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Evaluation of wood biochar and compost soil amendment on cabbage yield and quality

M.R. McDonald, C. Bakker, and M.R. Motior

Abstract: Biochar application on agricultural soils is an interesting emerging technology with promising potential for long-term carbon storage and the enhancement of soil fertility. The effect of a biochar compost mixture with and without standard NPK fertilizer was assessed to determine the effects on the growth of cabbage over 3 yr at two locations. Field trials were established at the Holland Marsh and Simcoe Research Station in Ontario. The main purpose of this study was to determine the effect of biochar soil amendment on cabbage yield and quality. Biochar (a blend of 1:1 composted duck manure and biochar based on dry weight) was applied at rates of 0.6 and 2.4 kg m^{-2} with and without standard NPK fertilizer and compared with compost at the rate of 1.2 kg m^{-2}, which was the rate applied with the high rate of biochar. The biochar used was somewhat alkaline (pH 8.1) and increased the pH (>0.5) of the top 0–15 cm of the soil. It also had a high cation-exchange capacity (CEC > 25) and contained elevated levels of some trace metals and exchangeable cations (K, Ca, and Mg) in comparison to the untreated soil. None of the biochar or compost treatments increased yield compared with the nonamended check at either location. Treatments that included the standard NPK fertilizer resulted in the highest yields.

Key words: biochar, cabbage, compost, NPK fertilizer, yield.

Résumé : L'application de biocharbon aux terres arables est une nouvelle technologie intéressante, très prometteuse pour ce qui est de stocker le carbone à long terme et de rehausser la fertilité du sol. Les auteurs ont évalué les effets d'un mélange de compost et de biocharbon, appliqué avec ou sans un engrais NPK ordinaire, sur la culture du chou. L'expérience, qui a duré trois ans, s'est déroulée à deux endroits, en l'occurrence à Holland Marsh et à la station de recherche de Simcoe, en Ontario. L'objectif principal consistait à préciser les conséquences d'un amendement à base de biocharbon sur le rendement et la qualité du chou. Le mélange (parts égales, selon le poids sec, de fumier de canard composté et de biocharbon) a été appliqué à raison de 0,6 ou de 2,4 kg par m^2, avec ou sans engrais NPK, puis comparé à l'application de 1,2 kg de compost par m^2 uniquement, soit une quantité identique à sa concentration dans le mélange de biocharbon, appliqué à un taux plus élevé. Le biocharbon employé était légèrement alcalin (pH 8,1) et a relevé le pH (> 0,5) des 15 premiers cm du sol. Il se caractérisait également par une forte capacité d'échange de cations (> 25) et renfermait une quantité appréciable de quelques métaux à l'état de traces et de cations échangeables (K, Ca et Mg), comparativement au sol non bonifié. Le biocharbon et le compost n'ont augmenté le rendement à aucun endroit, comparativement à la parcelle témoin non amendée. Le meilleur rendement a été relevé sur les parcelles fertilisées avec l'engrais NPK habituel. [Traduit par la Rédaction]

Mots-clés : biocharbon, chou, compost, engrais NPK, rendement.

Introduction

Biochar is a carbonaceous material that contains polycyclic aromatic hydrocarbons with an array of other functional groups (Schmidt and Noack 2000; Krull et al. 2009). Biochar is produced through the thermal decomposition of organic material at temperatures up to 700 °C and at low oxygen levels, known as pyrolysis (Rodrigues et al. 2009; Lehmann and Joseph 2009). The use of biochar as a soil amendment has been promoted in many regions. The incorporation of biochar can influence soil structure, texture, porosity, particle size distribution, and density, thereby potentially increasing the oxygen content of the soil air and the microbial and nutritional status of the soil within the plant rooting zone

