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Does Cover Crop Radish Supply Nitrogen to Corn?

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ABSTRACT

Radish (*Raphanus sativus* L.) grown as a cover crop can accumulate a significant amount of N when planted by late summer. However, it remains unclear if the N in the radish biomass can supply N to a subsequent corn (*Zea mays* L.) crop. The objectives of this project were to: (i) measure radish growth and N uptake, (ii) determine the effect of radish growth on plant available N content in soil throughout the subsequent growing season, and (iii) determine the effects of radish on corn yields and response to N fertilizer. This study was conducted across nine site-years in northeastern and southern Wisconsin, with radish planted mid-August following winter wheat (*Triticum aestivum* L.) harvest. The experimental design was a randomized complete block, split plot design, with cover crop as the whole plot factor and N rate as the split plot factor. Radish N uptake was ranged from 19.7 to 202 kg ha^{-1} across all site-years. The effect of radish on in-season plant available N (PAN) content differed across growing seasons, with radish both increasing and decreasing PAN. The ANOVA and regression analysis showed mostly neutral effects of radish on corn yield, although corn yield increases and decreases following radish occurred. This research supports the use of radish as a trap crop for fall N, as environmentally meaningful yields of N were contained in plant biomass, but also demonstrates that radish has no N fertilizer replacement value to the subsequent crop.

Core Ideas

- Radish as a cover crop does not supply nitrogen to the subsequent corn crop.
- Radish can result in neutral, negative, and positive effects on corn yield.
- Radish can have substantial nitrogen uptake in the fall, but effects on spring soil nitrogen are variable.

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Cover crops provide multiple ecosystem benefits when used in agricultural fields through the reduction of erosion and compaction, general improvement of the soil physical condition and microbial community, and building of soil organic carbon (Blanco-Canqui et al., 2015). Radish in particular has been identified as a cover crop that can provide many of those benefits (e.g., Mutegi et al., 2013; Chen and Weil, 2010), although positive (Williams and Weil, 2004; Chen and Weil, 2011; O'Reilly et al., 2012; Dagel et al., 2014; Gieske et al., 2016), neutral (O'Reilly et al., 2012; Dagel et al., 2014; Acuña and Villamil, 2014; Li et al., 2015; Thilakarathna et al., 2015; Lacey and Armstrong, 2015; Hill et al., 2016; Gieske et al., 2016), and negative effects (Cicek et al., 2015) on subsequent crop yield have been reported. The potential yield benefit could come through changes to the physical structure of the soil. For example, Williams and Weil (2004) suggest that the root channels left behind by radish provided the subsequent soybean [*Glycine max* (L.) Merr.] crop roots with low resistance paths to water contained in the subsoil. Other research has shown that radish was deeper rooting compared to winter rye (>2.42 and 1.15 m, respectively), creating root channels deeper in the soil profile, indicating radish was more effective at capturing N from deep soil layers (Kristensen and Thorup-Kristensen, 2004).

Radish as a cover crop has shown clear benefits to water quality through reduction in fall soil nitrate. In the upper Midwest of the United States, N uptake by radish planted in mid-summer have reported N uptake ranges from 31 and 227 kg-N ha^{-1} (Lacey and Armstrong, 2015; Gieske et al., 2016), suggesting large amounts of N uptake can occur during optimal growing seasons. Reduction in fall soil inorganic N content compared to a no cover crop control has been reported widely throughout the literature (e.g., Vyn et al., 2000; Dean and Weil, 2009; O'Reilly et al., 2012; Cicek et al., 2015; Thilakarathna et al., 2015; Gieske et al., 2016; Hill et al., 2016). However, Li et al. (2015) reported no difference in fall soil nitrate content between radish and no cover crop and Thomsen and Hansen (2014) reported no reduction in nitrate leaching on a sandy soil with a radish cover crop.

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Abbreviations: AGB, aboveground biomass; BGB, belowground biomass; GDD, growing degree days; NR, no radish; PAN, plant available nitrogen; RAD, radish; RAD+67, radish plus 67 kg N ha^{-1}.

Another potential yield benefit of radish could come from N supplied from the decomposition of radish biomass. An N replacement credit appears possible for radish based on the amount of N in the whole plant biomass and a favorable C to N ratio for net mineralization. Unfortunately, while radish can reduce fall soil nitrate content, most studies report little effect on nitrate content in the subsequent growing season (pre-plant or in-season) (Vyn et al., 2000; O'Reilly et al., 2012; Li et al., 2015; Lacey and Armstrong, 2015; Cicek et al., 2015; Thilakarathna et al., 2015; Gieske et al., 2016; Hill et al., 2016). Radish has also been reported to have lower soil inorganic N content in the spring compared to no cover crop (Gieske et al., 2016; Cicek et al., 2015). In contrast, on soils in Maryland, Dean and Weil (2009) showed an increase in spring soil nitrate content on both a loamy sand and a silt loam following radish compared to the control. Hill et al. (2016) also found some in-season increases in soil nitrate with corn at V2 in two of three years at one location, and Vyn et al. (2000) found the same effect at sidedress timing at one location. So, it is clear that while not the norm, radish can release N during the subsequent growing season that it took up in the previous fall and this N may have value as a fertilizer replacement. However, differences in climate and soil type may influence the availability of the N released from decomposing radish biomass. Furthermore, most of the previous studies that concluded there was not an N credit of radish based this from discrete soil sampling. While this is a reasonable approach, evaluating crop yield response across a range of N rates provides greater insight into N availability in the presence of fertilizer N. Three previous studies have specifically evaluated a potential N credit for radish based on N response. Thilakarathna et al. (2015) showed no difference in corn grain yield or corn stover biomass following fall applications of manure between radish and no cover at N rates of 0 and 200 kg ha^{-1}, which suggests no difference in N response assuming a linear response. Averaged across three site-years (across two locations in Minnesota), Gieske et al. (2016) reported no difference in corn yield response to N between radish and no cover treatments. Fontes et al. (2017) reported a negative N fertilizer replacement value of radish when averaged across three site-years.

Radish can be grown easily following winter wheat or early harvested vegetable crops. In Wisconsin, wheat straw is often harvested for use in dairy production and thus little soil coverage exists after harvest or in low residue vegetable productions systems. Legumes have been well studied as a beneficial cover crop following or interseeded into winter wheat. Red clover (*Trifolium pretense* L.) as a cover crop has been shown to have a fertilizer replacement value up to 115 kg ha^{-1} of N (Stute and Posner, 1995) and multiple studies have shown corn grain yields to be greater following leguminous cover crops compared to no cover crops (Miguez and Bollero, 2005). Radish is of interest as a cover crop in this rotation as it will winterkill, in contrast to red clover which will need to be chemically or mechanically terminated. Radish can provide more N scavenging benefits, but more evidence is needed to suggest a consistent fertilizer N replacement value can be obtained.

