

Article

Evaluation of Post-Harvest Organic Carbon Amendments as a Strategy to Minimize Nitrogen Losses in Cole Crop Production

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Abstract: Cole crops (*Brassica* vegetables) can pose a significant risk for N losses during the post-harvest period due to substantial amounts of readily mineralizable N in crop residues. Amending the soil with organic C has the potential to immobilize N and thereby reduce the risk for N losses. Four field trials were conducted to determine the effects of organic C amendments (OCA) on N dynamics and spring wheat (*Triticum durum* L.) harvest parameters proceeding early- and late-broccoli (*Brassica oleracea* var *italica* L.) systems in 2009 and 2010. The experimental controls represented the traditional grower practice of incorporated broccoli crop residue (CR-control) and the pre-plant application of N fertilizer (CRN-control) to subsequent spring wheat. Alternative practices were compared to the controls, which included broccoli crop residue removal (CR-removal), an oat (*Avena sativa* L.) cover crop (CC-oat), and three different OCA of wheat straw (OCA-straw), yard waste (OCA-yard), or used cooking oil (OCA-oil). The treatments, which demonstrated reduced autumn soil mineral N (SMN) concentrations after broccoli harvest, relative to the CR-control, were CR-removal, OCA-straw, and OCA-oil. Although CR-removal and OCA-straw indicated a reduced potential for autumn soil N losses in the early-broccoli system, these practices are not recommended for growers because subsequent spring wheat yield and profit margins were reduced compared to the CR- and CRN-controls. The OCA-oil reduced autumn SMN concentrations by 53 to 112 kg N ha^{−1} relative to the CR-control after both early- and late-broccoli harvest, suggesting a larger potential for reduced autumn soil N losses, compared to all other treatments. No detrimental effects resulted from the OCA-oil

treatment on the subsequent spring yield or grain N. The OCA-oil reduced spring wheat profit margins relative to the CR-control, like the OCA-straw and CR-removal treatments, however profit margins were similar between the OCA-oil and the CRN-control. Therefore, in areas with a high risk of environmental N contamination, growers should consider the OCA-oil practice after cole crop harvest to minimize the risk of N losses.

Keywords: nitrogen immobilization; broccoli; soil amendment; sustainable agriculture; profit margins

Abbreviations

OCA: organic carbon amendments

SMN: soil mineral N

CR-control: broccoli crop residue incorporation

CRN-control: broccoli crop residue incorporation with spring applied N fertilizer

CR-removal: broccoli crop residue removal

CC-oat: oat cover crop

OCA-straw: wheat straw amendment

OCA-yard: yard waste amendment

OCA-oil: used cooking oil amendment

1. Introduction

Nitrogen fertilizer applications are frequently used to enhance vegetable crop production, and much research has been done to reduce N losses during the vegetable crop growing season [1,2]. However, after harvest, a large quantity of N can remain in vegetable crop residues [2–4], which readily mineralizes [3] and may be susceptible to post-harvest losses. There is need to minimize N losses during the post-harvest season when the risk of losses is much greater due to the annual water budget in Ontario [5] and elsewhere. Losses include nitrate (NO_3^- -N) leaching and denitrification, which can have negative environmental consequences such as groundwater and atmosphere contamination. Thus, the development of more sustainable agricultural practices, which are focused on soil N management after vegetable harvest, is necessary.

Cole crop (*Brassica* vegetables), in particular, produce optimal yields with high N applications, ranging from 270 to 550 kg N ha⁻¹ for broccoli (*Brassica oleracea* var *italica* L.) [4,6–9]. Cole crop residues may leave ≈ 100 to 330 kg N ha⁻¹ in the field at harvest [2,3], and post-harvest mineral N losses are more related to crop residue N rather than N fertilizer remaining in the soil [3]. Considering that 35 to 60% of broccoli crop residue N has been found to mineralize in controlled incubation studies [10,11], and that the crop residue may contain up to 330 kg N ha⁻¹ [1], then up to 198 kg N ha⁻¹ would be mineralized in the field after harvest from broccoli crop residue [11]. Thus, cole crop residue poses a significant risk for N losses due to the large quantity of mineralizable N in the post-harvest season.

Amending the soil with organic C material has the potential to reduce soil mineral N (SMN) concentrations through N immobilization [11,12]. By redirecting organic C materials from waste streams, a new sustainable method of utilizing these materials could be developed. Some high C materials, which are expected to be readily available for vegetable producers in Ontario, are wheat straw, yard waste, or used cooking oil. For example, winter wheat typically has 1.4 Mg ha⁻¹ of straw residue [13]. Up to 326,000 ha⁻¹ of winter wheat was harvested in Ontario in 2010 [14]. Also, 400,000 Mg yr⁻¹ of leaf and yard waste has been estimated from Ontario residential collection [15], and approximately 450,000 Mg of oily food waste is produced annually in Ontario [16,17]. Considering that the estimated total production of broccoli, cabbage, and cauliflower in Ontario was on 4147 and 4247 ha⁻¹ in 2010 and 2011 [18], respectively, there is potential for incorporating the organic C waste materials as amendments for N management after cole crop production.

Research has demonstrated that SMN concentrations may be reduced via N immobilization by the applications of wheat straw [19–21], yard waste [22–24], and oily food waste [16,25,26]. In the aforementioned studies, immobilized N was derived from fertilizers or indigenous SMN. The synchrony of cole crop and organic C material decomposition is crucial for the immobilization of N derived from crop residue. In an incubation study, N derived from broccoli crop residue was immobilized by the addition of wheat straw, yard waste, and used cooking oil [11]. The rapid decomposition and synchrony of the crop residue N mineralization rate relative to the organic C amendment (OCA) decomposition suggested promise for field application [11].

Even though a reduced potential for N losses may result if the period of N immobilization coincides with periods of high risk for N losses in the field, it is necessary to assess potential effects of OCA on the subsequent crop. Early- rather than late-season N fertilizer input is recommended to achieve a desired yield goal for spring wheat (*Triticum durum* L.) production [27]. Therefore, if N immobilization due to the OCA after cole crop harvest is not followed by re-mineralization early enough in the spring wheat growing season, a negative effect on spring wheat yield could result. Conversely, if N mineralization is synchronous with spring wheat N demand, then N use efficiency may be enhanced.