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(Amonette and Joseph 2009), thus improving plant productivity. Biochar generally bears a negative charge and serves as a cation-exchange site in soils. In addition, biochar commonly has a remarkably high surface area, which results in a high cation-exchange capacity (CEC), and it physically sorbs a great variety of substances, including negatively charged plant nutrient forms such as phosphate and nitrate. The high surface area of biochar also enhances soil water-holding capacity, and its low density will generally reduce soil bulk density and so enhance soil aeration and root penetration (Verheijen et al. 2010; Sohi 2010; Jeffery et al. 2011; Haefele et al. 2011; Thomas 2013). The high affinity for nutrients and water can reduce onsite nutrient loss and offsite pollution from nutrient leaching (Lehmann et al. 2006). Biochar can enhance processes such as soil nitrification, with the added benefits of catalysing N_2O reduction, reducing GHG emissions (O'Neill et al. 2009).

Potential benefits of biochar in sandy soils include the addition of organic matter, nutrient retention and recycling, enhanced microbial activity, and long-term carbon sequestration (Nair and Lawson 2016). Sandy soils have a low moisture-holding capacity and low levels of biochar amendment can increase seedling resistance to wilting (Mulcahy et al. 2013) and water-holding capacity with the addition of only 5% biochar in the mass of top soil (Case et al. 2012).

While the potential agricultural influences of biochar use have been identified in tropical regions, the use of biochar in temperate regions, especially in the northern hemisphere, has not been studied in sufficient critical detail. The adoption and use of biochar by vegetable growers has been slow because information is lacking on how biochar will affect crop production on a long-term basis. Some previous research suggests that the greatest positive effect of biochar is seen at an application rate of 100 Mg ha^{-1} (Sokchea et al. 2013) and that biochar applications of up to 140 Mg ha^{-1} on weathered soils in the tropics resulted in improved crop yields relative to the control (Lehmann et al. 2006). Trials on oat found that compost application produced the highest yield during two growth periods, followed by the biochar plus compost mixture (Schulz and Glaser 2012). The yield was slightly lower during the second growth period compared with the first, but biochar plus mineral fertilizer significantly increased plant growth compared with mineral fertilizer alone. Adding biochar and compost significantly increased total organic C content during the two growth periods (Schulz and Glaser 2012). As most of the mineral matter in the biomass is composed of salts of K, Na, and Ca, it has a strong alkaline reaction, giving rise to a pH of between 8 and 10 (Rodrigues et al. 2009). This increase in pH can increase alkaline metal (Mg^{2+}, Ca^{2+}, and K^{+}) oxides. This also reduces the soluble forms of Al, which may be the most important mechanism by which biochar affects P solubility (DeLuca et al. 2009). Nutrients are directly available through the solubilisation of ash in the solid biochar residue and other nutrients may become available through microbial utilization of a small labile carbon component of biochar (IRRI 1997). Thus, the application of biochar as a soil amendment is especially appropriate in acid soils with a low content of organic matter. The biochar may elevate levels of soil exchangeable K, Ca, Mg, and a few trace metals in comparison to levels of these elements without biochar amendments (Carter et al. 2013).

Biochar is unlikely to have a major role as a fertilizer, but, as described above, it can be expected to increase water-holding capacity and provide a good habitat for microbes, and hence, increase plant nutrient turnover (Asai et al. 2009). Biochar combined with fertilizer applications can lead to plant growth benefits (Chan et al. 2007; Saarnio et al. 2013), but a negative effect is sometimes observed without fertilization, due to the reduced bio-availability of plant nutrients through the sorption of nitrogen (Zavalloni et al. 2011; Case et al. 2012). Several studies have shown the positive effects of the combined use of mineral and organic fertilizers in fields that continuously received only N, P, and K without any micronutrients or organic fertilizer (Kaur et al. 2005; Chand et al. 2006). Biochar plus compost was found to increase soil fertility and plant-available water-holding capacity in an infertile sandy soil as compared with compost alone (Liu et al. 2012).

