationships between monthly soil $\text{NO}_3\text{-N}$ data with grain yield ($P \leq 0.05$) using the CORR procedure.

RESULTS AND DISCUSSION

Weather

Following CC seeding, mean August through November 2014 air temperatures were below the 30-yr mean but above the 30-yr mean from September through November 2015 (Table 1).

Cover crops received 27 to 35 mm rainfall within one week of planting in both years followed by near to above normal rainfall in August and September. Following corn planting in May 2015, mean June through August air temperatures were 0.8 to 1.2°C below normal while September through October was 0.8 to 2.2°C above normal. Precipitation was 28, 116, and 46% above 30-yr means in May, June, and Aug. 2015, respectively, which may have increased N loss due to denitrification in saturated soils. Following corn planting in May 2016, mean monthly air temperatures were 0.1 to 1.6°C above normal May through September. In contrast with 2015, May and June 2016 precipitation was 39 and 80% below normal, respectively, and resulted in dry soil conditions followed by wetter July through September soils due to 15 to 94% above normal precipitation.

Cover Crop Effects on Soil P, K, Mg, and Ca Concentrations

When year was included in the model, no interaction with CC was observed for P ($P \geq 0.15$), K ($P \geq 0.87$), Mg ($P \geq 0.27$), or Ca ($P \geq 0.27$) in the autumn or spring. Data were combined across years for autumn and spring observations (data not presented). At autumn CC biomass harvest, soil test P, K, Mg, and Ca levels were 35 to 42, 106 to 120, 160 to 223, and 947 to 1093 mg kg^{-1} , respectively. Autumn soil test base cation levels were not affected by active CC growth ($P \geq 0.18$). At corn planting the following spring, soil test P, K, Mg, and Ca levels were 39 to 40, 128 to 141, 176 to 189, and 1078 to 1153 mg kg^{-1} , respectively. Similar to autumn observations, soil test base cations were unaffected by CC treatments at corn planting in May ($P \geq 0.28$). In a previous Michigan study on muck soils, radish increased April soil test P (Bray-P1) 15.4% as compared with no CC, but CC residues were incorporated at termination the previous autumn (Wang et al., 2008). In the current study, CCs had only been incorporated up to 15 d prior to May soil sampling. Other studies have observed no effect of radish on Bray-P1 or increased Mehlich 3P (0–2.5 cm depth) relative to no CC (White and Weil, 2011; Acuña and Villamil, 2014). Although CCs are perceived to transfer nutrients from deeper horizons up to the plow layer, current results did not support this concept for P, K, Ca, or Mg (Fageria et al., 2005).

Table 1. Monthly and 30-yr mean precipitation and temperature data for Lansing, MI, 2014 to 2016.

Month	Precipitation†				Air temperature‡			
	2014	2015	2016	30 yr	2014	2015	2016	30 yr
	mm				°C			
Apr.	–	23	75	73	–	8.2	7.5	8.7
May	–	109	52	85	–	16.3	14.8	14.7
June	–	192	18	89	–	19.2	20.3	20.0
July	–	62	96	83	–	20.9	23.0	22.1
Aug.	86	123	163	84	20.2	20.3	22.9	21.3
Sept.	85	95	106	92	15.4	19.1	17.4	16.9
Oct.	57	48	82	70	9.2	11.2	9.2	10.4
Nov.	37	31	49	71	0.8	6.9	4.7	4.6

† Precipitation and air temperature data were collected from Michigan Automated Weather Network (<http://www.agweather.geo.msu.edu/mawn/>) and determined as a mean of the average monthly high and low.

‡ 30-yr mean source for precipitation and air temperature: NOAA (<https://www.ncdc.noaa.gov/cdo-web/datatools/normals>; verified 17 Aug. 2017).

