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ARTICLE

Rye cover crop improves vegetable crop nitrogen use efficiency and yield in a short season growing region[1]

Soudeh Farzadfar, J. Diane Knight, and Kate A. Congreves

Abstract: Cover crops have the potential to immobilize nitrogen (N) that would otherwise be lost before or after the main crop production, leading to improved N management. However, information on how cover crops influence N management in intensive vegetable cropping systems is scarce. This study aimed to determine how an overwintering rye cover crop impacts crop yield and N cycling, for three common prairie vegetable crops. From 2017 to 2019, a broccoli – sweet corn – root crop sequence was tested (in which all crops of rotation were present each year), with each crop type receiving five N fertilizer treatments, ranging from 0 to 300 kg $N{\cdot}ha^{-1}$. After harvest each year, sub-plots were established with vs. without a rye cover crop, and the effect on vegetable yield, soil inorganic N, and N use efficiency (NUE) was followed into the subsequent growing season. In most cases, the cover crop increased vegetable crop productivity and N content in the subsequent growing season. The cover crop also lowered soil inorganic N levels at vegetable planting but increased levels at harvest. Vegetable crop NUE indices were frequently improved with vs. without the cover crop. As for the N fertilizer response, increasing N fertilizer rate did not continually increase vegetable crop productivity and N content. Higher N fertilizer rates increased soil inorganic N levels at vegetable planting and harvest, and often lowered vegetable crop NUE indices. These results demonstrate the importance of adjusting soil N levels to better align with crop needs — and that including a rye cover crop in the vegetable rotation is one method of doing so.

Key words: broccoli, sweet corn, root crop, cover crop, nitrogen use efficiency.

Résumé : Une culture-abri pourrait immobiliser l'azote (N) susceptible d'être perdu avant ou après la culture principale, ce qui améliorerait la gestion de cet élément. Malheureusement, on sait peu de choses concernant l'influence d'une culture-abri sur la gestion du N dans les systèmes de maraîchage intensif. Les auteurs voulaient préciser comment une culture-abri hivernale de seigle agit sur le rendement de trois légumes couramment cultivés dans les Prairies et sur le cycle de l'azote. De 2017 à 2019, ils ont donc testé un assolement de brocoli, de maïs sucré et de culture-racine (les trois étant présentes chaque année), avec cinq applications d'engrais azoté allant de 0 à 300 kg de N par hectare pour chacune. Tous les ans, après la récolte, des sous-parcelles ont été ou pas ensemencées avec du seigle et on a mesuré les effets de cette culture-abri sur le rendement, la concentration de N inorganique dans le sol et l'efficacité de l'assimilation du N par le légume, la saison suivante. Dans la plupart des cas, le seigle accroît la productivité de la culture maraîchère et la concentration de N la saison qui suit. La culture-abri diminue aussi la concentration de N inorganique dans le sol aux semis, mais elle l'augmente à la récolte. L'efficacité de l'assimilation du N par la culture maraîchère est souvent plus importante avec la culture-abri que sans. Quant à la réaction à l'engrais azoté, augmenter la quantité d'engrais ne rehausse pas continuellement la productivité de la culture maraîchère ni la teneur en N. En augmentant le taux d'application de l'engrais N, on accroît la concentration de N inorganique dans le sol à la plantation et à la récolte, mais réduit souvent l'efficacité de l'assimilation de cet élément par la culture légumière. Ces résultats montrent qu'il est important d'ajuster la concentration de N dans le sol d'après les besoins de la culture et qu'inclure une culture-abri de seigle à l'assolement de cultures maraîchères est une façon d'y parvenir. [Traduit par la Rédaction]

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Mots-clés : brocoli, maïs sucré, culture-racine, culture-abri, efficacité de l'assimilation de l'azote.

Introduction

Nitrogen management is a persistent challenge for sustainable vegetable crop production because it is difficult to balance crop yields and N losses when crop N demand and input requirements are inherently high. More than half of the inorganic N fertilizer applied to vegetable crops is not taken up by the plant (Congreves and Van Eerd 2015; Wang et al. 2020), which presents a serious risk to ecological and human health via N losses to surrounding waterbodies and the atmosphere (Galloway et al. 2003; Erisman et al. 2011; Fowler et al. 2013). Adding to this concern, global vegetable production must continue to expand to provide sufficient nutrition to a growing population (Bahadur et al. 2018). In this regard, improving N use efficiency (NUE) without negatively impacting vegetable crop yields or quality would not only benefit the food industry by reducing the cost of N inputs and increasing individual farm profits, but it would also come with added environmental and marketing benefits such as reduced potential for N losses (Congreves and Van Eerd 2015; Jahanzad et al. 2017) and improved N footprints (Liang et al. 2019). Further, improving crop NUE may confer societal benefits through reduced greenhouse gas emissions thus mitigating climate change (Gabriel et al. 2016; Radicetti et al. 2016*a*).

The use of cover crops is an important strategy for soil fertility management in vegetable crop production (Congreves and Van Eerd 2015; Norris and Congreves 2018; Van Eerd 2018). Shoulder-season cover crops are grown during periods when the soil would otherwise be fallow, typically after the main crop is harvested in late summer/early fall and before planting of the next crop in early spring. They are not grown for commercial purposes but act as ground cover and green manure (Pantoja et al. 2015). Cover crops improve soil C storage (Campiglia et al. 2014), reduce N losses by retrieving NO_3^- from deep soil layers prior to leaching to groundwater (Korucu et al. 2018), and provide a valuable source of mineralizable N thereby reducing the reliance of subsequent crops on inorganic N fertilizer (Radicetti et al. 2016*a*, 2017). However, viability of cover crops to benefit the cropping system depends on numerous factors, including: growing season precipitation, temperature and length; method and timing of cover crop termination; cover crop species, C/N ratio and biochemical composition; soil inorganic N levels and moisture variability; and historical field management (Campiglia et al. 2014; Pantoja et al. 2015; Coombs et al. 2017; Cúpina et al. 2017; Radicetti et al. 2017; Van Eerd 2018). Grass cover crop species such as rye (*Secale cereale* L.) are efficient in capturing and using soil residual N (Shipley et al. 1992; Lacey and Armstrong 2015). Fall planted rye has greater residual fall N uptake compared with hairy vetch, crimson clover, and native weeds in cold northern climates due to rapid growth and N uptake throughout the fall (Shipley et al. 1992; Lacey and Armstrong 2015; Pantoja et al. 2015; Radicetti et al. 2016*a*). In addition, rye has quick establishment and cold tolerance (Feyereisen et al. 2006; Teasdale et al. 2008). As a cover crop, it is considered a soil builder due to its extensive roots and biomass potential; thus, is a good candidate for vegetable crop rotations. Rye cover crops have provided N credits of 17–55 kg N·ha^{-1} to subsequent crops, indicating the potential of this cover crop for decreasing the dependence on external N inputs and improving fertilizer NUE (Burket et al. 1997; Pantoja et al. 2015; Sievers and Cook 2018). However, there is no research in cold northern and semi-arid climates where access to nutritious vegetables is paramount.