While biochar appears to have the greatest benefits for low fertility, low pH, and low organic matter soils in the tropics, there was interest in determining the potential to use biochar in commercial vegetable production in Ontario. Biochar could be available from several sources and might improve the retention of water and nutrients, leading to greater water-use efficiency and lower rates of fertilizer application. There has also been the suggestion that biochar use is advantageous in sequestering carbon in the soil. Thus, there could be long-term environmental benefits and benefits for growers. The two locations chosen for this study were in regions of intensive vegetable production with somewhat different climates and soils.

A wide range of rates of biochar have been studied, ranging from 5 to 50 t ha^{-1} (Major 2010). The median rate for biochar application in temperate countries was 30 t ha^{-1}, and in tropical countries, was 15 t ha^{-1}. Biochar should be applied near the soil surface in the root zone (Major 2010). To be most effective, biochar should be applied as a 1:1 mixture with compost (Fischer and Glaser 2012). The mixture should be allowed to charge for some weeks before it is applied to soil. A single application of biochar or biochar–compost mixture should show benefits for many years, but the benefits may not be seen in the first year of application. Biochar produced by slow pyrolysis is better than biochar from fast pyrolysis for application to the soil (G. Walsh, personal communication, York Region Environmental Alliance, Richmond Hill, ON).

Table 1. Physicochemical properties of compost, biochar, and organic (muck) and sandy loam soil at Holland Marsh (HM) and sandy loam soil at Simcoe Research Station (SRS), Ontario.

Material	Bulk density ($g\ cm^{-3}$)	CEC ($cmol + kg^{-1}$)	OM (% dry)	pH	Nitrate-N ($mg\ kg^{-1}$)	P ($mg\ L^{-1}$)[a]	Mg ($mg\ L^{-1}$)[a]	K ($mg\ L^{-1}$)[a]
Sandy loam[a]	1.2	10.5	2.1	7.4	2.3	36	70	98
Organic soil[a]	0.4	155.0	48.0	7.5	27.2	110	560	190
Sandy loam[b]	1.5	5.9	1.4	6.3	4.3	76	130	280
Compost	0.4	34.7	17.6	7.3	549.0	320	820	3500
Biochar (1:1 biochar–compost blend)	0.3	25.8	13.0	8.1	188.0	180	400	1600

Note: Chemical properties were assessed on dry soil samples.
[a]One composite soil sample collected from the HM field sites on 23 May 2013 before treatment application.
[b]One composite soil sample collected from the SRS field site on 13 June 2013 before treatment application.

The main objective of the trial was to determine the benefits, if any, of using biochar for cabbage (*Brassica oleracea* var. *capitata* L.) production in representative field soils in Ontario. Cabbage was selected for this study as it is more responsive to nutrients than many vegetable crops (Brady 2003; Christy 2015). Cabbage is an important fresh and processing vegetable crop that was produced on an area of 2293 ha in 2016 (AAFS 2017) in Ontario. Cabbage relies heavily on adequate soil nutrients, especially the macronutrients nitrogen (N) phosphorous (P), and potassium (K), to form full green heads. Modern midseason cultivars of cabbage require between 150 and 308 kg N ha^{-1} (Csizinszky and Schuster 1993), while late-storage cultivars respond to N rates up to 500 kg ha^{-1} (Zebarth et al. 1991). The N requirements of both types are often higher than the current rate recommended by the Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA) of 170 kg N ha^{-1} (OMAFRA 2000), which can result in reduced yield of cabbage (Westerveld et al. 2003).

The second objective was to compare the effects of compost alone to the biochar and compost mixture to determine if any benefits could be attributed to the compost or the biochar. A third objective was to determine if the nutrients provided by compost plus biochar were more beneficial than conventional NPK fertilizer when both were applied at the same rate of NPK (conducted on one soil type only).

Materials and Methods

Materials and field sites

The biochar used in these trials was purchased from New England Biochar LLC, MA, USA. It was made by slow pyrolysis using native hard and soft woods. Duck compost was obtained from a commercial source. It originated from King Cole Ducks in Newmarket, ON and was made by Cliffords Haulage, Mount Albert, ON. It consisted of duck manure and bedding shavings. The compost was aged for several months, then mixed with the biochar (1:1 based on dry weight) and left for 2 wk prior to application to the soil.