Since cover crop N uptake and availability to subsequent crops can be affected by cover crop species, precipitation, temperature, length of growing season and soil fertility (Stute and Posner, 1993; Decker et al., 1994), it is crucial for research to be conducted on a regional basis to provide site-specific cover crop recommendations to growers. The objectives of this study were to (i) quantify the amount of N taken up by radish, (ii) determine the effect of radish on plant available N concentrations in soil, and (iii) determine the effect of radish on crop yield and response to N. This study specifically addresses these effects on soils in south central Wisconsin, representative of soils in the Midwestern corn belt and soils in eastern Wisconsin within the Lake Michigan watershed.

MATERIALS AND METHODS

Site Description and Experimental Design

The experiment was conducted at three locations in Wisconsin (Rock County, Sheboygan County, and Washington County) during three cover and corn crop growing seasons (which began in the summer with planting of the cover and ended following corn harvest; 2011 to 2012, 2012 to 2013, and 2013 to 2014), for a total of nine site-years. Specific treatments and tillage practices varied by site-year.

Rock County

The three fields at the Rock County Farm in Janesville, WI (42°43′37″ N, 89°1′26″ W) were located within 1 km of each other. Each field at the Rock County Farm had a long history of no-till, 5 yr or more, depending on the field. The crop rotation was soybean-winter wheat-corn, with the radish treatments planted following winter wheat harvest. The predominant soil series was Plano silt loam (fine-silty, mixed, superactive, mesic Typic Argiudolls). This soil is characterized as very deep, well-drained soil on 0 to 2% slopes. In the first 15 cm of the soil profile, the pH in water of the soil was 6.5, the organic matter content was 53 g kg^{-1} (by loss on ignition), and soil test P and K values (Bray 1) were 340 mg kg^{-1} and 460 mg kg^{-1}, respectively. No P or K fertilizer was applied. Treatments at this location were arranged in a randomized, complete block, split plot design with four replications. Each block contained three whole plot treatments: (i) no cover crop (NR), (ii) radish with no N added (RAD), and (iii) radish with 67 kg N ha^{-1} added at the time of radish planting (RAD+67). The whole plot dimensions were 3 m by 46 m. Each whole plot contained six subplots (3 m by 7.7 m), which were N rates of 0, 45, 90, 134, 179, and 224 kg ha^{-1}.

Sheboygan County

The three fields in Sheboygan County were located near Sheboygan Falls, WI (43°47¢57² N, 87°54¢55² W) within 1 km of each other. The crop rotation was soybean-winter wheat-corn, with the radish treatments planted following winter wheat harvest. The predominant soil series was Kewaunee silt loam (fine, mixed, active, mesic Typic Hapludalfs). This soil is characterized as very deep, well drained soil on 2 to 6% slopes. Across all sites and based on soil samples (0–15 cm) collected December 2014, soil pH ranged from 7.3 to 7.4, soil organic matter was 32 g kg^{-1} at all sites (loss on ignition), and soil test P and K values (Bray 1) ranged from 31 to 47 mg kg^{-1} and 156 to 193 mg kg^{-1}, respectively. No P or K was applied at these sites. Treatments were arranged in a randomized, complete block, split plot design with four replications. Each block contained two whole plot treatments: no cover crop (NR) and radish

(RAD). The whole plot dimensions were 9 m by 36 m in 2012 and 9 m by 48 m in 2013 and 2014. In 2012, each whole plot contained six subplots (4.5 × 12 m), which were N rates of 0, 112, 140, 168, 196, and 224 kg ha^{-1}. In 2013 and 2014, each whole plot contained eight subplots, which were N rates of 0, 34, 67, 101, 134, 168, 202, and 235 kg ha^{-1}. Whole plot treatments not receiving radish were chisel-plowed in the fall and field cultivated in the spring. The radish plots did not receive tillage between winter wheat harvest and corn harvest.

Washington County

The three fields in Washington County near West Bend, WI (43°21′18″ N, 88°16′24″ W) within 2 km of each other. The fields used in this experiment were under no-tillage management. The crop rotation was soybean-winter wheat-corn, with the radish treatments planted following winter wheat harvest. The predominant soil series was Hochheim loam (fine-loamy, mixed, active, mesic Typic Argiudolls). This soil is characterized as well drained soil on 12 to 20% slopes. Across all sites and based on soil samples (0–15 cm) collected December 2014, soil pH ranged from 6.8 to 7.2, soil organic matter ranged from 24 to 25 g kg^{-1} (via loss on ignition), and soil test P and K values (Bray 1) ranged from 26 to 37 mg kg^{-1} and 84 to 123 mg kg^{-1}, respectively. No P or K was applied. Treatments were arranged in a randomized, complete block, split plot design with four replications. Each block contained two whole plot treatments: no cover crop (NR) and radish (RAD). The whole plot dimensions were 9 m by 27 m. Each whole plot contained six subplots (4.5 m by 9 m), which were N rates of 0, 45, 90, 134, 179, and 224 kg ha^{-1}.

Cover Crop and Corn Management

Rock County

Radish (Tillage Radish, Cover Crop Solutions LLC) was planted on 15 Aug. 2011, 30 Aug. 2012, and 28 Aug. 2013 following the harvest of winter wheat using a no-till drill with 17.8 cm row spacing, with a seeding rate of 11 kg ha^{-1}. On the planting date, 67 kg N ha^{-1} as ammonium nitrate was broadcast surface applied to RAD+67. Volunteer winter wheat and summer annual weeds were controlled before planting with a broadcast application of glyphosate (210 g a.i. ha^{-1}). Four rows (76 cm spacing) of corn (O'Brien hybrid 1155) were planted per plot with a no-till planter at a seeding rate of 79,000 seeds ha^{-1} on 15 May 2012, 16 May 2013, and 30 May 2014. Fertilizer was surface applied at planting as ammonium nitrate hand applied in row in bands for the subplot N rates. Post emergence herbicides were applied as needed for weed control.

Sheboygan County

Radish (Tillage Radish, Cover Crop Solutions LLC) was planted on 15 Aug. 2011, 15 Aug. 2012, and 12 Aug. 2013, following the harvest of winter wheat using a no-till drill with 17.8 cm row spacing, with a seeding rate of 11 kg ha^{-1}. Before radish planting, 45 kg of urea (21 kg N ha^{-1}) was applied across the whole field, including all radish and no radish plots. Six rows (76 cm spacing) of corn were planted per plot with a no-till planter at a seeding rate of 79,000 seeds ha^{-1} on 20 May 2012, 12 June 2013, and 28 May 2014. Fertilizer was broadcast applied at planting as urea with a urease inhibitor (Agrotain, Koch Agronomic Services LLC, Wichita, KS). Post emergence herbicides were applied by the farmer as needed for weed control to terminate any winter wheat regrowth.