Autumn CC Biomass, N Uptake, and Residual Soil $\text{NO}_3\text{-N}$

Data were combined across years due to no interaction between CC and year for dry matter production, N uptake, and November soil $\text{NO}_3\text{-N}$ measurements ($P \leq 0.10$) (Table 2).

The CC growth period consisted of 74 to 81 d each year. Following autumn termination, mean radish dry matter production (i.e., above- and belowground biomass) was 68% greater than aboveground oat biomass resulting in 56% greater total N uptake. Radish achieved anthesis each year while oats did not, and may explain the greater radish biomass observed (O'Reilly et al., 2012). In contrast, both aboveground radish and oat biomass and N uptake did not differ in Indiana research (Vyn et al., 2000) suggesting that the growth of non-leguminous CCs was limited by low soil $\text{NO}_3\text{-N}$ (4.4 to 8.3 mg kg^{-1}) concentrations following wheat harvest.

In the current study, soil $\text{NO}_3\text{-N}$ concentrations at CC planting were 8.7 to 12.7 mg kg^{-1} , which support the greater radish and oat biomass production and N uptake values observed. At autumn termination, soil $\text{NO}_3\text{-N}$ concentrations (0–30 cm) averaged across CCs were reduced 78 to 84% relative to no CC. Despite reduced biomass and N uptake compared with radish, oat further reduced soil $\text{NO}_3\text{-N}$ levels 25% suggesting that a substantial amount of N remained in the oat roots which were not collected. Both CCs sequestered and reduced soil $\text{NO}_3\text{-N}$ compared with no CC which further suggests utility as a trap crop for residual autumn N and reduced post-harvest N losses (Vyn et al., 2000; Weinert et al., 2002; O'Reilly et al., 2012).

Spring CC Biomass, N Uptake, and Monthly Soil $\text{NO}_3\text{-N}$

Radish residues were visually decomposed prior to March biomass sampling, similar to other studies (Dean and Weil, 2009; Hill et al., 2016). A lack of spring radish residues indicated that decomposition was rapid in autumn and spring growing conditions and that the previously sequestered radish N may

Table 2. Autumn cover crop dry matter biomass production†, total N uptake, and soil residual NO₃-N concentrations, Lansing, MI, 2014 to 2015.

Cover crop	Dry matter Mg ha ⁻¹	Total N uptake‡ kg ha ⁻¹	soil NO ₃ -N mg kg ⁻¹
No CC¶	–	–	6.88 a§
Radish#	10.0 a††	189 a	1.50 b
Oats	5.9 b	121 b	1.13 c
CV (%)	34	37	98
Source of variation (<i>P</i> > <i>F</i>)			
Cover crop (C)	< .01	0.01	< .01
Year (Y)	0.01	0.01	0.56
C × Y	0.15	0.28	0.13

† Cover crop residues were sampled on 3 Nov 2014 and 30 Oct. 2015.

‡ Total N uptake relative to aboveground biomass only for oat cover crops.

§ Soil NO₃-N data transformed to meet normality assumption using root function. Untransformed means are presented. CV represents untransformed data.

¶ Radish biomass was collected above and belowground in contrast to oats which were aboveground only.

Cover crops consisted of daikon radish [*Raphanus sativus* (L.)] and forage oat (*Avena sativa* [L.]).

†† Means followed by same letter in a column are not significant different at *P* > 0.10.

have released N to the soil during decomposition, and was subject to denitrification, leaching, or volatilization N loss mechanisms during and after decomposition (Thomas et al., 2017). In contrast, approximately 50% of oat residue remained in March (2.9 Mg ha⁻¹, 21% CV) with 38% of the autumn total N uptake remaining immobilized in the biomass (45.9 kg N ha⁻¹, 18% CV). Data indicated that radish decomposition may have been too rapid to synchronize N availability with corn N uptake.