Although it is commonly assumed that cover crops are not viable in short-season, semi-arid, and northern regions (Reese et al. 2014; Liebig et al. 2015), designing better N management practices for northern vegetable cropping systems can allow growers to exploit the beneficial effects of cover crops (Flood and Entz 2019; Liu et al. 2019). Canada is the sixth largest producer of fresh vegetables in the world (Statistics Canada 2019). In the cold semi-arid regions of Canada, vegetable production has expanded by 8% over the past 5 yr (Statistics Canada 2019). A cold tolerant and fast-growing rye cover crop could be suitable in a northern vegetable crop rotation, influencing N cycling and crop NUE. In north central USA, winter rye took up residual soil N after corn silage harvest, reducing soil N concentrations prior to planting a subsequent crop, and then releasing it back into the soil during growth of the succeeding cash crops (West et al. 2020). The release of N from cover crops is faster when cover crop residues are incorporated into the soil compared with when they are left on the soil surface (Drinkwater et al. 2000; Campiglia et al. 2014), which would be desirable in a northern cold climate with a relatively short growing season. Hence, we hypothesized that fall rye would increase soil N supply to subsequent vegetable yields in a northern vegetable crop rotation compared with the conventional practice (no cover crop), reducing the requirement for inorganic N fertilizer and improving crop NUE. Because N fertilizer rate is a critical aspect of crop NUE, this hypothesis should be considered under a range of N fertilizer rates. Therefore, the main objectives of our study were to: (*i*) determine the influence of shoulder-season cover cropping on vegetable crop NUE and productivity in a northern climate, (*ii*) determine the influence of N rate on crop productivity, soil N cycling and NUE, and (*iii*) evaluate the interaction of cover crops and N

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Table 1. Weather data from 2017 to 2019 and 30-yr mean in Saskatoon, SK.[a]

	Mean temperature (°C)				Total precipitation (mm)			
Month	2017	2018	2019	30-yr mean	2017	2018	2019	30-yr mean
January	—	−11.9	−13	−14.7	—	12	8.4	15.5
February	—	−15.9	−22	−12	—	2.9	14.2	9.3
March	—	−7.3	−4.5	−4.9	—	13.5	3.9	13.8
April	—	0.2	5.9	4.9	—	13.3	2.9	22.9
May	12.8	15.3	10.5	11.5	48.6	25	11.7	39.4
June	16.6	18.2	16.8	16.2	25.4	19.7	78	66.6
July	20.4	19.7	18.7	18.7	28.1	41.9	82.1	59
August	19.1	18.4	17	18	39.2	19.8	19.9	46.5
September	13.9	8.3	13.1	12.2	33.6	44.7	44.8	37
October	5.8	3.7	—	4.6	15	7.4	—	19.2
November	−8.5	−6.2	—	−5	13.6	12.9	—	13.4
December	−10.7	−8.7	—	−12.9	4.1	3.2	—	12.7

[a] Data obtained from the Climate Reference station located 1800 m from the experimental site.

fertilizer on crop productivity and NUE over a range of N fertilizer rates.

Materials and Methods

Experimental site, experimental design, and cultural practices

This research was performed at the Horticulture Field Research Station in Saskatoon, SK (52°8′N, 106°38′W; 515 m asl) on a Dark Brown Chernozem (Haplic Kastanozem) of the Sutherland clay association. The field trial was initiated in 2017 (Field A) and repeated on an adjacent field in 2018 (Field B). To characterize each field site, a composite soil sample (0–30 cm depth; made up of 7–9 individual cores) was collected using a Dutch auger (4-cm diameter) from across the entire plot area prior to establishing the trials. Field A and Field B, respectively, had a pH of 7.6 and 7.3, organic matter of 5.3% and 5.1%, cation exchange capacity of 29.2 and 31.6 m_{eq} 100 g^{-1}, Bray-P of 508 and 443 $mg \cdot kg^{-1}$, extractable K of 1253 and 1461 $mg \cdot kg^{-1}$, extractable S of 35 and 27 $mg \cdot kg^{-1}$, nitrate-N of 89 and 93 $kg \cdot ha^{-1}$, and ammonium-N of 17 and 15 kg $N \cdot ha^{-1}$. Field A in the previous year produced a mixture of bell pepper (*Capsicum annuum* L.), eggplant (*Solanum melongena* L.) and pumpkin (*Cucurbita pepo* L.) grown on plastic mulch, whereas Field B in the previous year produced romaine lettuce (*Lactuca sativa* L. var. *longifolia*), head lettuce (*Lactuca sativa* L. var. *capitata* 'Iceberg'), onion (*Allium cepa* L.), cabbage (*Brassica oleracea* L. var. *capitata*) and brussels sprouts (*Brassica oleracea* L. var. *gemmifera*). Both fields did not receive organic manure for at least 2 yr prior to our study. The temperature and precipitation conditions during the experimental period are shown in Table 1, relative to the 30-yr normal.

For the experiment, vegetables were produced according to a 3-yr annual sequence of broccoli (*Brassica oleracea* L. var. *italica*) – sweet corn (*Zea mays* var. *saccharata*) – root crop, where the root crop was carrot (*Daucus carota* L. subsp. *sativus*) for Field A, and garden beet (*Beta vulgaris* L. subsp. *maritima*) for Field B. We followed this sequential crop rotation for a multiyear study (from 2017 to 2019 for Field A; from 2018 to 2019 for Field B). All crop phases were present each year, where each crop type was produced in one of three sections of the field and arranged next to each other according to the rotation sequence. Each crop type section had a randomized complete block, split-plot design with three replicates. Each replicate had five main plots to test a range of N fertilizer rates ($n = 5$). The main plots were 3-m wide by 12-m long. The main-plots were subdivided into two split-plots (3 m by 6 m) to compare the cover crop vs. no cover crop ($n = 2$).

We tested five N fertilizer treatments that incrementally increased from no fertilizer (0-N control) to a high rate (i.e., 220–300 kg $N \cdot ha^{-1}$ depending on the crop; Table 2). The fertilizer N source was granular urea, broadcast and incorporated into the soil via rototilling (10-cm depth) prior to planting. Shortly after urea application, broccoli (cv. Green magic) was mechanically transplanted (as 4-wk old transplants, which were produced in a greenhouse) on 30 May 2017, 29 May 2018, and 29 May 2019. Sweet corn (cv. Vision), carrot (cv. Bolero) and beet (cv. Merlin) were directly seeded on 25–28 May 2017, 26–29 May 2018, and 28 May 2019, respectively. Broccoli was planted with 50-cm between-row spacings and 30-cm in-row spacings. Sweet corn was seeded with 1-m between-row spacings and with 20-cm in-row spacings. Root crops were seeded with 50-cm between-row spacings and with 2-cm in-row spacings. During the growing season, the crops were irrigated with over-head irrigation on a weekly basis, receiving at least a total of 2.5 cm of irrigation and (or) precipitation per week.

Crops were harvested between late July and early September, depending on the species and weather (broccoli on 24 July 2017, 25 July 2018, and 22 July 2019; sweet corn on 28 Aug. 2017, 27 Aug. 2018, and 5 Sept. 2019;

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carrot on 14 Aug. 2017, 14 Aug. 2018, and 8 Aug. 2019; beet on 31 Aug. 2018, and 31 July 2019). After harvest samples were collected (as described below) the harvestable vegetable component was removed from the field. Then, the vegetable crop residues were flailed and rototilled into the soil to a depth of approximately 15–20 cm. Immediately after incorporating the vegetable crop residues each year (on 2 Aug. 2017 and 20 Aug. 2018 after broccoli; on 24 Aug. 2017 and 17 Aug. 2018 after carrot; and on 11 Sept. 2018 after beet), a shoulder-season rye cover crop was seeded. The rye seed was hand broadcast at a rate of 123 $kg \cdot ha^{-1}$, the typical recommended rate for this region into one of the split-plots and the other split-plot was left unplanted. In the following spring, the rye cover crop was terminated before the booting stage around the middle of May each year (22 May 2018 and 16 May 2019) via an application of 1000 $g\ a.e. \cdot ha^{-1}$ glyphosate. The fall rye was then incorporated into the soil by rototilling prior to fertilizing and planting the subsequent vegetable crop, according to the rotation. To ensure nutrients other than N were not limiting, pre-plant soil nutrient tests were performed and recommended rates of P and (or) S fertilizer applied as needed.