Washington County

Radish (Tillage Radish, Cover Crop Solutions LLC) was planted on 13 Aug. 2012, and 8 Aug. 2013, following the harvest of winter wheat using a no-till drill with 17.8 cm row spacing, with a seeding rate of 11 kg ha^{-1}. Before radish planting, 45 kg N ha^{-1} was applied to the whole field, including all no radish and radish plots. Six rows (76 cm spacing) of corn (Nu Tech 5N001, Great Lakes hybrid 4875) were planted per plot with a no-till planter at a seeding rate of 79,000 seeds ha^{-1} on 20 May 2013, and 24 May 2014. Starter fertilizer was applied each year with planting (22 kg ha^{-1} of N). Fertilizer was broadcast applied by hand one to 4 d after corn planting as urea with a urease inhibitor (Agrotain). Post emergence herbicides were applied by the farmer as needed for weed control to terminate any winter wheat regrowth.

SAMPLING AND ANALYSIS

All weather data (daily high and low temperatures and daily rainfall) were obtained from National Weather Service Reporting Stations and obtained through the Wisconsin State Climatology Office website (http://www.aos.wisc.edu/~sco/climhistory/acis_stn_meta_wi_ index.htm, Verified 19 Mar. 2018). Seasonal growing degree days (GDD) for each cover crop growing season was determined as the difference sum of daily maximum and minimum temperatures (with 30°C and 4.5°C thresholds, respectively) divided by two and subtracting the base temperature of 4.5°C. All reporting stations were within 13 km of field locations. Rainfall and GDD for each site-year are reported in Table 1.

Radish biomass was sampled in the fall when growth had been suppressed or stopped, but before winterkill conditions and from one 0.5 m^2 area per whole plot. The radish was frost-killed in the winter when air temperature dropped below −4°C for several nights in a row. Radish biomass was sampled as whole plants (stems, leaves, and roots) in 2011 and separated into aboveground biomass (AGB) (leaves and stems) and belowground biomass (BGB) (main tap root) in 2012 and 2013, although it should be noted that although the tap root often protruded above ground, we are considering the entire tap root belowground biomass. Roots were carefully dug out with a shovel with the goal of sampling as much of the thick portion of the tap root as possible; all identifiable root biomass was collected. All samples were dried in a forced air oven at 60°C; radish BGB was rinsed with water to remove soil prior to drying. Biomass samples were collected at Rock County on 1 Nov. 2011, 16 Nov. 2012, and 19 Nov. 2013; at Sheboygan County on 29 Nov. 2011, 16 Nov. 2012, and 15 Nov. 2013; and at Washington County on 28 Nov. 2011, 16 Nov. 2012, and 20 Nov.2013. Unfortunately, radish samples in 2011 from Sheboygan County and Washington County were disposed prior to analysis. There was regrowth of winter wheat at each site-year, but the growth was patchy and was not sampled; thus the no cover plots are not bare ground, but instead represent conditions that allowed regrowth of winter wheat before termination in the spring prior to corn planting. Radish biomass samples were ground and analyzed for total N and total carbon by dry combustion using a Flash EA 1112 CN Automatic Elemental Analyzer (Thermo Finnigan, Milan, Italy).

Table 1. Cover crop season growing degree days (GDD); rainfall; and radish biomass, N uptake and C to N ratio on a whole plant, aboveground biomass (AGB), and belowground biomass (BGB) basis. Statistical comparisons between treatments of radish (RAD) and radish with 67 kg ha^{-1} of N (RAD+67) were conducted on a site-year basis (Rock County only).

						Biomass		N uptake		C to N	
Year	Site	GDD†	Rainfall	Plant part	Treatment	Mean	SD‡	Mean	SD	Mean	SD
			mm			Mg ha^{-1}		kg ha^{-1}			
2011	Rock	884	182	Whole	RAD	6.02	1.77	202	56.8	11.5	3.52
				Whole	RAD+67	6.27	1.61	201	46.9	11.9	0.74
2012	Rock	622	181	AGB	RAD	0.91	0.27	25.1	7.52	13.8	0.42
					RAD+67	1.31	0.26	42.0	12.6	12.1	1.50
				BGB	RAD	0.81	0.49	18.4	11.2	17.6 a§	0.97
					RAD+67	1.28	0.21	36.6	9.28	13.9 b	1.75
				Whole	RAD	1.72 b	0.74	43.4 b	18.2	15.7 a	0.64
					RAD+67	2.60 a	0.44	78.6 a	21.5	13.0 b	1.58
	Sheboygan	797	221	AGB	RAD	3.22	0.37	77.5	13.9	14.0	2.13
				BGB		3.63	0.57	57.7	10.7	24.7	2.98
				Whole		6.90	0.50	135	15.6	19.3	6.21
	Washington	857	184	AGB	RAD	1.17	0.23	30.7	6.42	13.4	0.63
				BGB		1.49	0.13	23.1	1.56	25.1	1.16
				Whole		2.66	0.24	53.8	5.92	19.3	6.34
2013	Rock	737	183	AGB	RAD	0.27 b	0.11	13.1 b	2.94	9.03	1.15
					RAD+67	0.71 a	0.18	27.8 a	6.72	10.1	1.32
				BGB	RAD	0.20	0.02	6.28	0.94	11.7	0.84
					RAD+67	0.33	0.06	10.8	2.26	12.0	1.68
				Whole	RAD	0.47 b	0.07	19.7 b	3.81	10.1	1.36
					RAD+67	1.04 a	0.24	38.6 a	8.99	11.0	2.97
	Sheboygan	946	223	AGB	RAD	2.89	0.65	71.4	26.9	16.0	3.87
				BGB		2.55	0.36	51.2	19.7	21.5	5.22
				Whole		5.43	0.52	123	25.9	18.8	5.27
	Washington	869	262	AGB	RAD	3.29	0.59	80.8	21.5	14.7	1.65
				BGB		2.95	0.30	57.9	6.33	20.1	1.55
				Whole		6.24	0.47	139	19.3	17.4	3.18

† GDD, growing degree days.

‡ SD, standard deviation

§ Means followed by different letters are statistically different (a = 0.10).