A pattern of N immobilization followed by re-mineralization has been found in previous laboratory [11] and field [26] research after the OCA of used cooking oil. However, other researchers did not observe re-mineralization in the subsequent spring after autumn incorporation of cereal straw or green compost with cauliflower crop residue [12]. Research has found corn, lettuce, or leek production to be unaffected by the previous autumns' application of oily food waste [16], cereal straw or waste compost [12], respectively. Thus, it may be possible to reduce potential N losses during periods of high risk for N losses by applying an OCA, without negatively affecting the subsequent crop.

In addition to the environmental impacts of N management practices, consideration must be given to the economic impacts. Some studies have found a trade-off to exist between environmental and economic benefits because practices that reduced N losses did not have favorable economic outcomes in vegetable production [28,29]. Other studies have found an overlap for the optimal environmental and economic outcomes [30,31]. Thus, ambiguity exists in the literature with respect to the economic impacts associated with management practices for reducing N losses. Regardless, the economic implications of proposing a better management practice to minimize N losses should be evaluated.

Therefore, the objective of this field study was to evaluate the effects of three different OCAs of wheat straw (OCA-straw), yard waste (OCA-yard), and used cooking oil (OCA-oil) on N dynamics,

spring wheat production, and profit margins following broccoli harvest, compared to typical grower practices. This research could lead to the development of better N management practices, leading to more sustainable cole crop production by minimizing environmental N contamination.

2. Materials and Methods

The field sites at Ridgetown Campus in 2009–2010 and 2010–2011 were on a Brookston clay loam (Orthic Humic Gleysol) soil, with textures of loam and sandy-clay-loam, respectively (Table 1). The soil characteristics evaluated (Table 1) included pH (1:1 v/v method), organic matter (modified Walkley Black method), N (KCl extraction and colorimetric analysis method), P (Olsen bicarbonate extraction method), Ca, K, Mg (atomic absorption via ammonium acetate extraction), cation exchange capacity (CEC) (estimated based on ammonium acetate extraction and pH), and soil texture (hydrometer method) [32].

Table 1. Initial soil characteristics of the experimental sites prior to broccoli transplanting in 2009 and 2010.

Characteristics (soil sample depth 15 cm)	2009	2010
pH	6.1	5.6
Soil texture	Loam	Sandy Clay Loam
Sand:Silt:Clay (%)	46:28:26	58:18:24
OM (Mg ha ⁻¹)	55	80
CEC (cmol kg ⁻¹)	15	23
Bulk density (g·cm ⁻³)	1.4	1.4
Pre-plant nutrients (mg·kg ⁻¹)		
N	5	41
P	34	37
K	108	87
Mg	153	149
Ca	2433	2430

Broccoli (c.v. “Ironman”) was grown in two systems: Early- and late-harvest, which was followed by spring wheat production in the subsequent year. The experimental design was a randomized complete block with four replications within the early- and late-broccoli systems. Nitrogen was uniformly hand-applied at the typical grower rate of 342 kg N ha⁻¹ as urea, and incorporated by disking before broccoli was mechanically transplanted on May 23 and 17 for the early system and June 23 and 23 for the late system in 2009 and 2010, respectively. Early- and late-broccoli systems were grown in the same field, but considered as separate research trials. Typical management practices were followed for pre-plant fertilization of macronutrients, plant spacing (75 cm between rows and 30 cm between plants), insecticide application (Lambda-Cyhalothrin (13.1%) 19 mL ha⁻¹), and drip irrigation, as required. Temperature and precipitation data were obtained by the on-site weather station (Table 2).

Table 2. Monthly total precipitation and mean temperature and the 30-yr mean at Ridgetown, ON, Canada, during 2009–2011.

	Total precipitation (mm)				Mean temperature (°C)			
	2009	2010	2011	30 yr mean	2009	2010	2011	30 yr mean
January	147	227	61	61	−10.1	−5.5	−7.5	−3.7
February	106	98	137	54	−3.8	−4.8	−6.1	−2.4
March	106	67	88	60	1.1	3.4	−0.3	2
April	152	63	134	78	7.8	9.8	6.6	8.3
May	49	114	153	75	13.0	14.4	14.0	14.8
June	65	97	75	83	17.3	19.3	18.8	20.2
July	31	121	70	86	18.5	22.6	23.5	22.5
August	92	19	70	86	19.6	21.2	20.5	21.4
September	36	80	135	93	16.1	16.2	16.5	17.6
October	70	78	79	69	8.6	10.8	10.4	11.2
November	30	92	140	75	6.2	4.2	6.9	4.8
December	138	45	86	67	−2.5	−4.8	1.6	−1.2
Total	1022	1101	1228	887				

The early-broccoli system was harvested on August 4 and August 3, while the late-broccoli system was harvested on August 31 and September 20, in 2009 and 2010, respectively. Heads were hand harvested from the entire trial, and broccoli yield was estimated by recording head counts and weights in a 3 m harvest row from three random plots per replicate. Broccoli leaf, stem, and head samples were collected from a composite of three plants in each of three random plots per replicate for dry matter and N content determination.

Treatments were applied 1 to 2 d after harvest with plots 9 m long by 3 m wide. The control treatment representing the typical grower practice was the incorporation of broccoli crop residue (CR-control), and was established by mechanically mulching then disking the broccoli crop residue. The crop residue removal (CR-removal) treatment was established by hand-removing all the above-ground biomass from the plots prior to disking. An oat (*Avena sativa* L.) cover crop (CC-oat) was established by drilling seeds at a rate of 108 kg ha^{−1} after the broccoli residue was mulched and incorporated. The OCA treatments were established by uniformly hand-applying either wheat straw (OCA-straw, C:N ratio ≈ 65:1), yard waste (OCA-yard, C:N ratio ≈ 56:1), or used cooking oil (OCA-oil, C:N ratio > 1000:1), at a fresh rate of 5 Mg ha^{−1} onto mulched broccoli crop residue (C:N ratio ≈ 11:1), followed by disking. In addition to samples at broccoli harvest, post-harvest soil samples in autumn were taken for mineral N analysis from a composite of four soil cores per plot at depths of 0–30 and 30–60 cm on August 21, September 18, and October 22 for the early system in 2009, on August 20, September 1, September 22, and October 25 for the early system in 2010, on October 26 for the late system in 2009, and on October 6 and October 25 for the late system in 2010.