Soil NO₃-N was affected by CC in May, June, and September with the June sampling influenced by year (*P* = 0.04) and presented separately (Table 3). Soil NO₃-N levels were not increased by planting a CC suggesting that neither radish or oat provided additional N or any fertilizer N replacement value to the ensuing corn crop (Vyn et al., 2000; O'Reilly et al., 2012; Gieske et al., 2016a). The Northern Corn Belt soils of Michigan are unique in that agricultural soils may not often freeze during winter due to the proximity of this region to and between Lake Michigan, Lake Huron, and Lake Erie. Thomas et al. (2017) observed that CC decomposition during winter freeze-thaw cycles supplied labile C and N and stimulated N₂O emissions which suggests some immobilized CC N in the current study may not have been available to the ensuing corn crop. In June, radish and oat reduced soil NO₃-N 28–32% in wet soils (i.e., 2015) and 19% (oats only) in dry soils (i.e., 2016). June soil NO₃-N reductions from CCs suggest N immobilization and reduced soluble N availability both of which are primary objectives with autumn-planted CCs (Ketterings et al., 2015). Pearson correlations indicated that June was the only month soil NO₃-N was significantly correlated to grain yield (i.e., zero-N control) in both 2015 (*r* = 0.66; *P* = 0.04) and 2016 (*r* = 0.74; *P* = 0.04). Consistency of June correlations suggest that corn grain yield response to CCs was substantially affected by N availability (Vyn et al., 1999). Although rapid corn

Table 3. Effects of cover crop (CC) treatments not receiving N fertilizer on monthly† soil test nitrate (NO₃-N) (0–30 cm) concentrations, Lansing, MI, 2015 to 2016.

Cover crop	March	May	June	July	August‡	September
mg kg ⁻¹						
No CC	3.94 a§	6.56 ab	14.92 ¶	4.93 a	2.24 a	1.71 ab
Radish#	3.95 a	7.81 a	12.90	5.38 a	1.80 a	1.73 a
Oats	3.42 a	6.01 b	10.81	4.08 a	0.77 a	1.52 b
CV (%)	33	29	32	76	153	23
<i>P</i> > <i>F</i>						
Cover crop (C)	0.32	0.09	0.02	0.68	0.36	0.10
Year (Y)	< 0.01	< 0.01	< 0.01	< 0.01	0.01	0.04
C × Y	0.22	0.88	0.04	0.91	0.64	0.85
June C × Y interaction						
2015 2016						
No CC	19.37 a§	10.48 a				
Radish	13.97 b	11.84 a				
Oats	13.18 b	8.44 b				
CV (%)	26	21				
<i>P</i> > <i>F</i>	0.04	0.04				

† March samples were collected prior to corn plot establishment.

‡ August data were transformed using root functions. CV's represent untransformed data.

§ Means followed by same letter in a column are not significant different at *P* > 0.10.

¶ No means separation due to significant C × Y interaction. Data presented separately.

Cover crops consisted of daikon radish (*Raphanus sativus* [L.]) and forage oat (*Avena sativa* [L.]).

N uptake occurs between growth stage V10 through V14, reduced N availability at V6 may reduce yield potential (Binder et al., 2000; Bender et al., 2013). Reduced June soil NO₃-N levels in the current study from CCs suggested N availability was not synchronized with early (V4–6) corn growth N requirements.

Compared with radish, oat reduced soil NO₃-N levels 23, 29, and 12% in May, June (2016 only), and September, respectively, indicating less corn N availability. Previous studies suggested soil NO₃-N concentrations following oat were influenced by a slower rate of residue decomposition due to increased lignin concentrations and recalcitrant N in roots (Malpassi et al., 2000; Jahanzad et al., 2016). Data indicate radish and oat did not increase N availability to the ensuing corn crop. Similar findings in other studies have suggested no fertilizer N replacement value to the subsequent crop (O'Reilly et al., 2012; Ruark et al., 2018). However, results do suggest CCs remained effective as a trap crop for residual autumn N.