Soil samples (2.2 cm in diameter) were collected at two depths (0–30 and 30–60 cm) at the same time as fall biomass collection and immediately prior to corn planting as a composite sample of five to eight cores per plot, collected across whole plot treatments. Additional soil samples (0–30 cm) were collected from within the zero-N subplot (composite of four cores per plot) three to five times during the corn growing season in five site-years. Soil sample collection locations were random, but was never sampled near (within 8 cm) or in a hole left by the decomposing radish. Fall and at corn planting soil samples (0–30 and 30–60 cm) were analyzed for nitrate N (NO_3–N) and all corn season soil samples (0–30 cm) were analyzed for both NO_3–N and ammonium N (NH_4–N) content by the University of Wisconsin-Madison Soil and Plant Analysis Laboratory following extraction with 2 mol L^{-1} KCl with colorimetric analysis using flow injection (Lachat Quikchem 8000; Lachat Instruments, Milwaukee, WI). The sum of NO_3–N and NH_4–N is considered plant available N (PAN). Corn grain was harvested by a two-row combine at Rock County (center two rows, 1.5 m by 6 m) on 3 Nov. 2012, 25 Oct. 2013, and 3 Nov. 2014; at Sheboygan County (center four rows, 3 m by 10.7 m) on 13 Nov. 2012, 11 Dec. 2013, and 2 Dec. 2014; and at Washington County (center four rows, 3 m by 10.7 m) on 13 Nov. 2012, 20 Nov. 2013, and 2 Dec. 2014. Corn yield was reported at 15.5% moisture.

Statistical Analysis

Analysis of variance was conducted to determine the effect of N application to radish (Rock County site only) on AGB, BGB, total plant biomass, total N content, and biomass C to N ratio, using Proc MIXED in SAS (SAS Institute Inc., Cary, NC) with block as a random effect, and analyzed separately for each site for each year. Analysis of variance was conducted to determine the effect of cover crop treatment and soil depth on soil NO_3–N content at fall and planting sampling times on a site-year basis, using Proc MIXED with block and block by cover crop treatment as random effects and using SLICE in the LSMEANS statement to determine if there was a significant effect of cover crop treatment at each depth. The effect of cover crop treatment across corn season sampling times (planting through harvest) on soil NO_3–N, NH_4–N, and PAN (0–30 cm depth) was analyzed using Proc MIXED with block and block by cover crop treatment as random effects and sampling time as a repeated measure. The SLICE statement was used following LSMEANS to determine if there was a significant effect of cover crop treatment within each sampling time. Analysis of variance was conducted to determine the effect of cover crop, N rate, and their interaction on corn grain yield using Proc MIXED with block and block by cover crop treatment as a random effect, and analyzed separately for each site-year. If a significant cover crop or cover crop by N

Table 2. Soil nitrate (NO_3–N) content at two depths at the time of radish biomass collection (fall sampling) and at time of corn planting in the following spring from different cover crop treatments (NR, no radish; RAD, radish; RAD+67, radish with 67 kg ha^{-1} of N) at three site locations.

			Soil NO_3–N			
			Fall sampling		At corn planting	
Year	Site	Treatment	0–30 cm	30–60 cm	0–30 cm	30–60 cm
			mg kg^{-1}			
2011/12	Rock	NR	4.73	2.98	17.2 b‡	5.46 c
		RAD	8.15	3.48	29.4 a	15.7 b
		RAD+67	6.23	2.46	38.1 a	21.2 a
	Sheboygan	NR	16.7 a	nc†	9.51	5.50 a
		RAD	3.75 b	nc	13.0	3.05 b
	Washington	NR	2.41 a	nc	21.2	6.85
		RAD	1.38 b	nc	22.8	7.17
2012/13	Rock	NR	1.50	0.89	2.03	1.45
		RAD	3.81	3.08	2.86	1.75
		RAD+67	1.86	1.78	4.08	2.74
	Sheboygan	NR	9.35 a	7.33 a	6.11 a	4.96 a
		RAD	1.63 b	0.91 b	4.41 b	1.14 b
	Washington	NR	11.7 a	5.52 a	nc	nc
		RAD	1.01 b	0.60 b	nc	nc
2013/14	Rock	NR	3.29	2.02	3.66	2.57
		RAD	2.27	1.49	3.83	2.44
		RAD+67	2.36	1.77	4.22	3.14
	Sheboygan	NR	8.75 a	5.73 a	3.39 a	3.53 a
		RAD	1.96 b	0.97 b	2.23 b	1.22 b
	Washington	NR	12.9 a	9.85 a	11.2 a	7.00 a
		RAD	1.58 b	1.06 b	4.71 b	3.27 b

† nc, not collected.

‡ Means (in columns, within site-years) followed by different letters were statistically different (a = 0.10).

rate interaction occurred, regression analysis was performed to characterize corn grain yield response to N. Four models were run separately for each treatment for each site-year: linear and quadratic models (Proc REG) and linear plateau and quadratic plateau models (Proc NLIN). The model with the lowest root mean square error was considered the best fit with two caveats: (i) for the quadratic plateau model to be considered, it must have a RMSE lower than quadratic by at least 1% (i.e., a greater than 1% relative difference), and (iii) for the quadratic model to be considered over a linear model, it must have a greater adjusted R^2 compared to the linear model by 0.01. The goal of having predetermined caveats are to report the simplest model possible. Across the nine instances where regression was conducted the quadratic plateau model did not converge in five cases, had a RMSE within 1% of the quadratic in three cases, and had a greater RMSE compared to linear plateau in one case. Thus, quadratic plateau curves were not considered. Across all analyses, significance was determined at the a = 0.10 significance level.

RESULTS AND DISCUSSION

Radish Biomass

Whole plant radish biomass ranged from 0.47 to 6.27 Mg ha^{-1} across site-years, with both the greatest and least growth occurring at Rock County. The radish AGB typically ranged between 44 and 53% of the total biomass, with one occurrence of 68%. Whole plant radish biomass had a weak, but positive relationship with GDD and rainfall (R^2 = 0.32 and 0.40, respectively) across all fertilized site-years, indicating that weather was not the major driver of radish growth. Radish whole plant biomass and radish N uptake was not significantly different between the N treatments at Rock County in 2011 (Table 1). However, in 2012 and 2013, both whole plant biomass and N uptake was greater in RAD+67. This effect was also seen in AGB in 2013, but not in 2012 and never detected with BGB.