The trial was conducted at two locations that were representative of the intensive vegetable production in Ontario: the Holland Marsh (HM; 44°02′22.02″ N, 79°35′20.54″ W) and the Simcoe Research Station (SRS; 42°49′59.99″ N, 80°17′60.00″ W) over 3 yr, 2013–2015. At HM, a trial was conducted on an organic soil site (organic matter 48.0%, pH 7.5) in 2013 only. The mineral soil site at HM had a sandy loam soil (organic matter 2.1%, pH 7.4). The SRS site was also a sandy loam soil but with lower organic matter content and lower pH (organic matter 1.4%, pH 6.3). Physicochemical properties of the soil, composted duck manure, and biochar–compost manure blend are presented in Table 1.

There were five treatments that were the same at the three sites (Table 2). Two rates of a 1:1 (by dry weight) biochar–compost blend were applied. These rates were 0.6 kg m^{-2} (6 t ha^{-1}) (biochar at 0.30 kg m^{-2} + compost at 0.30 kg m^{-2}) and 2.4 kg m^{-2} (24 t ha^{-1}; 1.2 kg m^{-2} of each). For simplicity, this blend will be referred to as simply biochar herein. Compost alone, at the rate of 1.2 kg m^{-2} (12 t ha^{-1}; composted duck manure, dry weight) was included to compare the compost with the biochar–compost blend. The standard NPK fertilizer (170 kg ha^{-1} N, 110 kg ha^{-1} P, and 130 kg ha^{-1} K, the OMAFRA standard rate, as ammonium nitrate, triple super-phosphate, and muriate of potash) was included as the industry standard treatment. These were based on the nutrient requirements for cabbage at the HM mineral soil site. An equivalent rate was applied at the SRS site for comparison purposes, even though the soil test (Table 1) showed higher pre-plant levels of P and K. There was also an untreated check that received no fertilizer. At HM, the sixth treatment was the biochar–compost mixture at 2.4 kg m^{-2} plus the recommended rate of NPK fertilizer. At SRS, instead of NPK fertilizer + biochar at 2.4 kg m^{-2}, NPK was applied at a rate equivalent to the NPK contained in the biochar plus compost at 2.4 kg m^{-2} (9.5 kg ha^{-1} N, 9.1 kg ha^{-1} P_2O_5, and 80.7 kg ha^{-1} K_2O) (Table 2). The different treatment at SRS was used because there was not enough biochar–compost blend for the high rate plus NPK treatment.

Table 2. Treatments of biochar, compost, and NPK fertilizer applied to cabbage grown at HM and SRS in 2013, 2014, and 2015.

Treatment				
HM	SRS	Biochar + compost blend (kg m^{-2})	Composted duck manure (kg m^{-2})	Fertilizer rates (kg ha^{-1})
Untreated check	Untreated check	—	—	—
Compost[a]	Compost[a]	—	1.2	—
Biochar[b] 0.6	Biochar[b] 0.6	0.6	—	—
Biochar[b] 2.4	Biochar[b] 2.4	2.4	—	—
—	Low rate NPK[c]	—	—	Pre-plant: 9.5 N, 9.1 P, 80.7 K
Biochar 2.4 + NPK[d]	—	—	2.4	Pre-plant: 130 N, 50 P, 50 K; side-dress: 40 N
Standard NPK[d]	Standard NPK[d]	—	—	Pre-plant: 130 N, 50 P, 50 K; side-dress: 40 N

[a]Rate based on dry weight, applied in 2013 only.
[b]Based on dry weights of biochar and composted duck manure mixed at a 1:1 ratio, applied in 2013 only.
[c]N, P, and K applied as conventional fertilizers at a rate equivalent to the N, P, and K contained in the 2.4 kg m^{-2} biochar + compost treatment at SRS.
[d]Standard OMAFRA recommendation applied using ammonium nitrate, triple super-phosphate, and muriate of potash.