Plant and soil measurement and analysis

Vegetable yield data was collected by recording the fresh weight of the harvested portion collected from a 3-m row near the center of each plot: broccoli heads were cut approximately 4 cm from the top, ripe sweet corn cobs were clipped from stalks, and carrot or beet roots were lifted from the soil. Also, whole plants were collected by clipping three random plants at the soil surface or by digging up the root crops. The plant was separated into the harvestable portion and the crop residue portion. For these samples, fresh weights were recorded prior to oven drying at 60 °C for 48 h or until a constant dry weight was achieved, and dry weights recorded. Fall rye biomass was measured in April or May the year after it was planted by clipping biomass at the soil surface from within two 0.25 m^2 areas per split-plot. Biomass samples were weighed, dried, reweighed and ground (1 mm) prior to nutrient analysis. Plant tissue C and N concentrations was determined using a LECO CN628 elemental analyzer (LECO Instruments, Michigan, USA).

Soil samples were collected in the spring of each year before planting from 0–15 and 15–30 cm depths. Soils from three random cores for each split-plot were composited for each depth. Soil samples were homogenized and frozen (−10 °C) until analysis. Soil samples were thawed at 22 °C ± 2 for 4 h, sieved (<2 mm), and a sub-sample (~5 g) analyzed for inorganic N (Maynard et al. 2008). For analysis, the extracts were thawed and a sub-sample (~1 mL) analyzed for NO_3^- and NH_4^+ concentrations, using an air segmented, continuous flow colorimetric method with a SEAL AA3 HR chemistry analyzer (SEAL analytical Kitchener Ontario). Soil mineral N content was converted to $kg\ N \cdot ha^{-1}$ using the average bulk density measured by the cylinder method at each soil depth increment (Blake and Hartge 1986).

Nitrogen use efficiency calculations

The amount of N mineralized over the growing season was estimated from the unfertilized control treatments as follows (eq. 1):

$$(1) \qquad N_{min} = N_{res} + N_{plant} - N_{ini}$$

in which N_{min} is the soil N mineralized in the 0–30 cm depth, N_{res} is the residual soil N at harvest in the 0–30 cm depth, N_{plant} is the N uptake by plants, and N_{ini} is the initial soil inorganic N prior to planting/seeding in the 0–30 cm depth. This provides an estimate of inorganic N available in the soil for plant uptake throughout the growing season.

Nitrogen use efficiency indices were calculated using plant dry weights in $kg \cdot ha^{-1}$ for each crop and year, separately (Van Eerd 2007). Nitrogen content ($kg\ N \cdot ha^{-1}$) in the plant (P_n) and yield (Y_n), was determined by multiplying N percentage by dry matter content. Soil mineral N content (S_n) as sum of NO_3^--N and NH_4^+-N contents was calculated to 30-cm depth and the data converted to $kg\ N \cdot ha^{-1}$ based on soil bulk density. Nitrogen harvest index (NHI, %) is the proportion of N in the harvested plant part (i.e., the head, ear, or root) relative to total plant N content (Van Eerd 2007), and is calculated as follows (eq. 2):

$$(2) \qquad \text{Nitrogen harvest index} = \frac{Y_n}{P_n} \times 100$$

Nitrogen uptake efficiency (NUpE, %) is the proportion of N taken up by the crop, relative to soil available N (Van Eerd 2007), and is calculated as follows (eq. 3):

$$(3) \qquad \text{Nitrogen uptake efficiency} = \frac{P_n}{S_n} \times 100$$

Apparent N recovery (ANR, %) is the proportion of N taken up by the crop yield, relative to soil available N (Van Eerd 2007), and is calculated as follows (eq. 4):

$$(4) \qquad \text{Apparent nitrogen recovery} = \frac{Y_n}{S_n} \times 100$$

Statistical analysis

Prior to analyzing the data, the residuals were tested for normality and homogeneity using the Shapiro–Wilk and Bartlett tests, respectively ($p > 0.05$). Each crop, year, and field were considered as different experiments and analysed separately; data was subjected to an analysis of variance (ANOVA) using PROC MIXED in SAS (SAS version 9.1, SAS Institute Inc., Cary, NC, USA). To determine the impact of N fertilizer and the rye cover crop on plant and soil parameters, the ANOVA was conducted

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according to a split-plot design. The fixed effects were N level, rye cover crop, and their interaction. Replicates and the interaction between replication and the whole-plot factor (N levels) were set as random effects. Treatment means were compared using a Tukey's HSD test ($\alpha = 0.05$).

Results

Weather conditions

Average monthly air temperature during the vegetable growing seasons generally tracked the 30-yr mean (Table 1). Monthly rainfall during the study period was considerably below the 30-yr mean on multiple occasions, for example from June–August in 2017, May–August in 2018, and March–May in 2019 (Table 1). However, a few months received more than normal rainfall, i.e., June and July of 2019 when rainfall was 17% and 39% higher than the 30-yr mean (Table 1). As common practice for vegetable production in semi-arid regions, irrigation was supplied to supplement low rainfall on an as-needed basis.

Rye cover crop biomass, C/N ratio and N content

By the time that the rye cover crop was terminated in the spring prior to planting the vegetable crops, it produced 506–2344 $\mathrm{kg \cdot ha^{-1}}$ of aboveground biomass dry matter (DM), depending on the year and position in the rotation (Table 2). Sometimes the fertilizer N rate did not affect rye DM but other times it did, for example, after all crop phases in Field B in 2019, and after sweet corn in Field A in 2019 (Table 2). For these cases, higher N rates tended to increase the rye DM accumulation (Table 2).

The C/N ratio of the rye cover crop ranged from 10.3 to 13.7 and was relatively stable across years, fields, and position in the rotation (Table 2). While differences in the C/N ratio were often not significant, there was a general tendency for the ratio to decrease with increasing N rate, when N fertilizer was added to the soil (Table 2).

The rye cover crop contained 18.5–101.5 $\mathrm{kg\ N \cdot ha^{-1}}$ prior to its termination — with variability between years, fields, and position in the rotation (Table 2). More often than not, the quantity of N contained in the rye biomass was influenced by N rate; generally, a higher amount of N was associated with higher N rates (Table 2).

Few N rate by cover crop interactions on crop and soil parameters

There were limited or no two-way interactions (N rate by cover crop) on crop productivity parameters and NUE indices (Supplementary Table S1[2]). Likewise, there were only a few N rate by cover crop interactions on soil inorganic N contents (Supplementary Table S2[2]). Consequently, we hereafter focus on the main effects.

Cover crop effects

Rye cover crop maintained or increased vegetable crop productivity

The rye cover crop frequently influenced vegetable crop productivity (Supplementary Table S1[2]). Vegetable crop yields were 10%–26% greater in the rotation with vs. without the cover crop (Table 3). There was only one case where the cover crop did not influence yield — that being sweet corn in 2018 (Table 3). Further, vegetable crop harvest indexes (HIs) were generally (by 4%–24%) higher in the rotation with vs. without the cover crop (Table 3).

Rye cover crop increased vegetable crop N contents

The cover crop routinely influenced the amount of N contained in the vegetable crop yield and crop residue (Supplementary Table S1[2]), resulting in greater N contents compared with the without cover crop plots (Fig. 1). Including the rye cover crop in the rotation increased the amount of N in broccoli yield by 27%–38%, sweet corn yield by 43%–49%, and root crop yield by 29%–49% (Fig. 1). Furthermore, the rye cover crop increased the amount of N in the vegetable crop residues by 12%–37% for broccoli, 7%–41% for sweet corn, and 14%–33% for root crops (Fig. 1).