The lack of significant differences in biomass and N uptake between radish cover crop treatments at Rock County in 2011 indicated that in ideal growing conditions extra N may not be necessary for good establishment and radish growth. However, in both 2012 and 2013, the growing conditions were less than ideal, having the lowest GDD and rainfall among all site-years (Table 1). In both 2012 and 2013, the whole plant RAD+67 treatment did have significantly more biomass and N uptake than the whole plant RAD treatment, suggesting that extra N may be beneficial for establishment and growth in dry, stressed environmental conditions. In addition, the AGB part of the RAD+67 treatment had a significantly higher biomass and N uptake than the ABG part of the RAD treatment (Table 1), which may have indicated that the extra N affects plant growth aboveground more than belowground. Thorup-Kristensen (1993) found that N uptake by cover crops increased with increasing amounts of soil mineral N which supports N uptake results from 2012 and 2013. In multiple studies, the N uptake of radish was found to be significantly larger than other cover crops and contain up to 119 kg N ha^{-1} (Dean and Weil, 2009), 158 kg N ha^{-1} (Kristensen and Thorup-Kristensen, 2004), and 240 kg N ha^{-1} (O'Reilly et al., 2012). Nitrogen yield in radish biomass at Rock County in 2011 appeared to be near the high end reported in the literature.

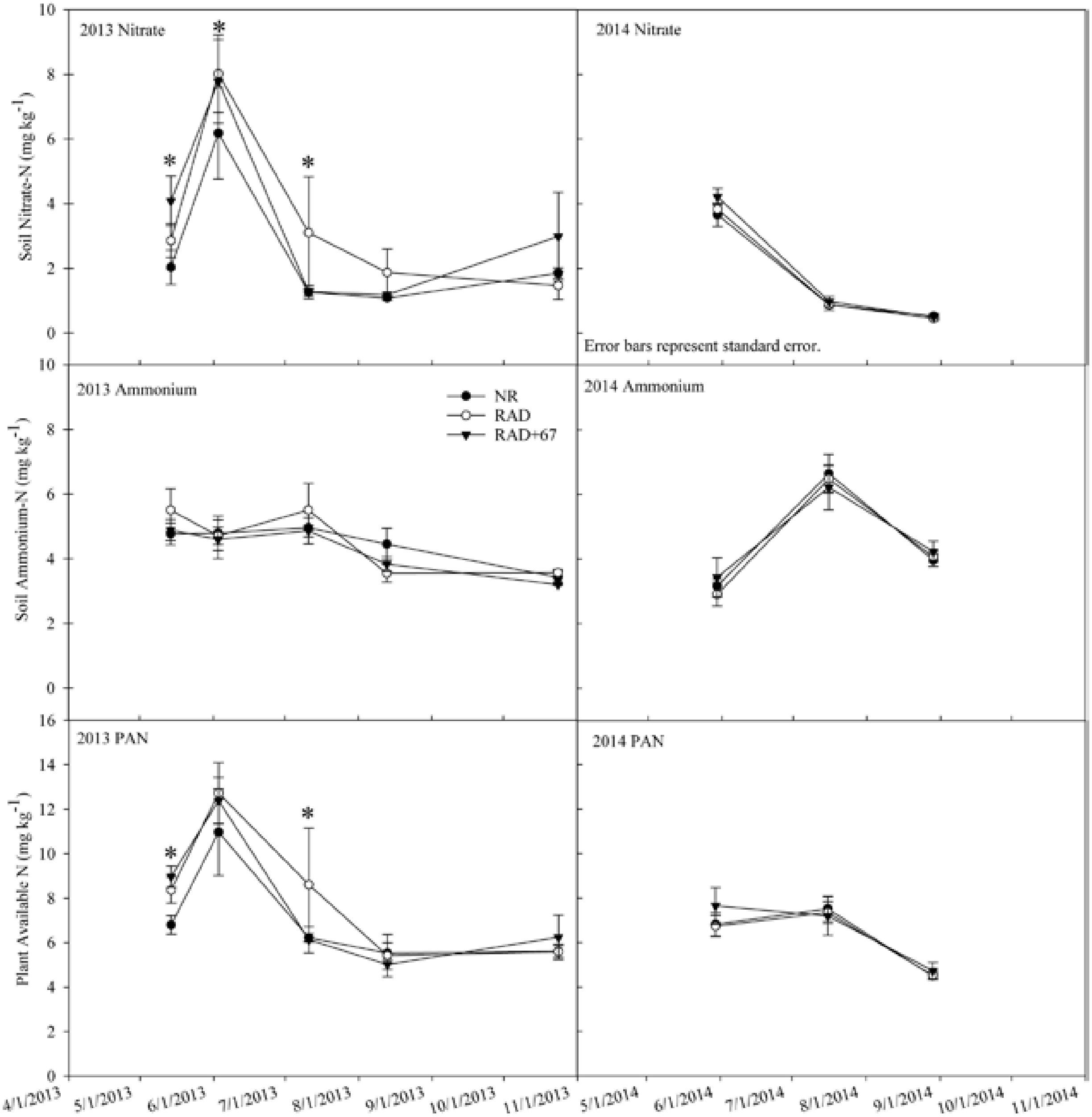

Fig. 1. Soil nitrate and ammonium content (0–30 cm) at Rock County in plots or subplots not receiving N fertilizer (the first two sampling times in 2013 and the first sampling time in 2014 were sampled across whole plots; all remaining were sampled in subplots at the 0 kg ha^{-1} N rate). Asterisks (*) indicate significant differences among treatments (NR, no radish; RAD, radish; RAD+67, radish with 67 kg ha^{-1} of N).

Across all site-years, the C to N ratio of radish whole plant biomass ranged from 10.1 to 19.3, with AGB ranging from 9.02 to 16.0 and BGB ranging from 11.7 to 25.1 (2012 and 2013 only) (Table 1). A similar trend was summarized by Clark (2007), who reported a C to N ratio of 10 to 20 for AGB and 20 to 30 for BGB. At Rock County in 2012, the addition of N fertilizer resulted in lower C to N ratios of whole plant and BGB, but this was the only year where this effect was determined (Table 1). These C to N ratios would indicate that net mineralization rather than net immobilization would occur during radish decomposition.