In the subsequent growing season, the entire trial area was cultivated and spring wheat seed was drilled at 154 kg ha^{−1}, without N fertilization. A broccoli residue incorporated treatment with pre-plant urea applied at 103 kg N ha^{−1} (CRN-control) was also established as the treatment representing the typical grower practice. Usual management practices were followed for spring wheat production [33]. Grain was mechanically harvested from the center area of 6 by 1 m, and grain and straw were collected

to assess the above-ground plant biomass (grain + straw) and grain yield (Mg ha^{-1}), N content (kg N ha^{-1}), and N harvest index (%). Harvest occurred on August 3, 2010 and August 23, 2011. Soil was sampled, as described above, for mineral N analysis from depths of 0–30, 30–60, and 60–90 cm at spring wheat planting and harvest.

2.1. Nitrogen Measurements

Plant N content (broccoli and spring wheat) was determined by dry combustion method [34] using a LECO CN analyzer (Leco Corporation, St. Joseph, MI, USA), following grinding with a 2 mm diameter mesh screen opening on a Wiley Mill (Thomas Scientific, Swedesboro, NJ, USA). Soil NO_3^- -N and NH_4^+ -N concentrations were quantified by the KCl extraction method [35]. Briefly, 5 g of soil was extracted with 25 mL of 2 M KCl, shaken for 30 min, filtered and analyzed colorimetrically on an AutoAnalyzer3 (SEAL Analytical Inc., Mequon, WI, USA) with high resolution digital colorimeter to quantify NH_4^+ -N (method G-102) and NO_3^- -N (method G-200). Soil mineral N was the sum of NO_3^- -N and NH_4^+ -N and expressed as kg N ha^{-1} based on soil bulk density.

2.2. Economic Analysis

The economic analysis was conducted through a comparison of spring wheat profit margins for each treatment. Profit margins were calculated by subtracting costs that varied across post-harvest treatments from revenues. Revenues were calculated based on spring wheat yields from each treatment and the average spring wheat price in Ontario between 2010 and 2011, as reported by the Ontario Ministry of Agriculture Food and Rural Affairs [36]. Costs that varied included those associated with mulching residue (all treatments except the CR-removal treatment), residue removal, pre-plant N fertilizer for spring wheat crop, seeding cover crop, and applying the OCA as listed in the OMAFRA's Custom Rate Survey [37]. Costs associated with the OCA included transportation and application as well as baling wheat straw. Some assumptions were made regarding the equipment and the associated rates that would be used to conduct the required activities on a large field scale. For example, application costs were based on the rates for manure spreading, while transportation costs were based on trucking rates for wheat straw, yard waste, used cooking oil, and spring wheat grain [37]. In addition, the CR-removal method costs were based on custom rates for forage harvesting [37]. Other costs which factored into the profit margin calculation included the fertilizer cost, which was based on the average spring price reported in surveys of retail outlets across Ontario between 2009 and 2011 [38] and the oat seed cost, which was based on prices provided by seed retailers in southern Ontario. All other costs were assumed to be constant across treatments; thus, they were not accounted for in the profit margin calculation.

2.3. Statistical Analysis

Because the analyses of variance (with fixed effects of treatment, system, year, and respective interactions, and a random effect of block (system)) found significant year x system effects ($P < 0.05$) in datasets for SMN in autumn, spring, and spring wheat harvest, a separate analysis of variance for each year and each early- or late-harvested system was necessary (with a fixed effect of treatment and a random effect of block). Other than the late-broccoli-system in 2009 (which had only one sample date),

the autumn SMN repeated measures had no treatment by sample day effect ($P > 0.05$) in each system in each year, thus the average of each repeated measurement was investigated. A multiple means comparison to the CR-control and CRN-control (typical practices) with a Dunnett-Hsu adjustment was applied to each dataset. All significant differences were set at $P < 0.05$.

3. Results and Discussion

3.1. Broccoli Harvest

Broccoli yields varied by system and year, but not by system $\times$ year. The early-broccoli system had fresh yields of 22.2 and 22.9 Mg ha⁻¹ and late-broccoli yielded 25.0 and 36.2 Mg ha⁻¹, in 2009 and 2010, respectively. Similar yields, 16 to 35 Mg ha⁻¹, have been reported in the literature [2,6–9]. The lower yield in the early-broccoli compared to the late-broccoli system agrees with previous research, which also found lower total and head plant mass in summer harvested broccoli compared to autumn harvest [39], likely due to different environmental conditions during the broccoli growth periods. The crop residue (leaves + stems) fresh weight ranged from 50 to 75 Mg ha⁻¹, similar to broccoli and cauliflower crop residue rates in earlier studies [11,12]. The early-broccoli crop residue contained 202 and 247 kg N ha⁻¹, while the late-system residue had 212 and 207 kg N ha⁻¹, in 2009 and 2010, respectively. Similarly, previous research observed above-ground broccoli N accumulation of 96 to 465 kg N ha⁻¹, with fertilizer N application rates up to 500 kg N ha⁻¹ [1,2,4,6,40].