Rye cover crop lowered soil inorganic N levels at vegetable planting but increased levels at harvest

The cover crop regularly influenced soil inorganic N contents at vegetable crop planting and at harvest (Supplementary Table S2[2]). Prior to planting all vegetables, soil $\mathrm{NO_3^-}$-N and $\mathrm{NH_4^+}$-N contents were consistently lower with vs. without the rye cover crop in the rotation (Fig. 2). However, by the time that vegetables were harvested, soil $\mathrm{NO_3^-}$-N and $\mathrm{NH_4^+}$-N contents were higher with vs. without the rye cover crop in the rotation (Fig. 2).

Rye cover crop maintained or improved vegetable crop N use efficiency

The cover crop frequently increased vegetable crop NUE indices compared with no cover crop (Supplementary Table S1[2]; Fig. 3). For broccoli, including the rye cover crop increased the crop NUpE by 17%–34%, the ANR by 15%–31%, and the NHI by 11%–30% (Fig. 3). Similar changes were observed for sweet corn where the rye cover crop increased the crop NUpE by 18%–24%, the ANR by 34%–49%, and the NHI by 28%–38% (Fig. 3). For root crops, the rye cover crop increased NUpE by 23%–24%, ANR by 20%–49%, and NHI by 9%–20% (Fig. 3).

N fertilizer rate responses

Increasing the N fertilizer rate did not consistently increase vegetable crop productivity

Since there were few/no N fertilizer rate by cover crop interactions, the results of N application rates are

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[2] Supplementary data are available with the article at https://doi.org/10.1139/cjps-2021-0032.

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Table 2. Aboveground rye cover crop production and quality at the time of termination, as influenced by the amount of fertilizer N that was applied to vegetable crops the previous year.

Vegetable crop grown in the previous year	Fertilizer N applied to the previously grown crop (kg N·ha^{-1})	Rye biomass (kg DM·ha^{-1})			Rye C/N ratio			Rye N content (kg N·ha^{-1})		
		Field A 2018	Field A 2019	Field B 2019	Field A 2018	Field A 2019	Field B 2019	Field A 2018	Field A 2019	Field B 2019
Root crop										
	0	714	953	950b	13.7	12.5a	11.7	24.92	36.40b	39.18b
	55	789	1109	1177ab	13.3	13.1a	12.3	28.06	39.38ab	47.14ab
	110	776	924	1202ab	13.1	11.8b	11.8	27.34	36.11b	48.87ab
	165	753	1266	1330ab	12	11.8b	11.7	29.65	50.40a	55.75ab
	220	897	1198	1480a	11.8	11.7b	11.4	36.23	49.94a	64.55a
	p value	0.8169	0.0543	**0.0491**	0.3368	**0.0001**	0.52	0.2899	**0.0061**	**0.0346**
Broccoli										
	0	1804	776	638b	12.6	13	12.3	71.96	26.52ab	24.82b
	75	2344	681	666b	12.9	12.6	12.6	90.07	26.30b	26.24b
	150	2158	678	709b	12	12.4	12.2	88.8	26.66ab	28.54b
	225	1849	816	856ab	11.1	11.6	11.5	82.47	33.53ab	36.51ab
	300	2201	797	1004a	11	11.6	11.1	101.5	33.86a	43.88a
	p value	0.1201	0.1017	**0.0119**	0.1163	0.3608	0.0512	0.1439	**0.012**	**0.0069**
Sweet corn										
	0	524	973ab	456b	12.1a	11.9	11.9ab	20.83b	38.57b	18.46b
	75	512	922b	506b	12.1a	11.4	13.1a	21.61ab	38.76b	18.55b
	150	529	1205ab	508b	10.7ab	11.4	11.3b	23.83ab	51.27ab	21.49b
	225	558	1298a	601ab	11.1ab	11.1	11.5b	25.61ab	59.95a	26.03ab
	300	560	1389a	752a	10.3b	11	11.3b	26.83a	65.03a	33.18a
	p value	0.5511	**0.0269**	**0.0017**	**0.0195**	0.5424	**0.0109**	**0.0227**	**0.0061**	**0.0027**

Note: Bold values indicate significance at $\alpha = 0.05$. Within each column and crop phase, the means followed by different letters are significantly different ($\alpha = 0.05$).

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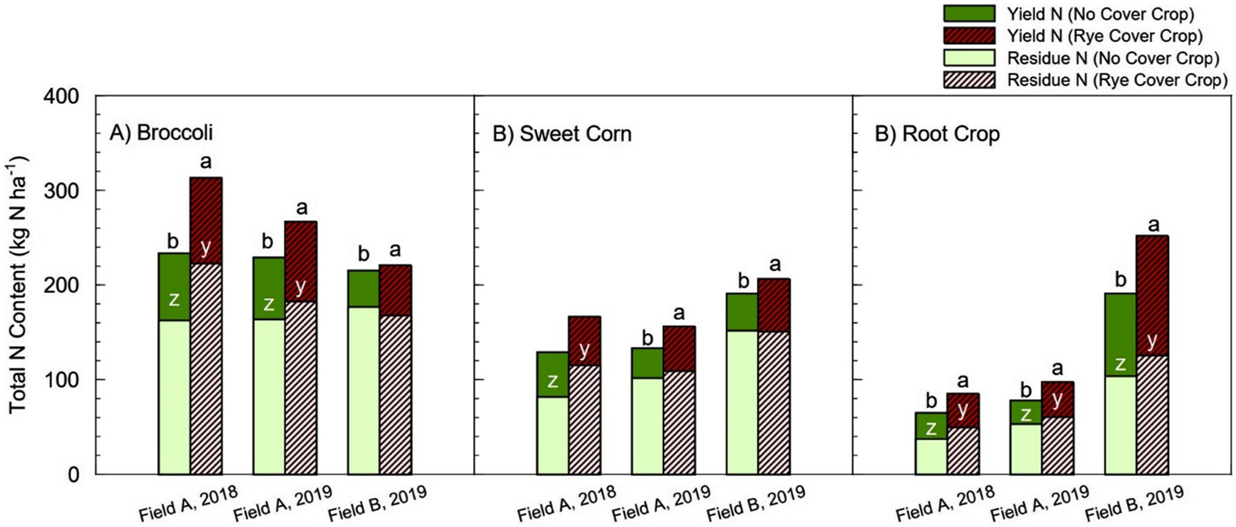
Table 3. Productivity of vegetable crops grown in rotation with and without shoulder-season rye cover crop (CC).

		Vegetable yield (Mg·ha^{-1})		Vegetable harvest index	
Vegetable	Site, year	Without CC	With CC	Without CC	With CC
Broccoli	Field A, 2018	20.06b	24.16a	0.24b	0.28a
	Field A, 2019	18.83b	22.08a	0.26b	0.28a
	Field B, 2019	11.85b	13.03a	0.13b	0.16a
Sweet corn	Field A, 2018	13.96	14.99	0.35	0.30
	Field A, 2019	10.00b	12.27a	0.24b	0.29a
	Field B, 2019	11.28b	14.16a	0.21b	0.26a
Root crop	Field A, 2018	16.67b	20.65a	0.68	0.68
	Field A, 2019	17.68b	22.22a	0.57b	0.60a
	Field B, 2019	33.16b	38.83a	0.50b	0.52a

Note: For each row and within each productivity measure, the means followed by different letters are significantly different due to the cover crop effect, at $\alpha = 0.05$.