Soil Nitrogen Content

At the end of the radish growing season, radish significantly reduced the nitrate content in 0 to 30 cm in six of nine site-years and in 30 to 60 cm in four of seven site-years (Table 2). These results coincide with the results of several other studies (Vyn et al., 2000; Kristensen and Thorup-Kristensen, 2004; Dean and Weil, 2009; O'Reilly et al., 2012) which showed that radish significantly reduced soil NO_3–N concentrations in the fall when compared to other cover crops or the no cover crop control. Interestingly, all of the significant differences occurred at Sheboygan and Washington Counties and never at Rock County, even though Rock County had treatments with and without application of N to radish. However, at the time of corn planting in 2012, radish increased soil nitrate content at both soil depths at Rock County (Table 2). In contrast, across the remaining site-years, soil nitrate content at corn planting with radish was reduced in three of eight site-years for 0 to 30 cm and four of eight site-years for 30 to 60 cm. This indicates that the N the radish had accumulated resulted in a drawdown of soil nitrate at the time of planting and thus decomposition of plant material had not yet released N back to the soil. However, we cannot rule out other possibilities such as quick

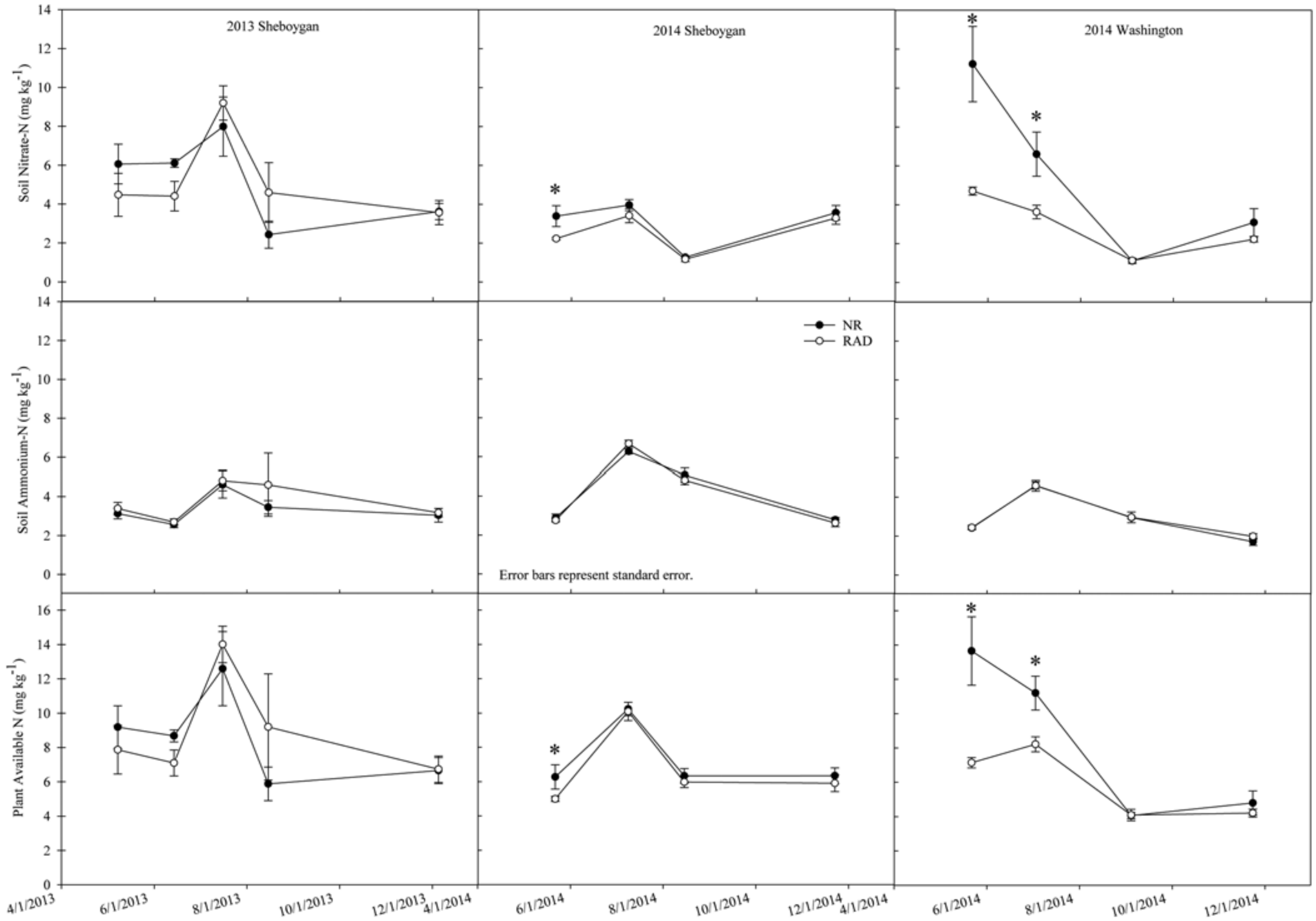

Fig. 2. Soil nitrate and ammonium content (0–30 cm) at Sheboygan County in 2013 and 2014 and Washington County in 2014 in plots or subplots not receiving N fertilizer (the first two sampling times in 2013 and the first sampling time in 2014 at both locations were sampled across whole plots; all remaining were sampled in subplots at the 0 kg ha^{-1} N rate). Asterisks (*) indicate significant differences among treatments (NR, no radish; RAD, radish).

decomposition leading to nitrate export out of the sampling area or that nitrate may be concentrated near the radish hole. The soil sampling was not conducted near or in the radish holes, so these results do not reflect N dynamics in that area of the soil.

When soil nitrate was analyzed across the Rock County growing season in 2013, the radish also increased soil nitrate content in May, June, and July sampling times (Fig. 1). No effect of ammonium was determined, but there were significant effects of radish on PAN at two of the first three sampling times. Radish had no effect on any PAN components at Rock County in 2014 (Fig. 1) or at Sheboygan County in 2013 (Fig. 2). In contrast, radish decreased nitrate and PAN content in 2014 at both Sheboygan County (first sampling only) and Washington County (first and second sampling) (Fig. 2).

Conflicting results in this study as to the radish's effect on PAN in the subsequent spring reflect the contrasting results in the literature, with there being more evidence that decomposing radish will not likely provide N to the subsequent crop. At Rock County in 2013, soil nitrate concentrations increased more in the radish treatments than in the NR treatment in May, June, and July most likely due to increasingly available decomposing radish material. This result was confirmed by Dean and Weil (2009) who found that N was released into the surface soil in the spring as radish decomposed, as well as O'Reilly et al. (2012) who detected higher plant available N following radish compared to no cover crop. The RAD+67 had higher soil NO_3–N concentrations than RAD at the second depth (30–60 cm) in spring of 2012 at Rock County even though the radish treatments took up the same amount of N in the previous fall (Table 2), indicating that N fertilizer applied at radish planting was not completely taken up. In 2013 at Rock County, the RAD treatment still had significantly larger vales than the NR treatment, indicating that the radish could be supplying N to the soil, but again, this only occurred in one of five site-years where in-season PAN was monitored. In contrast, at Washington County in 2014, radish treatments decreased both nitrate and PAN early in the season. This is of particular interest because the soils are similar in classification, both classified as a typic Argiudoll. Again, these results reflect plant available N dynamics in the bulk soil, and not what may be occurring in or very near the radish holes.