Normalized Difference Vegetation Index (NDVI)

Active canopy sensing at V6 indicated that year affected NDVI response to CC (*P* = 0.08) but not N management (*P* = 0.67), and results are presented by year for CC (Table 4).

Radish differentially affected corn V6 NDVI response each year (*P* = 0.01). In 2015 radish and oat increased NDVI 22 to 26%, relative to no CC while in 2016 oat increased NDVI 23 to 25% relative to radish and the no CC control. Plant heights at V7 were similar to V6 NDVI measurements across years in that radish and oat increased height 17 to 29% (*P* = 0.01) rela-

Table 4. Mean corn V6 normalized difference vegetation index (NDVI) measurements as affected by previous cover crop (CC), Lansing, MI, 2015 to 2016.

Cover crop	NDVI	
	2015	2016
No CC	0.355 b†	0.325 b
Radish‡	0.431 a	0.320 b
Oats	0.446 a	0.401 a
<i>P</i> > <i>F</i>	0.01	0.01

† Means within each column followed by same lowercase letter are not significantly different at *P* > 0.10.

‡ Cover crops consisted of daikon radish (*Raphanus sativus* [L.]) and forage oat (*Avena sativa* [L.])

tive to no CC in 2015 while oat increased height 17 to 22% (*P* = 0.01) in 2016 (data not shown). Increased corn growth with both CCs may have resulted from a rotational effect rather than N contributions (Andraski and Bundy, 2005). In the dry spring 2016, P deficiency was observed on V4 corn preceded by radish and the no CC but not in oats. Phosphorus availability and uptake requires soil moisture for diffusion and indicate oat residues may have increased soil moisture thus limiting P deficiencies. Previous Michigan studies observed increased soil volumetric water content (79%) at planting due to previous cereal rye residues (Hill et al., 2016). However, while soil moisture may have been a mechanism of the rotation effect it did not translate into a positive yield response.

Chlorophyll Content

A significant CC × N strategy interaction (*P* = 0.038) occurred for SPAD measurements (Table 5).

Year did not impact treatment response and data were combined across years. Within CCs, SPAD values were increased

Table 5. Interaction between cover crop (CC)† and corn N management (pre-plant incorporated (PPI) N, poultry litter (PL), or 5×5 starter N in combination with sidedress (SD) timings) on mean R1 chlorophyll meter measurements, Lansing, MI‡, 2015 to 2016.

N management	Cover crop			<i>P</i> > <i>F</i>
	No CC	Radish	Oats	
	SPAD index			
Zero N control	49.8 d\$A¶	48.0 bB	44.9 dC	< 0.01
PPI N	54.7 bcAB	56.1 aA	54.3 bB	0.07
PL# + V11 SD	54.5 cA	55.0 aA	52.6 cB	0.01
5×5 starter†† + V4 SD	56.1 aA	55.9 aA	55.5 aA	0.72
5×5 starter + V11 SD	55.8 abA	55.2 aAB	54.3 bB	0.09
5×5 starter + V4/V11 SD	56.3 aA	56.2 aA	55.2 abA	0.26
<i>P</i> > <i>F</i>	< 0.01	< 0.01	< 0.01	

† Cover crops consisted of daikon radish (*Raphanus sativus* [L.]) and forage oat (*Avena sativa* [L.]).

‡ Strategies requiring N fertilizer received total maximum return to N rate of 179 kg N ha⁻¹ in all years.

\$ Means within each column followed by same lowercase letters are not significantly different at *P* > 0.10.

¶ Means within each row followed by same uppercase letters are not significantly different at *P* > 0.10.

Poultry litter applied at 2.2 Mg ha⁻¹ PPI.