Fig. 1. The amount of N removed with yield and returned as crop residues of broccoli, sweet corn and root crop when grown in rotation with vs. without the shoulder season rye cover crop. For each site-year and each vegetable crop type, the means followed by different letters are significantly different at $\alpha = 0.05$ (the top letters with black font apply to yield data; the bottom letters with white font apply to crop residue data).



presented as an average response (with and without cover crops). Generally, vegetable crop yields increased with N application but not always in a consistent and incremental fashion (Table 4). For example, the point at which a higher N rate no longer increased yield was obtained when only a small amount of N was added to broccoli in Field B in 2019 (i.e., 75 kg N·ha^{-1}), when a medium amount of N was added to sweet corn in Field B in 2019 (i.e., 150 kg N·ha^{-1}), and when a high amount of N was added to broccoli in Field A in 2019 (i.e., 225 kg N·ha^{-1}). Application of any amount of N fertilizer reduced yield of sweet corn on Field A in 2018 (Table 4). The crop HI was frequently influenced by N rate but the effect was inconsistent across crop types, fields, and years in that sometimes higher N rates resulted in higher HI, and at other times lower HI (Table 4).

Increasing the N fertilizer rate did not consistently increase vegetable crop N contents

After inclusion of cover crop, the N rate often impacted the quantity of N removed from the field in crop yields (Supplementary Table S1[2]). In general, higher N rates corresponded to greater vegetable crop N contents, but the response tended to plateau prior to the highest N rate applied (Table 5). The amount of N returned to the soil as crop residues, where affected by

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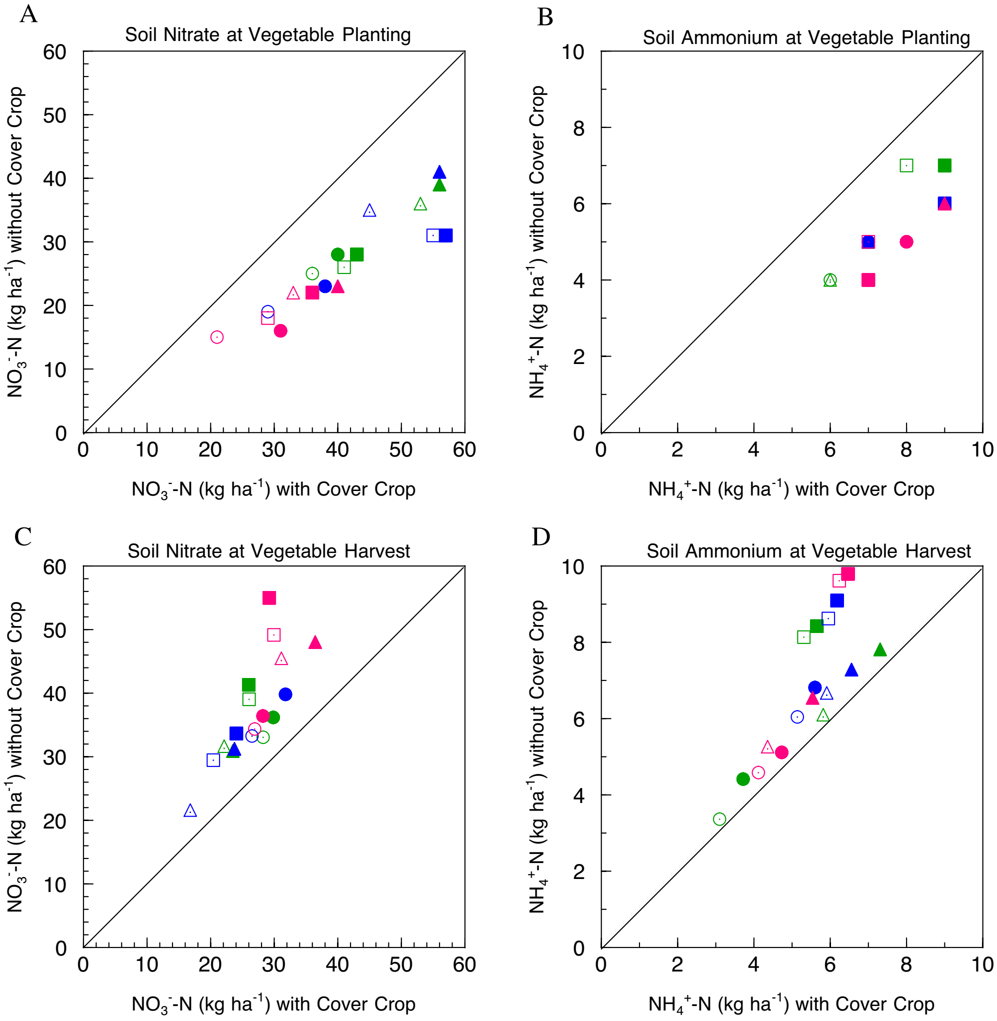
Fig. 2. Increase or decrease in soil nitrate-N and ammonium N as a result of growing a rye cover crop before the vegetable crop. Panel (A) and (B) are soil inorganic N values at the time of planting the veg crop, and (C) and (D) are soil inorganic N values after the vegetable crop was harvested. The 1:1 line represents no difference in nitrate or ammonium between vegetable grown with vs. without cover crop. The green, blue, and pink markers represent broccoli, sweet corn, and root crops, respectively. Different shapes represent different site-years: the squares, triangles, and circles correspond to Field A 2018, Field A 2019, and Field B 2019, respectively. Data for the soil depths of 0–15 and 15–30 cm are indicated by the solid and dotted markers, respectively.



N rate, ranged from 88 to 226 kg·ha^{-1} for broccoli, 85 to 126 kg·ha^{-1} for sweet corn, and 38 to 84 for carrot (Table 5).

Increasing the N fertilizer rate increased the soil inorganic N levels at vegetable planting and harvest

After inclusion of cover crop, the N rate significantly affected soil NO_3^--N and NH_4^+-N contents in the 0–15 and 15–30 cm depths prior to planting vegetable crops (Table 6). As a general pattern, higher soil NO_3^--N and NH_4^+-N contents at planting corresponded to the treatments that received higher N fertilizer applications year after year (Table 6). At harvest, the N rate significantly influenced soil NO_3^--N and NH_4^+-N contents (0–15 and 15–30 cm depths) in many cases — such that soil NO_3^--N and NH_4^+-N contents were generally higher with higher amounts of N fertilizer (Table 6). On average, total amount of soil inorganic N in the top 0–30cm (0–15 + 15–30) that remained after harvest of broccoli, sweet corn and root crops were 73, 69 and 87 kg N·ha^{-1}, respectively (Table 6).

Lower N fertilizer rates improved vegetable crop N uptake and recovery efficiency but reduced N harvest index

After the establishment of the cover crop, the vegetable crop NHI generally increased with N fertilizer rate, but not always in an incremental manner as the NHI tended to plateau prior to reaching the highest N rate (Table 7). The NUpE and ANR were significantly impacted by N rate in nearly all cases (Table 7). Overall, NUpE decreased with increasing N fertilization rate for all vegetable crops, except for broccoli in Field B, 2019 (Table 7).