Subsequent Corn Crop Yields

There was no effect of cover crop or N rate on corn yield at Rock County in 2012 or 2014 (Table 3). The low seasonal rainfall in 2012 and the fact that corn smut (*Ustilago maydis* L.) was observed in the field in 2014 (likely causing low yields) may have caused the lack of significant N response. There was a significant effect of both cover crop and N rate on yield in 2013, but their interaction effect was not significant (Table 3). Averaged across all N rates, the RAD+67 treatment had a significantly greater

Table 3. Average corn yield and ANOVA results for 2012, 2013, and 2014 for cover crop treatments (NR, no radish; RAD, radish; RAD+67, radish with 67 kg ha^{-1} of N), N rate, and interaction effects for Rock County.

Effect	Treatment	Yield 2012	Yield 2013	Yield 2014
			Mg ha^{-1}	
Cover Crop	NR	9.65	10.1 ab†	6.83
	RAD	10.0	9.96 b	6.74
	RAD+67	10.1	10.8 a	6.52
N Rate (kg ha^{-1})	0	10.1	6.90 e	7.52
	45	10.4	8.45 d	6.47
	90	10.1	9.97 c	5.89
	134	9.95	11.3 bc	7.21
	179	9.74	12.3 ab	5.30
	224	9.15	12.9 a	7.81
Variation			P > F	
Cover Crop		0.441	0.047	0.904
N Rate		0.208	<0.001	0.107
Cover Crop × N Rate		0.163	0.445	0.418

† Means (in columns, within effects) followed by different letters were statistically different (a = 0.10)

yield than the RAD treatment, but not the NR treatment. Corn yield following RAD and RAD+67 had linear responses, with RAD+67 having a 1.2 Mg ha^{-1} yield advantage over RAD (Fig. 3), thus indicating that the addition of N at the time of radish planting resulted in a consistent yield increase regardless of N applied. The corn yield response to N following no cover crop in 2013 was quadratic with a peak yield of 12.4 Mg ha^{-1} at 200 kg ha^{-1} of N. It should be noted that the response was very flat around the vertex of the quadratic function (Fig. 3); predicted corn yields at 134 and 179 kg ha^{-1} of N were only 5.6 and 0.6% less than peak yield, respectively. Also at Rock County in 2013, corn following either radish treatment continued in increase in yield up to the highest N rate (224 kg ha^{-1}), in contrast to corn not following radish having little yield gain past 179 kg ha^{-1}. At the 224 kg ha^{-1} N rate the mean yields were 12.1, 12.8, and 13.7 Mg ha^{-1} for NR, RAD, and RAD+67, respectively. The result here implies similar corn yields can be achieved between NR and RAD+67 at 179 kg N ha^{-1}, but corn following radish achieved more yield but required more N (compared to the NR) for this to occur. This was also the growing season where radish appeared to increase PAN during the early growing season (Fig. 1), but this effect did not translate into a fertilizer N replacement value determined from the difference in optimum N rates among cover crop treatments.

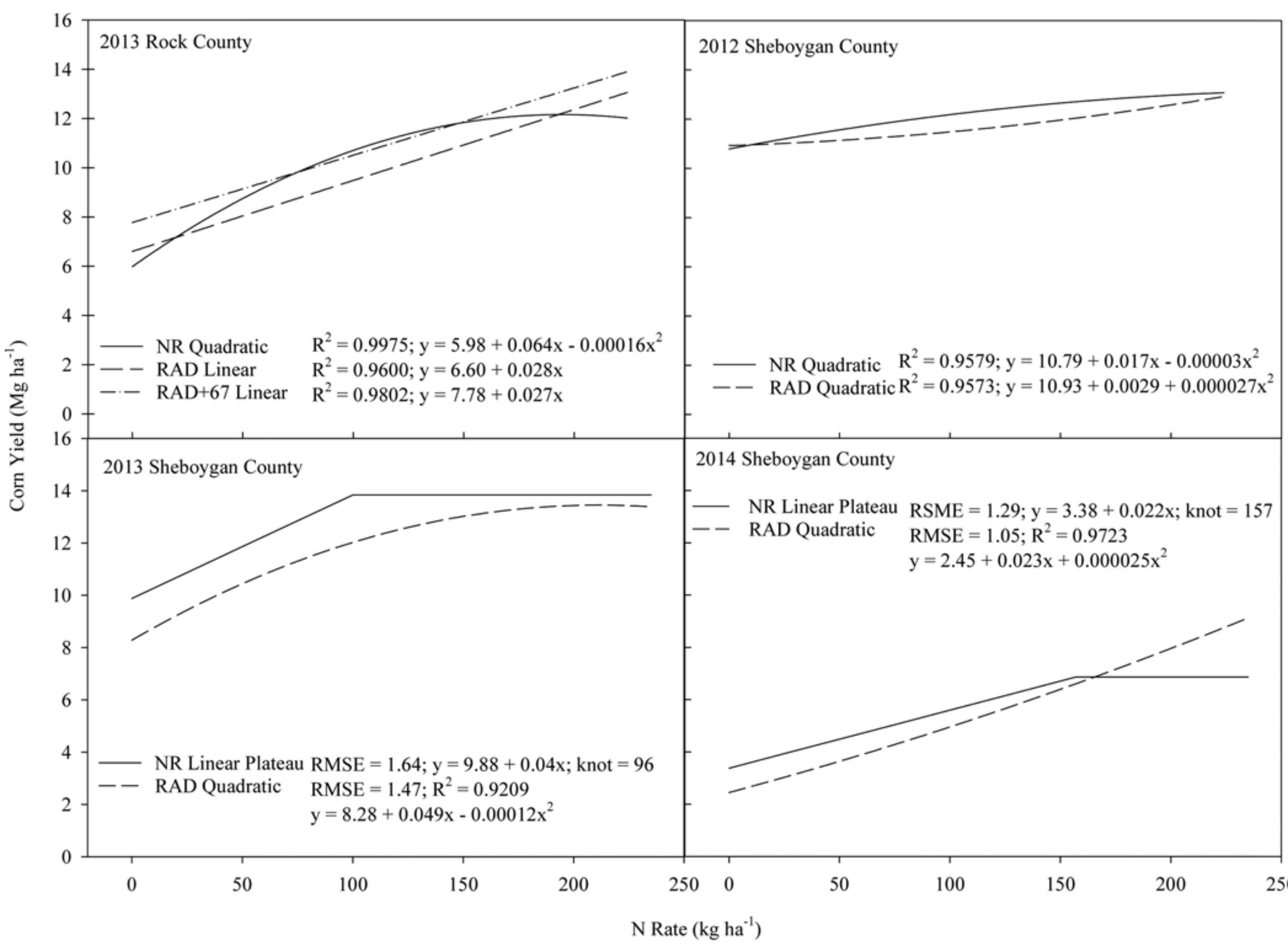

Fig. 3. Corn yield nitrogen response curves as linear, quadratic, or linear-plateau models for each cover crop treatment for Rock County in 2013 and Sheboygan County in 2012, 2013, and 2014 (NR, no radish; RAD, radish; RAD+67, radish with 67 kg ha^{-1} of N). The response curve represents the best fit across the model types based on RMSE and R^2 values.