Trial establishment

Cabbage (*B. oleracea* var. *capitata*) 'Adaptor' was grown at all sites. The cabbage was seeded in 128-cell plastic plug trays for both sites and all years, except in 2015 at SRS, where 200-cell trays were used. At HM, cabbage was seeded on 7 May 2013 and 15 May in 2014 and 2015, and then transplanted into the field on 4 July 2013, 20 June 2014, and 25 June 2015. At SRS, cabbage was seeded on 28 May 2013, 15 May 2014, and 13 May 2015 and then transplanted into the field on 12 July 2013, 18 June 2014, and 19 June 2015. The trial on muck soil at the HM site was only conducted in 2013, as this soil type already had high organic matter and high moisture-holding capacity, so it was thought that there would be few benefits from applying biochar or compost, which was confirmed after the first year of the trial.

The experiments were arranged in a randomized complete block design with four replications. Each experimental unit consisted of four 8-m-long rows spaced 0.9 m apart. Plants were spaced 0.45 m apart in the row. Biochar and compost were applied once, in 2013 only, at both locations. Biochar, compost, and granular NPK fertilizer was spread evenly on top of the soil by hand and cultivated 15 cm into the soil using a tractor-drawn cultivator. Nitrogen was applied as ammonium nitrate (34% N) for both locations, P was applied as mono-ammonium phosphate (52% P) at the HM site, and P_2O_5 was applied as triple super-phosphate (46% P_2O_5) at the SRS site; K was applied as potassium sulfate (50% K) at HM and as muriate of potash (60% K_2O) at SRS. The N portion of the standard NPK treatment was split, with 130 kg ha^{-1} applied before planting and the remaining 40 kg ha^{-1} N side-dressed at 35 d after transplanting. Pre-plant fertilizer treatments with conventional NPK fertilizers were applied at the SRS on 17 June 2014 and 18 June 2015, and 40 kg ha^{-1} N was side dressed on 2 Aug. 2013, 10 July 2014, and 2015. Pre-plant fertilizer was applied on 2 July 2013, 19 June 2014, and 24 June 2015, at the HM and a side dress of 30 and 40 kg ha^{-1} N at the muck and mineral sites, respectively, was applied on 9 Aug. 2013 and to the mineral soil site on 25 July 2014 and 28 July 2015.

Assessments

The growth and assessments of the field trials were kept as consistent as possible at both field locations, but there were some minor differences, often because of the type of equipment that was available at each location. Yield was assessed when the heads in the conventional fertilizer treatment reached marketable size and weight. At HM, 20 heads per replicate were cut on 4 Nov. in 2013 and 2014, and 1 Oct. 2015. At the SRS site, cabbage heads were harvested from the inside 5.4 m of the middle two rows of each replicate (~24 heads) on 25 Oct. 2013, 9 Oct. 2014, and 15 Oct. 2015. Heads were graded into marketable and unmarketable grades based on head size and were weighed for yield.

At HM, visual assessments were done to determine insect damage and disease incidence. Ratings for insect damage (mainly imported cabbage worm, *Pieris rapae* L.) were taken on 4 Nov. 2014 and on 1 Oct. 2015 using a 0–5 scale, where 0 = no damage, 1 = 1%–10% of leaf area with insect damage, 2 = 11%–25%, 3 = 26%–50%, 4 = 51%–75%, and 5 = >75% of leaf area with insect damage. Disease (mainly black leaf spot caused by *Alternaria* species) was rated on a 0–5 scale, where 0 = no disease, 1 = 1%–10% of leaf area with disease symptoms, 2 = 11%–25%, 3 = 26%–50%, 4 = 51%–75%, and 5 = >75% of leaf area diseased.