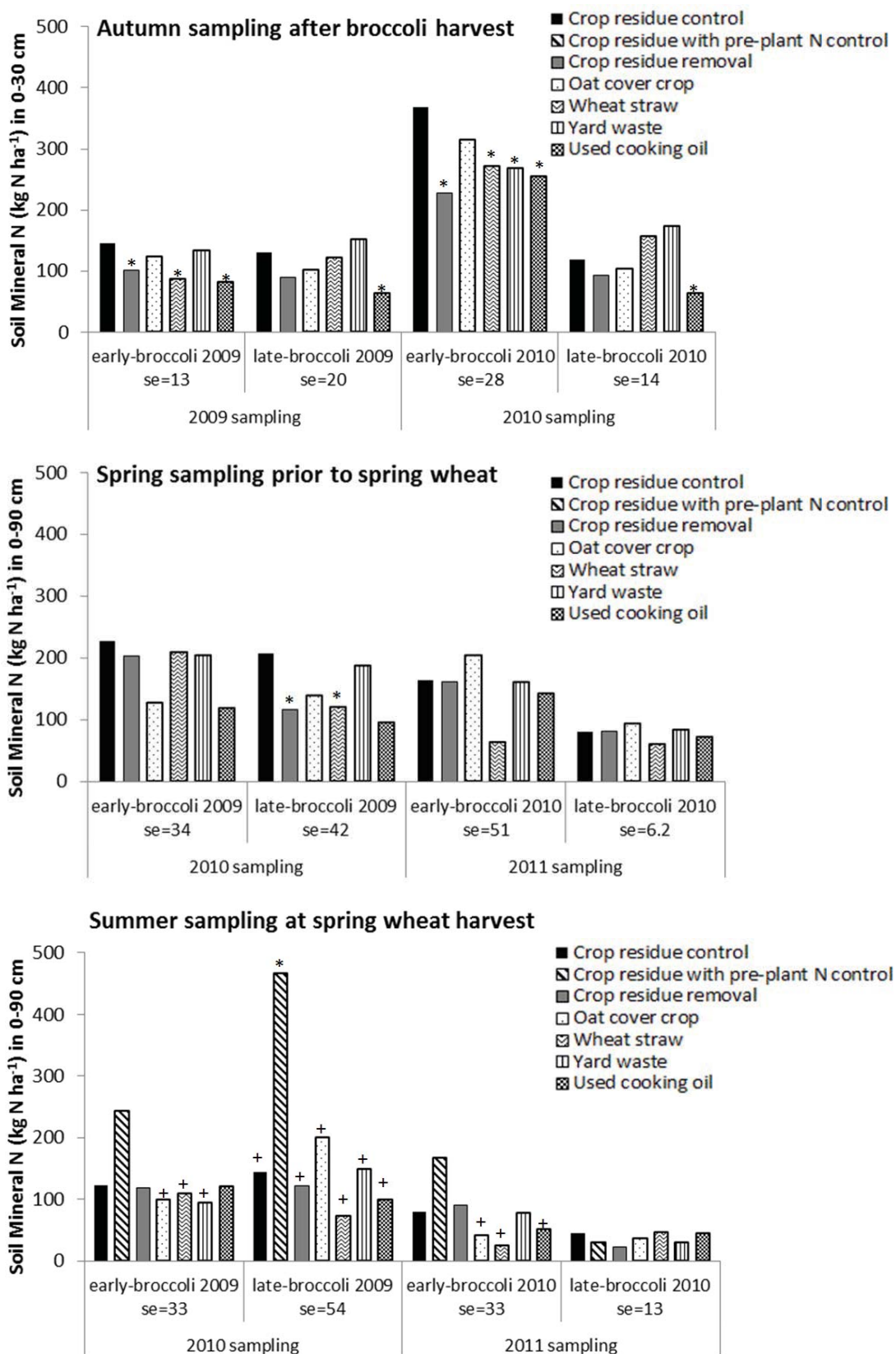
At broccoli harvest, 0–30 cm SMN ranged from 68 to 168 kg N ha⁻¹, yet greater quantities of N (207 to 247 kg N ha⁻¹) were in the broccoli crop residue. Thus, between 265 to 415 kg N ha⁻¹ remained in the field after harvest, which was consistent with other research [1,6]. Clearly, strategies that minimize N losses during the post-harvest season would be valuable.

3.2. Soil Mineral Nitrogen in Autumn

Soil mineral N data were investigated, because both NO₃⁻-N and NH₄⁺-N are susceptible to losses. The treatment effect on soil N was similar for NO₃⁻-N and SMN concentrations, but the soil NH₄⁺-N was largely unaffected by treatment. Thus, the SMN results were presented. The 0–30 and the 30–60 cm depths were analyzed separately for the autumn dataset to assess the downward movement and leaching potential of SMN in autumn. The year variation in autumn SMN between 2009 and 2010 could be a residual N effect attributed to the type of crop grown the year prior to broccoli production, which was corn and soybean, respectively. Additionally, the higher autumn SMN variation in the early- compared to the late-broccoli systems may be due to higher temperatures during the early autumn (August to November) which may have permitted more decomposition and resulted in a greater N mineralization, compared to cooler temperatures after the late-broccoli system (September to November).

In the CR-control, autumn 0–30 cm SMN concentration ranged from 118 to 368 kg N ha⁻¹ (Figure 1) and SMN was affected by treatment. After the early-broccoli system and relative to the CR-control, the 0–30 cm SMN concentrations were reduced by the OCA treatments of OCA-straw in 2009 and 2010, OCA-yard in 2010 but not in 2009, and OCA-oil in 2009 and 2010 (Figure 1).

Figure 1. Soil mineral N concentrations in the autumn, spring, and summer after the 2009 and 2010 early- and late-broccoli harvest treatments. Symbols denote a significant difference ($P < 0.05$) compared to the crop residue control * or the crop residue with pre-plant N control +, based on a multiple means comparison with a Dunnett-Hsu adjustment. The se values represent the standard error of the mean.



After the late-broccoli system, the only treatment which reduced SMN compared to the CR-control was the OCA-oil in both 2009 and 2010 (Figure 1). The CC-oat treatment did not have different 0–30 cm SMN concentrations compared to the CR-control (Figure 1). The CR-removal reduced the 0–30 SMN levels relative to the control in the autumn after early-broccoli system, but not after the late-system in both years (Figure 1). No treatment differences were found in the 30–60 cm depth (data not shown), with SMN concentrations ranging from 17 to 51 kg N ha⁻¹ in the CR-control.

Due to the lack of effect on SMN by the CC-oat compared to the CR-control (Figure 1, Table 3), it is suggested that oat cover crops may not reduce the potential for N losses after broccoli harvest. Conversely, the establishment of an oat cover crop after green pea production reduced autumn SMN concentrations in southwestern Ontario [41]. It is possible that the CC-oat had low N uptake compared to the plant available N in the soil after broccoli harvest, considering that 94 to 210 kg N ha⁻¹ remained as available N at green pea harvest [41] while 265 to 415 kg N ha⁻¹ remained at broccoli harvest.