Table 4. Average corn yield and ANOVA results for 2012, 2013, and 2014 for cover crop treatments (NR, no radish; RAD, radish), N rate, and interaction effects for Sheboygan County.

	2012		2013		2014	
Effect	Treatment	Yield	Treatment	Yield	Treatment	Yield
		Mg ha^{-1}		Mg ha^{-1}		Mg ha^{-1}
Cover Crop	NR	12.3 a†	NR	12.8 a	NR	5.61
	RAD	11.9 b	RAD	11.8 b	RAD	5.59
N Rate (kg ha^{-1})	0	10.9 c	0	9.05 b	0	3.10 d
	112	12.0 abc	34	10.2 b	34	3.43 d
	140	12.3 ab	67	12.5 a	67	4.23 cd
	168	11.8 bc	101	12.9 a	101	5.69 bc
	196	12.7 ab	134	13.4 a	134	6.10 b
	224	13.1 a	168	12.5 a	168	7.02 ab
			202	13.8 a	202	7.14 ab
			235	13.7 a	235	8.11 a
Variation				P > F		
Cover Crop		0.094		0.004		0.961
N Rate		0.001		<0.001		<0.001
Cover Crop × N Rate		0.786		0.464		0.021

† Means (in columns, within effects) followed by different letters were statistically different (a = 0.10).

Table 5. Average corn yield and ANOVA results for 2012, 2013, and 2014 for cover crop treatments (NR, no radish; RAD, radish), N rate, and interaction effects for Washington County.

	2012		2013		2014	
Effect	Treatment	Yield	Treatment	Yield	Treatment	Yield
		Mg ha^{-1}		Mg ha^{-1}		Mg ha^{-1}
Cover Crop	NR	6.67	NR	7.17	NR	10.9 a†
	RAD	6.50	RAD	7.05	RAD	10.2 b
N Rate (kg ha^{-1})	0	7.06	0	3.44 e	0	7.71 d
	112	6.53	45	5.23 d	45	9.06 c
	140	6.68	90	6.68 c	90	10.8 b
	168	6.45	134	8.12 b	134	11.6 ab
	196	6.52	179	9.51 a	179	11.8 a
	224	6.29	224	9.69 a	224	12.3 a
Variation				P > F		
Cover Crop		0.474		0.628		0.003
N Rate		0.550		<0.001		<0.001
Cover Crop × N Rate		0.141		0.348		<0.001

† Means (in columns, within effects) followed by different letters were statistically different (a = 0.10).

There was a significant effect of cover crop and N rate on corn yield at Sheboygan County in 2012 and 2013, but their interaction effect was not significant (Table 4). In both years, the NR treatment had a significantly greater yield than the RAD treatment when averaged across all N rates. In 2012, response curves were best fit with quadratic functions for both NR and RAD, with NR being concave and RAD being convex (Fig. 3). However, peak yields were similar for both NR and RAD and occurred at the highest N rates used. In 2013, the N response of NR was best fit with a linear plateau, plateauing with a yield of 13.7 Mg ha^{-1} at 96 kg ha^{-1} of N (the RMSE was 1.64 for the linear plateau and 1.95 for the quadratic); the response of RAD was best fit with a quadratic with a peak yield of 13.3 Mg ha^{-1} at 204 kg ha^{-1} of N. A linear-plateau will typically result in a lower optimum N rate compared to quadratic; however, the quadratic response of NR resulted in a lower optimum N rate as well (173 kg ha^{-1}). Soil nitrate at planting and in-season differed only slightly between RAD and NR; the differences in response curves in RAD and NR appear to have little to do with N availability, but reflect the inability of radish to function the same as a fall chisel plow on this soil (the NR plots were chisel plowed). In 2014 at Sheboygan County, both N rate and its interaction with cover crop had a significant effect on yield. The yield response to N for NR was a linear plateau which maximized yield (6.83 Mg ha^{-1}) at 157 kg ha^{-1} of N, while the yield response of RAD was quadratic and convex with a peak yield at the highest N rate used in the study (Fig. 3). This is a similar effect as in Rock County in 2013, where corn yields following RAD were only greater than NR when provided high rates of N. For comparison, yield at 235 kg ha^{-1} of N at Sheboygan 2014 was 6.67 Mg ha^{-1} for NR and 9.55 Mg ha^{-1} for RAD. It's possible that this effect is caused by something the radish is doing below ground to allow corn to achieve greater yields, but similar to the Rock County results in 2013, does not provide evidence the yield gain is caused by N supply from the radish. Regardless of year and response function used, there is no evidence that radish supplied N to the subsequent corn crop in Sheboygan County.

At Washington County in 2012, none of the effects on corn yield were significant and in 2013, only the N rate effect was significant (Table 5). In 2014, all of the effects were significant with the NR treatment having a significantly higher yield than the RAD treatment. Yields in 2014 at the zero-N rate were much greater for NR compared to RAD (3.68 Mg ha^{-1} greater), while yield differences at all other N rates were only different by 0.07 Mg ha^{-1}. Reanalysis with ANOVA after removal of the zero-N data resulted in no significant effect of cover crop or its interaction with N rate. Radish had much lower PAN at planting (Table 2) and in the early growing season in the early season in the zero-N plots (Fig. 2). Considering all site-year response data here, along with the no difference between radish and no radish reported by Gieske et al. (2016), all evidence points to there not being a fertilizer N replacement value of radish in the upper Midwest.

CONCLUSIONS

In Wisconsin, radish did not supply N to the subsequent corn crop. No nitrogen fertilizer replacement value of radish was determined through differences in N response curves, and only once did radish appear to increase PAN during the corn growing season. There were two instances of potentially positive effects from radish on corn yield, but additional N was required to achieve it, further negating any potential reduction in optimal N rate to a subsequent corn crop. In two of nine site-years, radish appeared to have a negative effect on yield, but only when radish was used with no-till and compared with no cover crop, chisel plowed treatments. In five of nine site-years, radish had no effect on corn yield. In a way, these results agree perfectly with the broader literature which has shown positive, neutral, and negative effects of radish as a cover crop on subsequent crop yields, as all of these responses occurred in this study. In our study, the cause of the variation in yield effects is not clear. This research supports the use of radish as a cover crop as a trap crop for fall N, as environmentally meaningful amounts of N were contained in plant biomass, but the ultimate fate of the N that is taken up remains unknown.

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