A SPAD-502 chlorophyll meter (Konika Minolta, Inc., Tokyo, Japan) was used to measure the relative greenness (chlorophyll levels) of the leaves. Measurements were taken on the youngest fully expanded leaf of 10 plants per plot. Ratings were taken at the HM site on 6 Aug. 2013 for mineral soil plots and on 9 Aug. 2013 for organic soils plots. In 2014 and 2015, visual assessments of greenness were recorded on 18 Sept. 2014 and 9 Oct. 2015. A 0–5 scale was used, where 0 = very light green, 1 = light green, 2 = light–medium green, 3 = medium green, 4 = blue–green, 5 = dark blue–green. The SPAD-502 chlorophyll meter was used each year at SRS, and readings were taken on 9 Aug. and 4 Sept. in 2013, on 10 July, 28 July, 11 Sept., and 8 Oct. in 2014, and on 11 Aug., 15 Sept., and 13 Oct. in 2015.

Moisture-holding capacity was assessed at the HM location and volumetric water content was measured at the SRS site. At HM, soil was collected from biochar 2.4 kg m^{-2}, biochar 0.60 kg m^{-2}, compost, and the untreated check treatments after harvest each year. Tall narrow pots (Conetainers, Stuewe Sons Inc., Corvallis, OR) were filled with soil and set in racks. Each experimental unit consisted of five cones. The soil in the cones was saturated with water, allowed to drain for 24 h and weighed to determine the wet weight of soil. Soil-filled cones were then air-dried for 1 wk, dried in an oven (60 °C) for 72 h, and re-weighed to determine the dry weight of soil. The water-holding capacity of the soil was determined using the following equation:

$$\text{Water-holding capacity}(\%) = \frac{\text{weight of wet cones} - \text{weight of dry cones}}{\text{weight of wet cones}} \times 100$$

At SRS, soil moisture was measured on 4 Nov. 2013, on 14 July, 11 Sept., and 8 Oct. in 2014, and on 6 Aug. 2015 using a Field Scout TDR 100 soil moisture meter (Spectrum Technologies Inc., Aurora, IL), which recorded volumetric water content to a depth of 20 cm.

Soil samples and plant tissue samples were collected at each site. At HM, plant tissue and soil samples were taken from each replicate and sent to SGS Agrifood Laboratories (Guelph, ON) for nutrient analysis. Soil samples for analysis were collected with a 30 cm stainless steel core sampler to a 20 cm depth. Ten cores per replicate plot were taken and mixed thoroughly by hand. Soil was collected before treatment application. At SRS, soil samples were taken at harvest on 24 Oct. 2013, on 16 June 2014 before application of the NPK treatments, before harvest on 8 Oct. 2014, and on 26 May 2015 and before harvest on 13 Oct. 2015. The laboratory used methods accredited by OMAFRA for the analyses. In short, these are the Olsen (sodium bicarbonate) method for phosphorous; the ammonium acetate method for potassium, calcium, and magnesium; and the phosphoric acid method for manganese. The laboratory used the DTPA (diethylenetriaminepentaacetic acid) test for zinc, copper, and iron. Percent organic matter was determined by the Walkley–Black method or by loss on ignition if the organic matter content was over 8%. Boron was assessed using the hot water method (J. Legg, personal communication, SGS Agrifood Laboratories). The laboratory reports nutrients in parts per million and, for manganese and zinc, also reports an availability index that represents the availability of these nutrients based on nutrient levels in the soil and soil pH (OMAFRA 2009). Tissue samples (five heads per plot) were collected on 13 Oct. 2015. A cross-section was cut from each head, weighed, dried, and then submitted to a commercial laboratory for nutrient analysis. At SRS, four heads per plot were taken from the inside 6 m of the middle two rows of each plot.

Air temperature and rainfall were recorded at both sites for all years of the trials. A Campbell's Scientific data logger (CR 21X) was within 2 km of the trial sites. Mean monthly temperature and rainfall were compared with the 10-yr average (Supplementary Table S1[1]).