Despite the removal of the N rich crop residue (CR-removal), the 0–30 cm SMN concentrations were only reduced in the autumn after the early-broccoli and not after the late-broccoli system (Figure 1). The difference in CR-removal effect between systems was likely a reflection of the cooler temperatures and slower N mineralization of the crop residue in the late-system. Regardless, high autumn SMN concentrations (89 to 227 kg N ha⁻¹) remained in the field in the CR-removal treatment (Figure 1). It is therefore suggested that the soil and/or below-ground crop residue provided substantial quantities of N during the post-harvest period. Thus, best management practices that minimize N losses after broccoli production would be beneficial.

Nitrogen immobilization is related to the biochemical composition of the decomposing substrate, and is positively associated with a high C:N ratio, lignin, and polyphenol content [42]. Incorporation of easily decomposable, high C:N ratio materials generally causes a rapid increase in microbial biomass and consequently SMN depletion as N is assimilated into microbial cells. Soil amendments such as yard waste, wheat straw, and used cooking oil/oily food waste have previously demonstrated N immobilization [11,19,23,25,26].

The OCA-yard reduced SMN compared to the CR-control only after the early-broccoli system in 2010 (Figure 1). The 2009 yard waste was composed of notably larger particles than that of 2010, thus it is possible that C decomposition took longer in 2009 and had less influence on microbial N immobilization. More recalcitrant substrates, such as the lignin-containing wood pieces of the OCA-yard, can have more limited decomposition at low temperatures than that of easily decomposed and more labile material [43]. It is likely that C decomposition of the OCA-yard was generally low, and consequently little microbial N immobilization occurred. Perhaps if the OCA-yard material was finely chopped, greater decomposition may occur. As opposed to the present study, previous laboratory research showed N immobilization by incorporating yard waste with broccoli crop residue [11], and field research has found that green waste compost mixed with cauliflower crop residue immobilized approximately 42 kg N ha⁻¹ within the first month after incorporation [12]. Yet, in agreement with the present study, green waste composts have not resulted in N immobilization during autumn after the incorporation with cauliflower or leek residues in a two-year study [44]. Thus, the composition and substrate size of OCA-yard greatly influences N immobilization and its applicability as a better management practice for minimizing N losses in the autumn after broccoli harvest.

Although OCA-straw reduced SMN after the early-broccoli system, it must be noted that some wheat seed germinated and established a cover crop during both years. Thus, the reduction in autumn SMN may be a reflection of cover crop N uptake as well as microbial N assimilation. Conversely, it appeared that the OCA-straw treatment after the late-broccoli system did not sufficiently lower SMN, compared to the CR-control, to reduce the potential for soil N losses in the autumn. The difference in effect between systems was likely due to cooler temperatures and slower decomposition (or cover crop uptake) after late-broccoli. In comparison to previous laboratory research, it was demonstrated that wheat straw incorporated with broccoli crop residue could significantly lower SMN via N immobilization, (relative to incorporating crop residue alone) after 8 weeks of incubation [11]. Previously, cereal straw immobilized 35 kg N ha⁻¹ within the first month after incorporation with cauliflower crop residues in the field [12]. It has been estimated that straw incorporation can result in the net N immobilization of 64 kg N ha⁻¹ after two months [45], or 39 to 44 kg N ha⁻¹ after one year [20], and reduce the amount of NO₃⁻-N leached by 27% after a year [45]. The current study has suggested that the OCA-straw treatment after the early-broccoli system can reduce SMN concentrations by 57 to 96 kg N ha⁻¹, which could otherwise be lost during autumn.

The OCA-oil treatment appeared to result in consistent N immobilization after both early- or late-broccoli systems (Figure 1). Compared to the typical grower practice (CR-control), the OCA-oil treatment had 53 to 112 kg ha⁻¹ less SMN, thus 30% to 50% less SMN could be available for losses from the top 30 cm soil layer during the autumn after broccoli harvest. This finding was consistent with previous field research, which found that oily food waste application in autumn reduced soil NO₃⁻-N by immobilization and lowered the potential for N losses by 47 to 56 kg N ha⁻¹ in the top 60 cm of soil [26]. Furthermore, a previous laboratory study suggested that OCA-oil immobilized more SMN than OCA-straw or OCA-yard, when incorporated with broccoli crop residue [11]. The rate of used cooking oil decomposition was synchronous with that of broccoli crop residue, whereas yard waste or wheat straw decomposed slower than broccoli crop residue or used cooking oil [11]. Because decomposition of more recalcitrant substances is more limited at low temperatures than that of easily decomposed material [43], the OCA-oil is likely the most promising material to reduce the potential for soil N losses due to its readily decomposable and labile matter. Thus, OCA-oil may be the most suitable amendment tested, because broccoli can be harvested anytime from early August to late October in southern Ontario.

3.3. Soil Mineral Nitrogen in the Subsequent Spring and Summer

The 0–90 cm profile was investigated to assess the quantity of SMN in the soil depth accessible for the crop, at spring wheat pre-plant and harvest. Prior to spring wheat planting, the SMN concentrations were generally not affected by the post-broccoli-treatments (Figure 1). Because the 2011 spring had a one and a half times higher precipitation (512 mm from February to May) compared to 2010 (343 mm from February to May), it is possible that SMN was subjected to different mechanisms of concentration reduction depending on the year. In the CR-control, NO₃⁻-N leaching may have occurred to a greater extent in 2011, thereby lowering spring SMN concentrations. Although NO₃⁻-N leaching could have also occurred in the OCA treatments, the amendments may have immobilized N in the spring, also lowering SMN concentrations. Additionally, the condition of high soil water content combined with the presence of a readily decomposable C source and SMN, denitrification could have been favored. Given

the possibility of different mechanisms of SMN concentration reduction across treatments, further investigation is required. Future research should focus on ^{15}N labeled crop residue to investigate the influence of the OCA treatments on the fate of the crop residue-derived N.

At spring wheat harvest, 0–90 cm SMN results indicated that the post-broccoli-harvest treatments did not lower SMN, compared to the CR-control (Figure 1). However, the application of N fertilizer at spring wheat pre-plant (CRN-control) left a larger quantity of SMN at harvest compared to most other treatments (Figure 1).