†† 5×5 starter was applied 5 cm beside and 5 cm below the corn seed furrow at planting (45 kg N ha⁻¹).

relative to the zero N control and indicated a response to N fertilizer. Within N management, radish and oat did not improve chlorophyll (i.e., SPAD) relative to no CC. The effect of CCs on R1 SPAD values were most pronounced within the zero N control where radish reduced SPAD values 3.6% from no CC while oats reduced values 6.5 and 9.8% from the radish and no CC treatments, respectively. Reduced SPAD values in the zero N control suggest both CCs reduced R1 chlorophyll indicating reduced N availability. Within strategies receiving N fertilizer, SPAD values were occasionally decreased by CC relative to no CC indicating N strategies may require adjustment to ensure N sufficiency. Relative to radish, oat reduced SPAD values 3.2% with urea PPI N possibly indicating reduced yield potential. When the 5×5 starter and V11 SD strategy was utilized, oat reduced SPAD values 2.7% relative to no CC indicating a reduced ability of 5×5 starter to supply sufficient N until V11 SD. When SD included a V4 timing, SPAD values were consistently > 55.0 across CC treatments, and suggested opportunities to improve N availability at R1 regardless of CC selection.

Corn Grain Yield Response and Profitability to CCs and N Strategies Grain Yield

A CC × N strategy interaction (*P* = 0.07) was observed. Treatment response was not affected by year thus data were combined across years (Table 6).

Within N management, corn yield was reduced 3 to 5% in the PPI N treatment following oat as compared with the radish or no

Table 6. Interaction between cover crop (CC)† and corn nitrogen (N) management (pre-plant incorporated (PPI) N, poultry litter (PL), or 5×5 starter N in combination with sidedress (SD) timings) on corn grain yield and response to N application, Lansing, MI‡, 2015 to 2016.

N management	Cover crop			<i>P</i> > <i>F</i>
	No CC	Radish	Oat	
	Mg ha ⁻¹			
Zero N control	12.7 b\$A¶	11.2 cB	10.9 cB	0.03
PPI N	15.3 aA	15.1 abA	14.6 bB	0.08
PL# + V11 SD	14.9 aA	15.5 aA	15.0 abA	0.28
5×5 starter†† + V4 SD	15.0 aA	15.1 abA	14.8 abA	0.77
5×5 starter + V11 SD	15.4 aA	14.8 bB	14.9 abB	0.06
5×5 starter + V4/V11 SD	15.1 aA	15.1 abA	15.2 aA	0.90
<i>P</i> > <i>F</i>	< .01	< .01	< .01	–
Response to N‡‡	2.4 B	3.9 A	4.3 A	0.03

† Cover crops consisted of daikon radish (*Raphanus sativus* [L.]) and forage oat (*Avena sativa* [L.]).

‡ Strategies requiring N fertilizer received total maximum return to N rate of 179 kg N ha⁻¹ in all years.

\$ Means within each column followed by same lowercase letters are not significantly different at *P* > 0.10.

¶ Means within each row followed by same uppercase letters are not significantly different at *P* > 0.10.

Poultry litter applied at 2.2 Mg ha⁻¹ PPI.

†† 5×5 starter was applied 5 cm beside and 5 cm below the corn seed furrow at planting (45 kg N ha⁻¹).

‡‡ Response to N determined as mean yield from plots receiving N fertility minus yield from zero N control plots within each respective CC.

CC treatments. Nitrogen applied PPI following oats may have been partially immobilized by decaying oat residue resulting in a yield reduction. When 45 kg N ha⁻¹ was applied at planting with full SD delayed until V11, radish and oat reduced yield 3 to 4% compared with the no CC control. However no differences between CCs were observed when V11 SD followed PL or when strategies included V4 SD indicating that CCs reduced effectiveness of the 5×5 placement to supply N until V11 SD time. Success of delayed SD N (i.e., V11) requires sufficient N supply to meet corn demands and maintain yield potential prior to SD timing (Binder et al., 2000). Corn preceded by radish and oat may require increased starter N rates (>45 kg N ha⁻¹) or slowly available N sources (e.g., PL) when using delayed N applications (i.e., V11). Following radish at the current 5×5 N rate, PL was more effective for increased yield when full SD was applied at V11 likely due to either the increased at-plant N rate or the slower availability of the PL N source (Rutan and Steinke, 2018). Following oats, split-applied N increased yield 4.1% relative to the PPI N strategy. Unlike radish, oat residue was still apparent at corn planting. Nitrogen applied PPI was in proximity with oat residue and may have been immobilized to a greater extent than radish, while V4 SD N was banded just below the residue. Nitrogen banded beneath residue may have helped reduce the amount of N immobilized in combination with N mineralization of residues to help synchronize N availability with corn uptake (Poffenbarger et al., 2015). Corn preceded by oat may require banded N applications to increase corn availability.