Data were analyzed using the general analysis of variance function of the linear models section of statistics version 10 (Analytical Software, Tallahassee, FL). Means separation was obtained by using Fisher's protected least significant difference test at a $P = 0.05$ level of significance to allow for pairwise comparisons of the treatment means.

Results

Cabbage yield

Significant differences in weight per head, marketable yield, and total yield were found among the treatments in all years at both locations (Table 3). At the mineral soil site at HM, cabbage grown in plots treated with biochar at 2.4 kg m^{-2} + NPK or just standard NPK fertilizer had significantly heavier marketable heads (2.3–2.7 kg), marketable yield (>31 t ha^{-1}), and total yield (>48 t ha^{-1}) compared with cabbage grown in plots treated with biochar at 0.6 kg m^{-2}, biochar at 2.4 kg m^{-2}, compost alone, or the untreated check (Table 3). The yield parameters for standard NPK and biochar + NPK were similar for all treatments except for marketable yield in 2013. It this case, marketable yield of the standard fertilizer and biochar treatments was higher (58.5 t ha^{-1}) than standard NPK treatment alone (46.1 t ha^{-1}). None of the other treatments were different from the untreated check. The trial on muck soils was only conducted in 2013, and the results were similar to the mineral soil site except for weight per marketable head, where there were no differences compared with the untreated control (Table 3).

At the SRS site, cabbage grown with standard NPK fertilizer produced the highest weight per head, marketable yield, and total yield in all years (Table 3). The biochar at 2.4 kg m^{-2} or 0.6 kg m^{-2} did not result in increased yield compared with the untreated check or compost in all years. Biochar applied at 2.4 kg m^{-2} resulted in significantly higher marketable yield than

[1]Supplementary Tables S1–S9 are available with the article through the journal Web site at http://nrcresearchpress.com/doi/suppl/10.1139/cjps-2018-0122.

Table 3. Yield of cabbage grown in mineral and muck soils treated with biochar, compost, and NPK fertilizer at HM and SRS in 2013, 2014, and 2015.

	Weight per marketable head (kg)				Marketable yield (t ha^{-1})				Total yield (t ha^{-1})			
	2013		2014	2015	2013		2014	2015	2013		2014	2015
Treatment	Muck	Mineral	Mineral	Mineral	Muck	Mineral	Mineral	Mineral	Muck	Mineral	Mineral	Mineral
Holland Marsh												
Untreated check	1.4abc	1.0b	1.4b	0.7b	18.8b	10.3c	13.0b	8.9b	29.7b	21.3c	21.9b	17.7c
Compost	1.1c	0.8b	1.1bc	1.0b	7.7c	6.6c	8.4b	10.0b	20.8d	17.3c	22.7b	21.2c
Biochar 0.6	1.2c	0.7b	1.4b	0.9b	12.3bc	9.3c	8.9b	8.2b	23.5cd	18.2c	22.1b	19.8c
Biochar 2.4	1.3bc	0.6b	0.4c	0.6b	11.9bc	2.5c	3.8b	5.6b	27.4bc	14.9c	18.2b	17.6c
Biochar 2.4 + NPK[a]	1.7a	2.3a	2.6a	2.4a	40.5a	58.5a	44.0a	59.2a	44.3a	58.5a	50.1a	60.3b
Standard NPK[a]	1.7ab	2.3a	2.3a	2.7a	31.7a	46.1b	43.0a	65.4a	40.0a	48.2b	48.2a	66.3a
Standard error	0.19	0.3	0.40	0.25	13.5	16.1	14.2	13.7	2.7	3.2	7.1	2.7
Simcoe												
Untreated check	—	1.5bc	1.7b	1.8b	—	33.6b	37.1bc	37.7bc	—	36.0bc	37.1bc	45.4b
Compost	—	1.4bc	1.7b	1.7b	—	33.5b	39.3bc	31.7c	—	34.8bc	39.3bc	41.1b
Biochar 0.6	—	1.4bc	1.6b	1.7b	—	33.1b	35.8c	33.9bc	—	35.0c	35.8c	43.1b
Biochar 2.4	—	1.7b	1.8b	1.9b	—	40.1b	44.1b	40.5bc	—	42.2b	44.1b	48.2b
Low rate NPK[b]	—	1.3c	1.7b	1.9b	—	33.4b	37.1bc	42.6b	—	32.6c	37.1bc	47.9b
Standard NPK[a]	—	2.6a	3.9a	3.1a	—	62.3a	96.1a	69.8a	—	63.9a	96.1a	76.5a
Standard error	—	0.15	0.15	0.19	—	4.1	3.8	4.8	—	3.6	3.8	4.6