3.4. Spring Wheat Production

Overall, the 2011 spring wheat grain contained 49 kg N ha^{-1} less N and had 1.6 Mg ha^{-1} less yield than 2010 (Figures 2 and 3). Early- and late-broccoli systems did not have different spring wheat yield or N contents. The yield ranged from 0.9 to 3.4 Mg ha^{-1} (Figure 3), similar to the average Ontario spring wheat yields of 3.5 Mg ha^{-1} in 2010 and 2011 [46]. The N harvest indices ranged from 55% to 90%, and did not vary by treatment (data not shown).

It must be noted that spring wheat plant N content, grain N content, plant biomass, or grain yield were never different between the CRN-control and the CR-control (Figures 2 and 3). It therefore appears that sufficient soil N was available for crop production subsequent to broccoli crop residue incorporation, regardless of pre-plant fertilizer application for spring wheat. Thus, growers may be able to reduce N fertilizer applications to spring wheat planting, following broccoli production because the mineralization of crop residue may provide sufficient SMN.

Relative to the CR-control, the treatments which indicated a detrimental effect on spring wheat production were the OCA-straw and CC-oat, based on a lower spring wheat plant N content, grain N content, plant biomass, and grain yield, compared to the CR-control or CRN-control (Figures 2 and 3). Also, the CR-removal treatment indicated a reduction in spring wheat plant biomass and grain yield compared to the CR-control or CRN-control in 2010 (Figures 2 and 3). Conversely, the OCA-yard and OCA-oil treatments did not have different plant N content, grain N content, plant biomass, and grain yield, compared to the CR-control or CRN-control (Figures 2 and 3). Therefore, it appears that the OCA-yard or OCA-oil treatments after broccoli harvest did not negatively impact the subsequent spring wheat production, but the OCA-straw, CC-oat, and CC-removal treatments resulted in spring wheat yield penalties.

It is possible that N supply was sufficient for spring wheat production in the CR-control, CRN-control, OCA-yard, and OCA-oil treatments. To optimize N use efficiency, early-season N availability has been recommended to achieve a desired spring wheat yield goal, rather than late-season N availability [27]. If early-season SMN levels were limiting for plant production, decreased vegetative dry matter accumulation and grain yield may occur [27]. Thus, the rate and timing of OCA and its decomposition is crucial for determining N dynamics. The grain yield results suggested that N supply was sufficient for the spring wheat growing season after the OCA-yard and OCA-oil, but perhaps not the OCA-straw (Figure 3). Likewise, the CC-oat and CR-removal treatments may not have had sufficient available N (Figure 3). Thus, N fertilizer applications may be required to maintain the spring wheat yield after OCA-straw, CC-oat, and CR-removal practices.

Figure 2. The N content (kg N ha^{-1}) of spring wheat plant biomass (grain + straw) and grain in 2010 and 2011, as affected by the previous years' treatments in the early- and late-broccoli systems. Symbols denote a significant difference ($P < 0.05$) compared to the crop residue control * or the crop residue with pre-plant N control +, based on a multiple means comparison with a Dunnett-Hsu adjustment. The se values represent the standard error of the mean.