In the zero-N control, radish and oat reduced grain yield 12 and 14%, respectively, compared with no CC, which is similar to oat yield reductions observed by Vyn et al. (2000). Decomposing CC residues were likely not limiting soil moisture to affect grain yield, although data were collected (Teasdale and Mohler, 1993; Hill et al., 2016). Instead, total CC biomass production may have limited N availability during corn growth. In a study by Hill et al. (2016) decomposing rye CC residues reduced soil inorganic N while grain yield, related to CC biomass ($r = -0.24$; $P = 0.05$), was reduced when CC production was maximized. Similarly, Tollenaar et al. (1993) observed corn harvest dry matter accumulation was reduced when biomass from a preceding rye cover crop was greatest. Further research is needed to determine the effects of early autumn CC termination dates and biomass production in relation to cash crop yields the following year. When mean grain yield from plots without N applied was subtracted from those plots receiving N, radish and oat increased yield response to N fertilizer by 63 to 79% (Table 6). Reduced corn yields from either radish or oat without N fertilizer and increased yield response to applied N (mean yield of fertilized minus mean yield of unfertilized) suggest CCs resulted in an N drag and corn N availability was reduced after CC. Nitrogen management may require adjustment following daikon radish or forage oat. Regardless of CC no benefit was observed to SD delayed from V4 to V11, consistent with another Michigan study utilizing 5×5 placement (Rutan and Steinke, 2018). Splitting N applications with PL or 5×5 starter N that includes V4 SD may offer greater yield consistency regardless of CC selection. All strategies receiving N fertilizer were equally effective where no CC was planted.

Profitability

A CC × N strategy interaction ($P = 0.06$) occurred when total treatment costs were subtracted from treatment gross returns. Treatments were not affected by year and data were combined across years. Across years net return was more correlated with grain yield ($r = 0.85$; $P < 0.01$) than application costs ($r = -0.13$; $P = 0.11$) or total N costs ($r = 0.20$; $P = 0.01$).

Within N management, radish and oat did not increase short-term corn profitability compared with the no CC treatment (Table 7). Except for PL plus V11 SD in radish, net returns were reduced within N fertilizer strategies due to radish (\$129 to 214 ha⁻¹) and oat (\$163 to 275 ha⁻¹) relative to no CC. Additionally, within the PPI N strategy, oats reduced net return relative to radish by \$97 to 106 ha⁻¹.

Oat seed cost averaged \$40 ha⁻¹ more than radish and contributed to net return reductions, further emphasizing the importance of seed cost considerations when choosing a CC species. However, the urea PPI strategy was the least expensive N fertilizer strategy and often resulted in similar or increased profitability relative to other strategies regardless of CC. Growers preferring a single-pass system may find the PPI N strategy desirable. Profitability differences were most pronounced within the zero-N control where CC reduced profit \$347 to \$427 ha⁻¹. Although radish and oat were not able to improve, and in some instances reduced, profitability within specific N strategies, consistent use of CCs may have other ecosystem benefits not measured by profitability and may impact return on investment over an extended period of time (Blanco-Canqui et al., 2015). Within each CC treatment, the PL and V11 SD strategy resulted in the lowest net return due to increased costs associated with PL as this strategy cost 333 and 384% more per kg N than urea and 28% UAN-N sources, respectively. Profitability data suggest PL may

Table 7. Interaction between cover crop (CC)† and corn nitrogen (N) management (pre-plant incorporated (PPI) N, poultry litter (PL), or 5×5 starter N in combination with sidedress (SD) timings) on corn profitability, Lansing, MI‡, 2015 to 2016.