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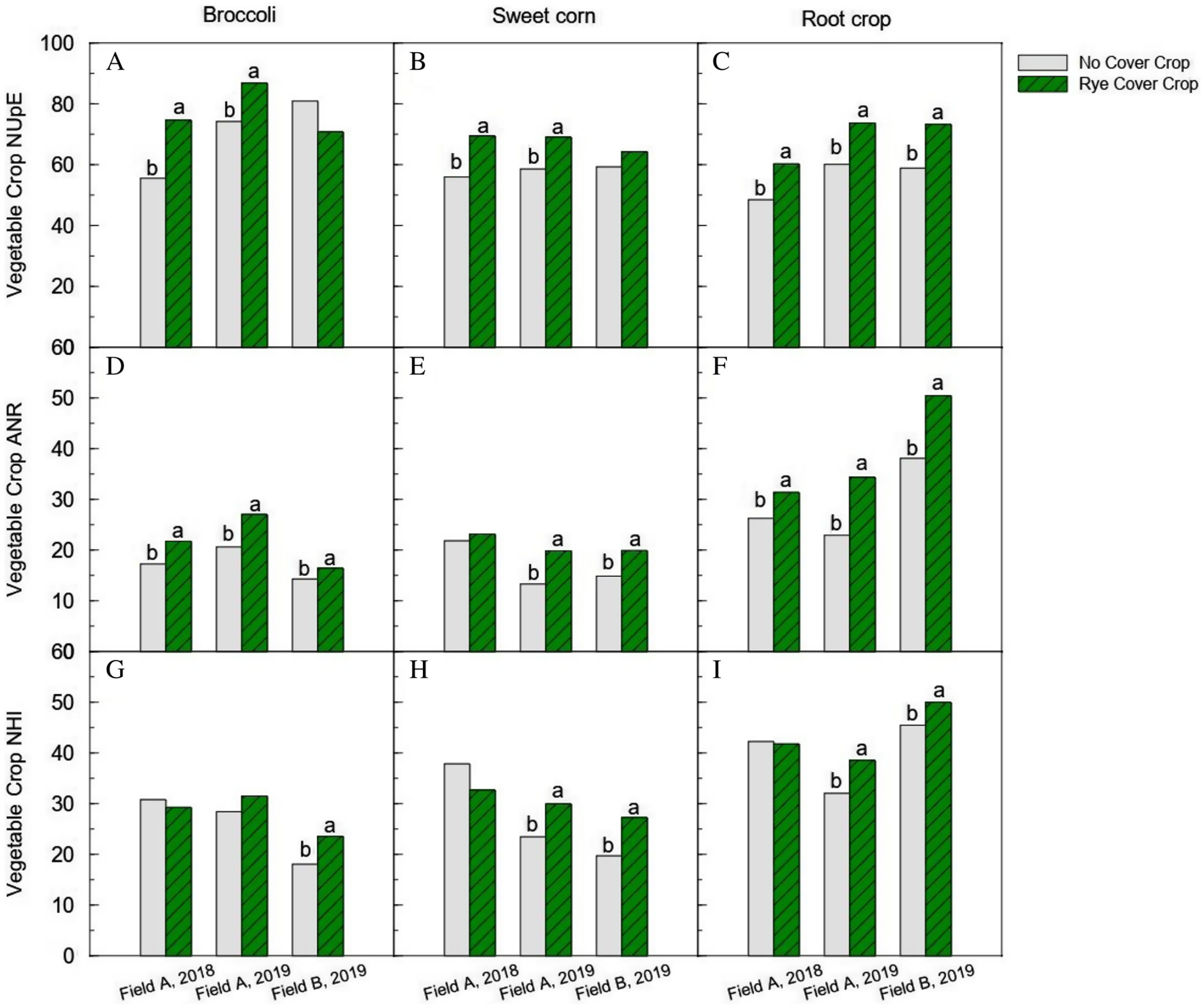
Fig. 3. The N uptake efficiency (NUpE), apparent N recovery (ANR) and N harvest index (NHI) for broccoli (A, D and G), sweet corn (B, E and H) and root crop (C, F and I) in rotation with and without the shoulder season rye cover crop. For each row and within each productivity measure, means followed by different letters are significantly different due to the cover crop effect, at $\alpha = 0.05$.



Similarly, ANR values decreased with increasing N rate for most of the cases in Field A, but just for one case in Field B (Table 7).

Discussion

Rye cover crop as part of a vegetable crop rotation in a cold climate

The rye cover crop was successfully established each fall prior to the onset of winter, and most of the growth occurred during the early fall and spring periods. However, the aboveground rye biomass observed in our study (conducted in a cold climate on the Canadian prairies) was generally low compared with other studies in more temperate climates and longer growing seasons (Clark et al. 1997; Feyereisen et al. 2006; West et al. 2020).

Cover crop maintained or improved vegetable crop yield and increased N use efficiency by influencing soil N cycling

The vegetable crop yields observed in our study were consistent with and somewhat higher than the provincial yield averages (Statistics Canada 2019). Vegetable crops grown after the rye cover crop had higher yields and HI compared with crops grown without a prior cover crop (Table 3). This might be explained by a closer synchrony between vegetable crop N uptake and N released from the rye biomass and the previous year's vegetable crop residues, via mineralization during the early part of the growing season (Griffin et al. 2000; Restovich et al. 2012; Radicetti et al. 2017).

Cover cropping not only increased the amount of N in the vegetable crop yields but also in the crop residues, compared with the no cover crop control (Fig. 1). The N returned to the soil as vegetable crop residues at harvest can serve as a nutrient source for the next vegetable crop if it is not lost from the system before then — a period which can be 8–10 mo in cold climates such as the Canadian prairies. Due to low C/N ratios [8–13 for broccoli, 17–30 for sweet corn, 11–17 for carrot, and 7–11 for beet (data not shown)] the vegetable crop residues likely mineralized shortly after harvest in late summer and

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Table 4. Mean crop yield and harvest index as affected by N fertilization.

Fertilizer N (kg N·ha^{-1})	Fresh yield (Mg·ha^{-1})			Harvest index (%)		
	Field A 2018	Field A 2019	Field B 2019	Field A 2018	Field A 2019	Field B 2019
Broccoli						
0	22.56	14.84d	6.89b	0.26	0.23c	0.12b
75	25.01	18.49cd	12.08a	0.28	0.26bc	0.13b
150	20.84	19.44bc	16.27a	0.25	0.30a	0.15a
225	22.23	23.36ab	14.45a	0.26	0.28ab	0.15a
300	19.90	26.12a	12.51a	0.24	0.27ab	0.16a
Sweet corn						
0	16.43a	6.54d	8.39c	0.37	0.31a	0.17c
75	16.88a	9.50c	9.91c	0.36	0.32a	0.21c
150	13.37ab	11.54b	18.89a	0.31	0.31a	0.30a
225	13.64ab	13.54a	14.34b	0.30	0.21b	0.27ab
300	12.05b	14.53a	12.06bc	0.28	0.17b	0.23bc
Root crops	Carrot	Carrot	Beet	Carrot	Carrot	Beet
0	19.29	13.89c	30.69c	0.68	0.57b	0.48b
55	22.96	18.51b	33.66bc	0.71	0.58b	0.50ab
110	19.11	20.38b	40.42a	0.67	0.61a	0.52a
165	16.97	22.25ab	38.38a	0.66	0.61a	0.53a
220	14.98	24.72a	36.83ab	0.67	0.58b	0.52a

Note: Within each column and vegetable crop, the means followed by different letters are significantly different ($\alpha = 0.05$).

Table 5. Mean crop yield and residue N content as affected by N fertilization.