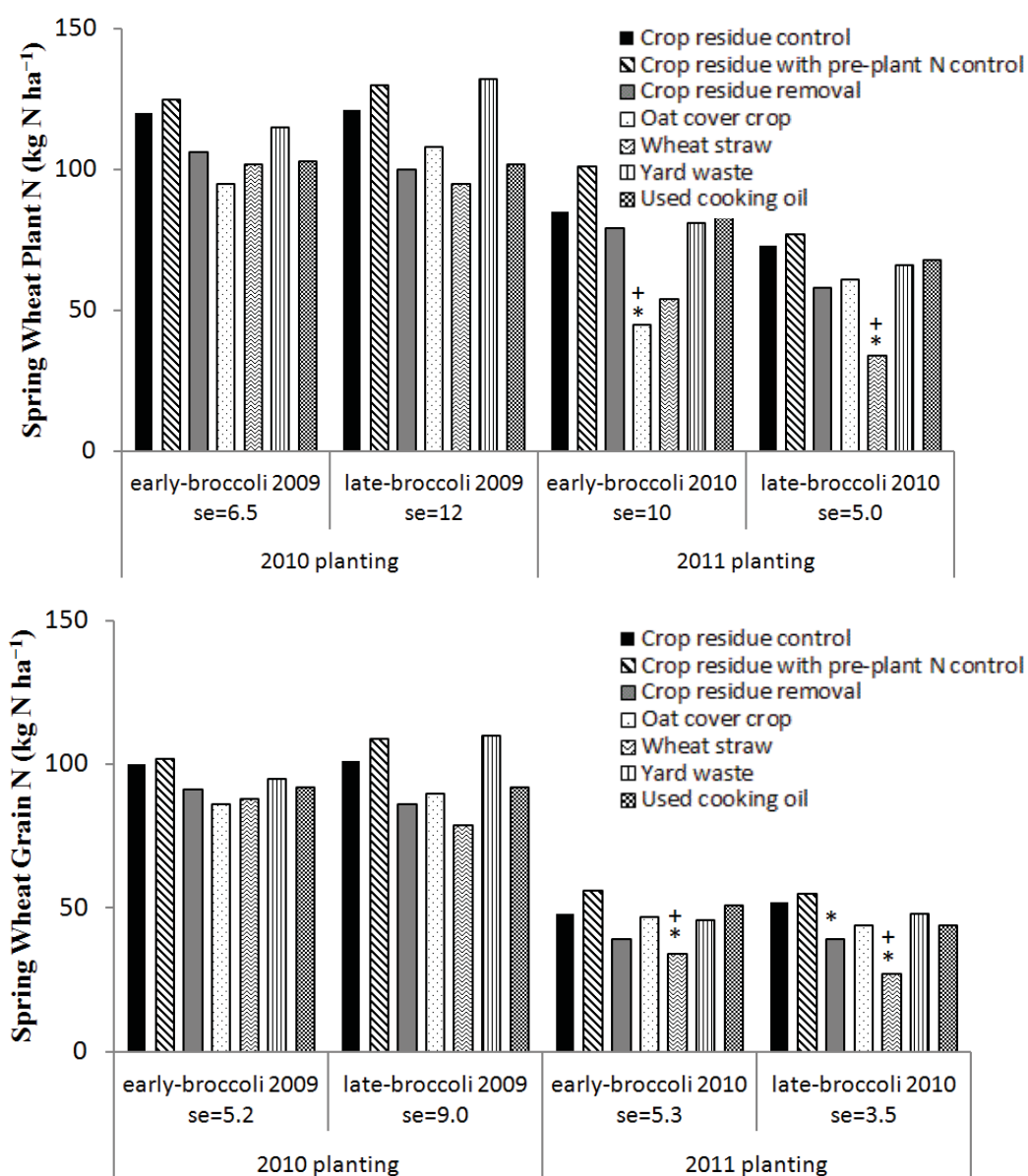
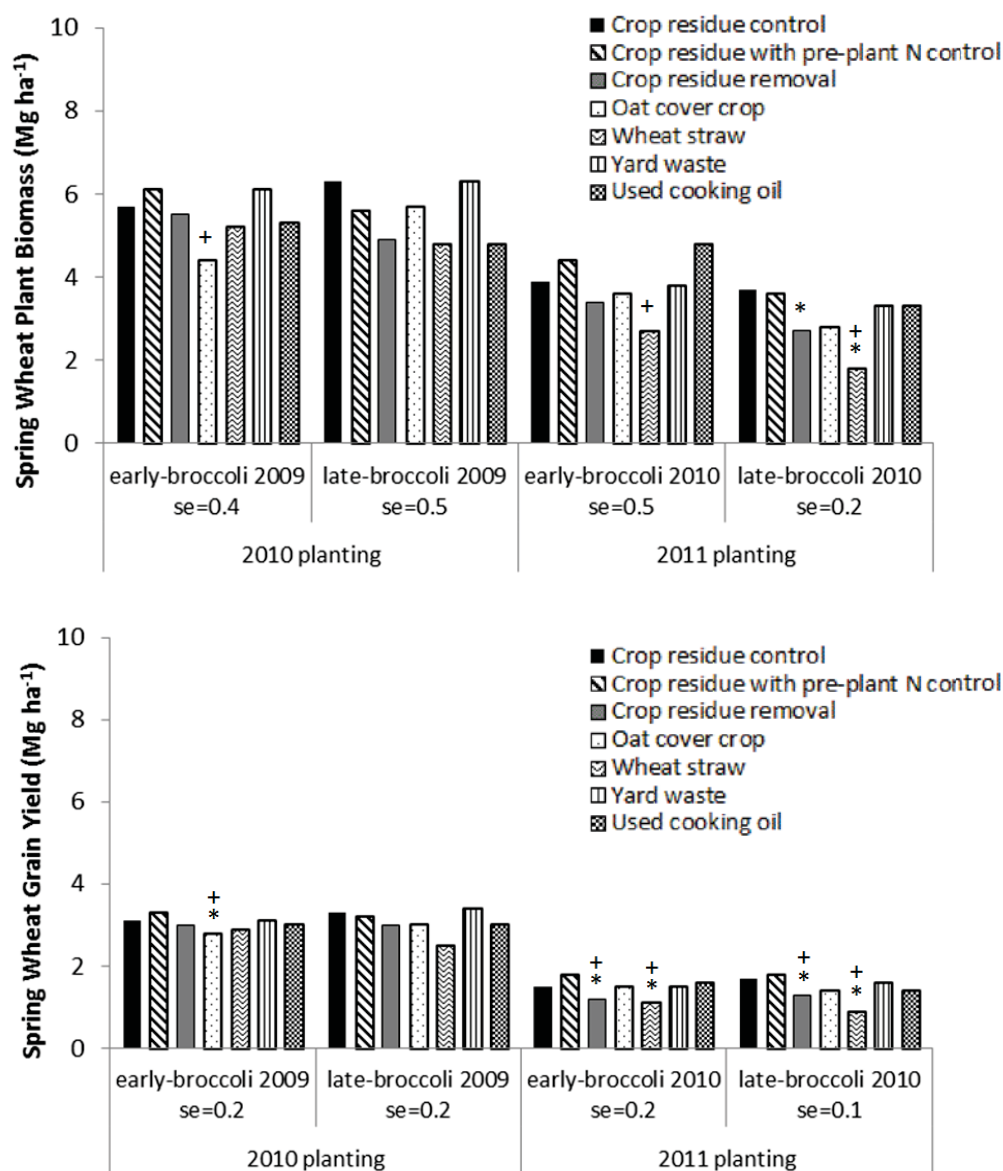


Figure 3. The spring wheat plant biomass (grain + straw) and grain yield (Mg ha^{-1}) in 2010 and 2011, as affected by the previous years' treatments in the early- and late-broccoli systems. Symbols denote a significant difference ($P < 0.05$) compared to the crop residue control * or the crop residue with pre-plant N control +, based on a multiple means comparison with a Dunnett-Hsu adjustment. The se values represent the standard error of the mean.



The lower spring wheat grain yield compared to the CR- or CRN-control in 2011 after the OCA-straw or CC-oat treatment (Figure 3) may have been an allelopathic result, because straw mulch often reduces subsequent wheat yields [47]. Considering that wheat seed in the OCA-straw treatment germinated and established a cover crop after broccoli harvest, the continuous cereal cropping from autumn to the subsequent summer may have accumulated phytotoxins or pathogens in the soil [47], which lowered the grain yield in 2011. Variation in environmental conditions between years likely contributed to the severity of phytotoxic or pathogenic factors. It is also possible that plant available N concentrations were

not sufficient for optimal spring wheat yield in the OCA-straw and CC-oat treatments. In a previous study, which incorporated cereal straw with cauliflower crop residues, a pattern of autumn N immobilization was followed by N re-mineralization in the following spring [12]. However, a different study found no apparent re-mineralization even one year after straw incorporation in the field [20].

The lack of effect on spring wheat harvest parameters from the OCA-yard treatment (Figures 2 and 3) may be related to the limited effect on SMN after broccoli harvest in autumn (Figure 1). Similarly, limited autumn N immobilization and no consistent N re-mineralization were found following the autumn incorporation of green waste compost or sawdust with cauliflower or leek crop residues [12,44]. It was suggested that rye, leek, or lettuce production may not be negatively affected following autumn cauliflower crop residue incorporation with compost or straw amendment because plant N uptake or dry matter accumulation were generally similar between amendment and crop residue alone treatments [12], which was similar to the present OCA-yard results.