N management	Cover crop			P > F
	No CC	Radish	Oat	
	US\$ ha ⁻¹			
Zero N control	1690 bSA¶	1343 dB	1263 cB	<0.01
PPI N	1834 aA	1665 aB	1559 aC	<0.01
PL# + V11 SD	1555 cA	1489 cA	1392 bB	0.01
5×5 starter†† + V4 SD	1773 abA	1644 abB	1574 aB	<0.01
5×5 starter + V11 SD	1816 aA	1602 bB	1577 aB	<0.01
5×5 starter + V4/V11 SD	1756 bA	1613 abB	1586 aB	<0.01
P > F	<0.01	<0.01	<0.01	–

† Cover crops consisted of daikon radish (*Raphanus sativus* [L.]) and forage oat (*Avena sativa* [L.]).

‡ Strategies requiring N fertilizer received total maximum return to N rate of 179 kg N ha⁻¹ in all years.

§ Means within each column followed by same lowercase letters are not significantly different at $P > 0.10$.

¶ Means within each row followed by same uppercase letters are not significantly different at $P > 0.10$.

Poultry litter applied at 2.2 Mg ha⁻¹ PPI.

†† 5×5 starter was applied 5 cm beside and 5 cm below the corn seed furrow at planting (45 kg N ha⁻¹).

reduce profitability when adjusting N management to CC, but growers with access to less costly PL may increase potential profit.

CONCLUSIONS

Daikon radish and forage oat as a CC were effective at sequestering residual soil $\text{NO}_3\text{-N}$ following winter wheat. Despite N contained in CC biomass at termination, assimilated N may not be protected from loss or available to the ensuing crop. Data from the zero-N control indicated CCs reduced plant available N and subsequently corn yield leading to the observed increased response to applied N fertilizer. Cover crops did not increase soil $\text{NO}_3\text{-N}$ levels in the zero-N control and occasionally reduced June soil $\text{NO}_3\text{-N}$ levels. Correlations between corn yield of the zero-N control and June soil $\text{NO}_3\text{-N}$ levels suggested CC N reductions occurred during an important time in corn ontogeny when yield potential was being determined. To effectively utilize CCs for N management or N rate reductions, N sequestered during CC growth will need to be available for corn N uptake and not limited during early corn growth and yield determination (i.e., V6). Including multiple N rates to quantify N immobilization during corn growth or adjusting CC termination stage to control biomass production may enhance future studies. Despite few yield differences observed between N strategies within CC species, reduced soil N availability suggested that years with apparent N loss conditions may exacerbate soil $\text{NO}_3\text{-N}$ reductions where radish and oat were planted. Results further demonstrate that N strategies may have to account for N immobilization due to CC residue placement and decay. Increased rates of starter subsurface applied N ($> 45 \text{ kg N ha}^{-1}$) may be required if full SD is delayed until V11. To increase plant available N during the growing season, a slowly-decomposing CC or green manure (e.g., oat) may require multiple N applications including banded subsurface applied N to reduce soil N immobilization. Results of the current study suggest radish or oat in between a winter wheat–corn rotation were effective tools for sequestering autumn residual soil N but neither CC supplied additional N to the ensuing corn crop. Contrasting spring precipitation patterns warrant future studies to assess the impact of additional site years under variable growing conditions.

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SUPPLEMENTARY MATERIALS

Table S1. Dates of field operations and observations in 2014 to 2015 and 2015 to 2016, Lansing, MI. Table S2. Prices received (returns) and variable input costs (investments) utilized used for profitability analysis, 2015 – 2016.

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