Fertilizer N (kg N·ha^{-1})	Yield N content (kg N·ha^{-1})			Crop residue N content (kg N·ha^{-1})		
	Field A 2018	Field A 2019	Field B 2019	Field A 2018	Field A 2019	Field B 2019
Broccoli						
0	81.65	44.89c	20.78b	187.05	138.66c	88.32b
75	88.78	67.48b	39.85ab	192.12	151.80bc	169.85a
150	75.87	81.75ab	53.61a	214.18	155.83bc	208.93a
225	85.41	89.79a	59.27a	187.51	192.21ab	217.79a
300	71.99	89.97a	55.25a	181.37	226.27a	175.87a
Sweet corn						
0	56.39a	18.55c	22.09c	78.47	93.84b	124.92
75	57.06a	29.76b	32.96c	91.11	112.09ab	128.87
150	46.09ab	39.63b	71.81a	96.24	85.27b	177.54
225	45.53ab	51.20a	58.12ab	120.12	108.69ab	148.87
300	41.75b	58.23a	52.11b	105.76	126.20a	175.20
Root crops	Carrot	Carrot	Beet	Carrot	Carrot	Beet
0	29.58	18.52c	71.40c	41.08	37.66c	101.30
55	40.23	27.03b	95.22b	46.61	48.28bc	113.76
110	32.22	33.75ab	118.89a	46.23	52.28bc	114.18
165	30.02	36.49a	123.90a	44.61	60.88b	113.74
220	26.03	39.25a	125.07a	38.20	84.19a	129.21

Note: Within each column, vegetable crop, and fixed effect, the means followed by different letters are significantly different ($\alpha = 0.05$).

early fall. Other researchers have reported rapid mineralization of residues with similar C/N ratios to ours (13–25), when conditions were favourable for decomposition (Radicetti et al. 2016*a*, 2016*b*). Therefore, a large amount of available N would be present in the soil during the post-harvest period throughout the fall and winter. The previous year's cover crops would have increased this amount by way of increasing the vegetable crop residue N contents. However, by repeatedly including the cover crop during the shoulder-season

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Table 6. At planting and harvest, average soil NO_3^--N and NH_4^+-N levels as affected by N fertilization.

	NO_3^--N at 0–15 cm (kg·ha^{-1})			NO_3^--N at 15–30 cm (kg·ha^{-1})			NH_4^+-N at 0–15 cm (kg·ha^{-1})			NH_4^+-N at 15–30 cm (kg·ha^{-1})		
Fertilizer N (kg N·ha^{-1})	Field A 2018	Field A 2019	Field B 2019	Field A 2018	Field A 2019	Field B 2019	Field A 2018	Field A 2019	Field B 2019	Field A 2018	Field A 2019	Field B 2019
At planting												
Broccoli												
0	19.40c	25.56d	20.51c	16.92c	23.82d	17.68d	6.35b	5.12	4.09c	6.26b	4.35c	4.47c
75	23.86c	39.45cd	26.39bc	22.90c	34.00cd	23.35cd	6.70b	5.51	5.22b	6.67b	5.39b	5.25b
150	33.88bc	45.90bc	32.78bc	31.40bc	45.39bc	29.32bc	7.36b	5.68	5.68ab	7.22ab	5.57b	5.41b
225	42.75ab	57.65ab	39.00b	39.48b	55.13ab	36.37ab	8.53ab	5.81	5.84ab	7.87ab	5.64ab	5.59ab
300	57.19a	68.92a	52.08a	55.86a	63.75a	45.19a	10.57a	7.32	6.31a	9.53a	6.02a	6.06a
Sweet corn												
0	26.78b	22.81d	20.24b	29.13b	19.11d	15.58c	6.96b	5.35b	4.91c	7.03b	5.50	4.68c
75	34.86b	38.10cd	23.95b	35.74b	31.20cd	19.02bc	7.15b	5.60b	5.53bc	7.29b	5.64	5.53bc
150	47.02ab	48.07bc	28.45b	42.36ab	40.82bc	24.00abc	7.45ab	5.84ab	5.56bc	7.48b	5.82	5.67abc
225	49.95ab	60.32ab	39.60a	46.44ab	50.51ab	29.32ab	7.67ab	6.02ab	5.86b	7.72ab	6.04	5.86ab
300	62.76a	72.24a	41.64a	61.51a	60.22a	32.95a	8.06a	7.46a	6.71a	8.49a	7.20	6.60a
Root crops	Carrot	Carrot	Beet	Carrot	Carrot	Beet	Carrot	Carrot	Beet	Carrot	Carrot	Beet
0	15.77c	18.49c	13.82b	14.08c	15.66c	13.76b	5.06b	7.01c	5.95c	4.96d	7.10c	5.59c
55	22.67bc	25.17bc	21.58ab	18.00bc	22.04b	14.13b	5.22b	7.38bc	6.13bc	5.36cd	7.34bc	6.66b
110	29.68abc	28.84bc	23.50ab	24.37abc	27.05b	16.66ab	5.54b	7.63bc	6.84abc	5.58bc	7.57bc	6.72ab
165	33.70ab	38.59ab	26.02a	28.09ab	33.99a	19.38ab	5.78ab	7.84b	7.12ab	5.91ab	7.75ab	6.90ab
220	42.61a	46.35a	32.97a	32.06a	40.07a	24.49a	6.51a	8.61a	7.55a	6.31a	8.16a	7.06a
At harvest												
Broccoli												
0	9.89d	13.18c	14.84c	9.17c	11.50c	14.38d	5.68c	5.56c	3.58b	5.75b	4.50c	2.81c
75	22.23cd	20.02bc	20.28bc	21.45b	17.00bc	19.23cd	6.48bc	6.00c	3.82b	6.68a	4.96bc	3.10bc
150	35.02bc	24.42bc	30.81b	30.82b	22.10bc	30.23bc	7.21ab	7.06bc	3.89b	6.83a	5.50bc	3.24ab
225	44.09ab	32.35b	44.05a	45.90a	33.65ab	41.03ab	7.52ab	8.58b	4.30ab	6.98a	6.44b	3.41ab
300	57.07a	46.04a	55.06a	55.34a	50.21a	48.36a	8.30a	10.62a	4.74a	7.37a	8.41a	3.60a
Sweet corn												
0	9.38c	11.37d	18.68d	10.02d	10.12c	16.29e	6.53b	5.07d	4.05c	6.21b	4.64c	3.96c
75	19.33c	16.14cd	22.59cd	14.98cd	12.99bc	21.57d	6.90b	6.14c	5.17bc	6.58ab	5.48bc	4.45c
150	26.85bc	21.17c	30.92bc	21.72bc	15.44bc	29.87c	7.30b	7.06bc	6.10bc	7.10ab	5.90bc	4.99bc
225	38.26ab	37.07b	40.53b	31.07b	20.82b	36.28b	7.76b	7.73ab	6.48b	7.46ab	7.15ab	6.65ab
300	50.39a	51.77a	66.21a	46.89a	36.62a	45.41a	9.70a	8.59a	9.22a	9.09a	8.27a	7.89a
Root crops	Carrot	Carrot	Beet	Carrot	Carrot	Beet	Carrot	Carrot	Beet	Carrot	Carrot	Beet
0	24.71c	20.29b	15.90c	22.72c	19.46c	15.45c	7.28c	4.65c	4.10d	7.16c	3.98d	3.33c
55	27.99c	25.41b	20.85bc	28.72c	22.84c	19.83bc	7.66bc	5.40bc	4.33cd	7.49c	4.51cd	3.77bc
110	42.42bc	33.46b	26.75b	35.54bc	32.01bc	27.35b	8.07bc	5.73bc	4.88bc	7.73c	4.78bc	4.34abc
165	52.24ab	56.34ab	45.58a	47.81ab	47.28b	42.13a	8.43ab	6.63ab	5.41ab	8.31b	5.17ab	4.87ab
220	63.13a	75.71a	52.47a	62.95a	69.92a	48.44a	9.20a	7.81a	5.88a	8.95a	5.64a	5.44a

Note: Within each column, vegetable crop, and fixed effect, the means followed by different letters are significantly different ($\alpha = 0.05$).