Considering that autumn N immobilization occurred in the OCA-oil treatment (Figure 1), yet spring wheat harvest parameters were generally not affected (Figures 2 and 3), it is possible that N losses may be reduced during a period of high risk for losses, without negatively affecting the subsequent crop. It is therefore suggested that the OCA-oil after broccoli harvest may be a better N management practice than the typical practice of the CR- or CRN-control. Although N was immobilized during the autumn after broccoli harvest, it appeared that OCA-oil did not conserve more N in the soil compared to the CR-control for subsequent spring wheat use (Figure 1). A reason may be that little or no NO_3^- -N leaching occurred in the CR-control treatment; the soil textures with 24% to 25% clay (loam or sandy clay loam) (Table 1) would support a slower rate of NO_3^- -N leaching than sandier soils. Alternatively, the soil may have provided substantial quantities of plant available N regardless of the treatment, as suggested earlier. Thus, future experiments should investigate the fate of broccoli crop residue-derived N as influenced by the used cooking oil in N limited soil, sandy soil, or trace the crop residue-derived N into the subsequent crop via ^{15}N studies.

A pattern of N immobilization followed by re-mineralization with used cooking oil or “fat oil grease” amendments has been found in previous laboratory [11] and field [26] research. In the present study, N immobilized in the OCA-oil after broccoli harvest in autumn could have re-mineralized for the subsequent spring wheat plant uptake. Net N mineralization has also been observed in the spring following an autumn application of oily food waste [26]. Previous research has found corn yields to be similar between un-amended treatments and autumn amendments of “fat oil grease” [16]. Based on the maximum economic rate of N applied to the corn crop, it was found that N availability to corn was not affected by autumn application of “fat oil grease” [16]. The authors suggested that sufficient time was probably available for decomposition of the C material when it was applied in autumn [16]. Also, researchers have found little concern for detrimental accumulations of oily food waste and observed that the waste can promote water stable aggregation [25]. However, the spring application of “fat oil grease” prior to corn production resulted in net N immobilization during the spring [26], reduced corn yields up to 23%, and the additional requirement of 60 kg N ha^{-1} to offset corn yield declines [16]. Thus, “fat oil grease” or OCA-oil applied in the autumn did affect the following corn yield [26] or spring wheat yield.

3.5. Economic Analysis

The potential environmental benefit of reduced N losses must be considered in combination with economic outcomes. Although the OCA-straw and CR-removal treatments showed some potential for reducing autumn N losses after early-broccoli systems (Figure 1), it not only resulted in reduced spring wheat production parameters (Figures 2 and 3), but also reduced spring wheat profit margins (Table 3), relative to the CR- or CRN-control. Even without detrimental effects on spring wheat production parameters, the OCA-oil treatment reduced profit margins compared to the CR- or CRN-control (Figures 2 and 3, Table 3). However, of all the treatments which demonstrated a potential for reduced autumn N losses, (after early-broccoli by OCA-wheat, CR-removal treatments, or after both early- and late-broccoli by the OCA-oil), the OCA-oil treatment may be the least likely to lower spring wheat profit margins compared to CRN-control (Table 3). Furthermore, the economic results suggest that pre-plant application of N fertilizer for spring wheat was not necessary due to the similar profit margins between the CR-control and CRN-control (Table 3).

Table 3. The effect of post-broccoli-harvest treatments on 2010 and 2011 spring wheat profit margins (\$ ha⁻¹) subsequent to the 2009 and 2010 early- and late-harvested broccoli.

Post-broccoli-harvest treatment	Broccoli production system			
	2009		2010	
	early-broccoli	late-broccoli	early-broccoli	late-broccoli
	Spring wheat profit margins (\$ ha ⁻¹)			
	2010		2011	
Crop residue control	586	617	263	306
Crop residue with pre-plant N control	527	511	228	229
Crop residue removal	429 *,+	422 *	75 *,+	84 *,+
Oat cover crop	394 *,+	440 *	144 *,+	131 *,+
Wheat straw	434 *,+	352 *,+	70 *,+	24 *,+
Yard waste	515	579	205	228
Used cooking oil	508 *	506	235	197 *
Standard error of mean (se)	31.7	39.5	34.2	25.1

Symbols denote a significant difference ($P < 0.05$) compared to the crop residue control * or to the crop residue with pre-plant N control +, based on a multiple means comparison with a Dunnett-Hsu adjustment.

It has previously been indicated that trade-offs exist between environmental and economic benefits, because practices which reduced NO₃⁻-N losses caused lower economic returns [28]. Also, vegetable production practices, which reduced NO₃⁻-N leaching, did not always coincide with those that generated optimal economic outcomes [29]. Although a prior study on “fat oil grease” amendments did not specifically determine the economic impact [16], the impact can be estimated based on the observed effects on the following corn yield and N requirements. The reported mean control plot yields [16] and the average Ontario prices in 1996 and 1997 for corn and urea [48] suggested that the use of “fat oil grease” reduced the revenue by as much as \$290 ha⁻¹ and increased the input costs by about \$52 ha⁻¹. The reduced profit margins of autumn applied OCA in corn was similar to the present study in a broccoli-spring wheat rotation. Thus, best management practices that have environmental benefit may also have an economic cost for growers.

4. Conclusions

Better N management practices are necessary after cole crop production due to the high SMN concentration and the risk for N losses in the post-harvest season. Although the OCA-straw demonstrated reduced autumn SMN concentrations after the early-broccoli system, it is not recommended if spring wheat is the following crop due to yield reductions. Also, the OCA-yard showed inconsistent potential for reduced autumn soil N losses. However, the practice of OCA-oil is recommended due to the reduced potential for autumn N losses via N immobilization after both early- and late-broccoli systems, without the subsequent spring wheat yield being detrimentally affected. This field study was consistent with previous incubation research, which found that OCA-oil demonstrated the most promise for the potential reduction in soil N losses after broccoli harvest [11]. Despite the environmental benefits of potentially reduced N losses by OCA, economic costs were associated. Thus, growers must evaluate the environmental vs. economic benefits of OCA-oil compared to the typical practice.

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