Table 7. The N harvest index (NHI), N uptake efficiency (NUpE) and apparent N recovery (ANR) for sweet corn, broccoli, carrot and beet as affected by N fertilization.

	NHI (%)			NUpE (%)			ANR (%)		
Fertilizer N (kg N·ha^{-1})	Field A 2018	Field A 2019	Field B 2019	Field A 2018	Field A 2019	Field B 2019	Field A 2018	Field A 2019	Field B 2019
Broccoli									
0	30.88	24.20b	19.15b	90.37a	104.68a	73.89ab	27.74a	25.57a	14.00
75	31.64	30.97ab	19.16b	75.44ab	87.59b	94.06a	24.03ab	26.93a	17.61
150	26.85	34.34a	20.50ab	64.84bc	73.02c	86.58ab	17.07bc	25.11a	17.42
225	31.68	31.79ab	21.46ab	52.25cd	70.44c	73.27ab	16.44c	22.41ab	15.45
300	28.99	28.34ab	23.67a	42.42d	66.53c	51.15b	12.11c	18.92b	12.12
Sweet corn									
0	42.23	16.63b	14.76c	106.61a	101.76a	77.38a	44.57a	19.03a	16.90b
75	39.16	21.33b	20.57bc	73.53b	76.49b	72.82ab	28.31b	17.25ab	16.18b
150	33.39	31.78a	29.40a	51.48bc	47.95c	62.08ab	16.67c	16.02ab	25.40a
225	31.83	31.85a	28.10a	47.12c	47.66c	49.67ab	12.95cd	15.88ab	16.20b
300	29.52	31.82a	24.44ab	34.58c	44.93c	46.75b	9.79d	14.65b	12.08b
Root crops	Carrot	Carrot	Beet	Carrot	Carrot	Beet	Carrot	Carrot	Beet
0	42.19	31.70c	41.64b	103.15a	115.80a	74.72a	60.99a	55.26a	51.35a
55	46.18	32.56bc	45.06ab	70.31b	72.75b	72.89a	38.86b	30.54b	48.85a
110	40.78	35.84ab	50.80a	43.95c	54.27bc	67.00ab	20.33c	23.51bc	46.26ab
165	40.22	37.17a	51.79a	31.96c	45.97c	59.44bc	14.06c	18.38c	40.18bc
220	40.53	39.03a	49.20ab	22.26c	45.60c	56.12c	9.70c	15.48c	34.63c

Note: Within each column, vegetable crop, and fixed effect, the means followed by different letters are significantly different ($\alpha = 0.05$).

period, it may help retrieve NO_3^--N from the soil in the fall and subsequent spring. These processes facilitate the cycling of N within the soil-crop system year after year and reducing the risk of N loss (Griffin et al. 2000; Campiglia et al. 2014; Radicetti et al. 2017; Snapp and Surapur 2018). We recommend future research determines the threshold whereby biomass accumulation translates into reduced N losses by directly measuring the N losses.

The rye cover crop reduced soil inorganic N prior to planting of the vegetable crops (Fig. 2) indicating that it served as a catch crop, lowering the levels of environmentally reactive N in the soil during a key period — when the soil would otherwise be fallow and a thaw or leaching event would risk N loss prior to planting crops and crop N uptake (West et al. 2016). After vegetable crops were produced and harvested, a cover crop effect was still apparent, but with the opposite result in that more soil inorganic N remained in the soil in the rotation with the cover crop vs. without the cover crop (Fig. 2). This in-season rebound of soil inorganic N in the cover cropped rotation suggests a net release of N from the cover crop biomass (West et al. 2020). Net N mineralization during the early part of the growing season would have been favoured by the low C/N ratio (10.3–13.7) of the rye cover crop biomass (Table 2). Plausibly, the timing of N release benefitted the vegetable crop, due to the higher yields, N contents, and NUE indices observed with vs. without the cover crop (Table 3, Figs. 1 and 3). The amount of mineralized N in cover cropped plots was estimated as 43%–217% higher than the amount of N mineralized in the plots with no cover crop across fields, growing seasons and vegetable crops. It is possible that the N immobilized by the rye cover crop was re-mineralized during the vegetable growing season when the crops were actively taking up N. This would reduce the potential for further N leaching loss later in the growing season.

However, cover crops may not always synchronize soil N supply with crop demand and may not impart crop yield or NUE benefits (Restovich et al. 2012; Snapp and Surapur 2018; Wang et al. 2018). The outcome is regulated by the rate and timing of cover crop decomposition as it compares to crop N demand. Environmental benefits associated with improving crop NUE sometimes come with agronomic trade-offs (Pantoja et al. 2015; Martínez et al. 2017; West et al. 2020), but in our case, the rye cover crop did not negatively affect vegetable crop yields nor NUE; rather, increased vegetable yield and NUE.

A little goes a long way: lowering N fertilizer rates improve vegetable crop NUE and maintain yield

Depending on the site and year, crop yields did not increase with N rates above 75–225 kg N·ha^{-1} for broccoli and sweet corn, and above 110–165 kg N·ha^{-1} for root crops (Table 4). However, crop NUpE and ANR decreased

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with higher N rates (Table 7). Together, these results point towards unnecessary N application when fertilizer exceeds these thresholds. There were no significant increases in NHI at N rates higher than 75–150 kg N·ha^{-1} for broccoli and sweet corn, and at N rates higher than 110 kg N·ha^{-1} for root crops across growing seasons, whereas the NUpE and ANR values generally decreased with increasing N rates (Table 7). Like others (Zhang et al. 2011; Pantoja et al. 2015), our results show that the most efficient N use is achieved with relatively low fertilizer rates, and that luxury N consumption at higher N rates does not improve NUE. Although N supply is necessary to support vegetative growth and yield, increasing the N supply beyond the crop needs will not result in further yield increases, and may actually reduce yield (Long et al. 2004; Pokluda et al. 2018). Evidence of this effect was observed for sweet corn yields and HIs, and carrot HIs (Table 4). These reductions in yield and HI might be ascribed to excessive soil available N, resulting in more vegetative growth at the expense of yield, a delay in time taken to reach the maturity and luxury N uptake (Griffin et al. 2000; Westerveld et al. 2007; Yoldas et al. 2008). Our results indicate that the recommended N rates should compensate for high background soil N especially when cover crops are not used in the rotation.

Conclusions

Our findings support the hypothesis that shoulder season rye cover crops benefit crop NUE by influencing soil N cycling in vegetable crop rotations — possibly by improving synchrony between soil N availability and crop N uptake. Also, the rye cover crop either improved or maintained vegetable crop yield and N contents, compared with the control. Repeatedly including a shoulder season rye cover crop in the vegetable crop rotation may decrease the dependence on external N inputs over time. Our study indicates that — even in a short-season growing region — the inclusion of a shoulder-season rye cover crop can significantly influence N cycling, which can be profitably used by high N-demanding vegetable crops in the rotation. Depending on the site and year, yields were maximized by capping N fertilizer applications between 75–225 kg·ha^{-1} for broccoli and sweet corn, and between 110–165 kg·ha^{-1} for root crops. However, even lower N rates maximized crop NUEs. This effect is ascribed to the mineralization of labile N pools in the soil and demonstrates the importance of adjusting fertilizer rates to better account for the background soil N available for crop production. Ultimately, excessive and repeated N fertilizer applications can result in an accumulation of inorganic N in the soil — beyond the levels needed by the vegetable crop, leading to environmental concerns if steps are not taken to better manage N. Further research on the benefits and possible drawbacks of including cover crop species in different regions, cropping systems, soil types, background fertility levels, and precipitation patterns will help expand the knowledgebase and understanding of how best to utilize cover crops as a tool to improve NUE.

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