Note: Means followed by the same lowercase letters are not significantly different at $P < 0.05$ according to Fisher's protected least significant difference test.

[a]Standard NPK is pre-plant 130 kg ha^{-1} N, 50 kg ha^{-1} P, and 50 kg ha^{-1} K, and side-dressed 40 kg ha^{-1} N, consisting of ammonium nitrate, triple super-phosphate, and muriate of potash.

[b]N, P, and K applied as conventional fertilizers at a rate equivalent to the N, P, and K contained in the 2.4 kg m^{-2} biochar + compost treatment at SRS: 9.5 kg ha^{-1} N, 9.1 kg ha^{-1} P, and 80.7 K all applied pre-plant.

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Table 4. Insect damage, disease rating, SPAD values, and greenness ratings for cabbage grown in mineral soil amended with biochar in 2013 at HM in 2013, 2014, and 2015.

					SPAD value		Greenness[a]	
	2014		2015		2013		2014	2015
Treatment	Insect[b]	Disease[c]	Insect	Disease	Muck	Mineral	Mineral	Mineral
Untreated check	2.0[d]	4.0b	1.3ns	2.0ab	64.3ns	56.4b	3.0b	3.4b
Compost	2.0	4.0b	1.0	2.8b	67.3	58.5b	3.0b	3.6b
Biochar 0.6	2.0	4.3b	1.3	1.8a	69.9	57.9b	2.9b	3.5b
Biochar 2.4	2.0	4.3b	1.8	2.0ab	68.9	56.7b	2.9b	3.2b
Biochar 2.4 + NPK[e]	2.0	1.3a	1.3	1.5a	69.4	62.8a	4.1a	4.6a
Standard NPK[e]	2.0	1.8a	1.0	1.3a	70.6	62.5a	4.4a	4.7a
Standard error	–	0.46	0.31	0.38	2.0	1.9	0.28	0.25

Note: Means in a column followed by the same lowercase letters are not significantly different at $P < 0.05$ according to Fisher's protected least significant difference test. ns, not significant.

[a]Greenness scale: 0 = very pale light green, 1 = pale light green, 2 = light green, 3 = medium green, 4 = blue–green, and 5 = dark blue–green.

[b]Insect (imported cabbage worm, *Pieris rapae*) damage scale: 0 = 0%, 1 = 1%–10%, 2 = 11%–25%, 3 = 26%–50%, 4 = 51%–75, and 5 = >75% (leaf area damaged).

[c]Disease scale (black leaf spot caused by *Alternaria* species): 0 = no disease, 1 = 1%–10%, 2 = 11%–25%, 3 = 26%–50%, 4 = 51%–75%, and 5 = >75% disease coverage.

[d]There is no variability in the data, hence statistical analysis is not appropriate.

[e]Standard NPK is pre-plant 130 kg ha^{-1} N, 50 kg ha^{-1} P, and 50 kg ha^{-1} K, and side-dressed 40 kg ha^{-1} N, consisting of ammonium nitrate, triple super-phosphate, and muriate of potash.

biochar at 0.6 kg m^{-2} in 2014, but there were no differences between these treatments in 2013 and 2015. However, biochar at 2.4 kg m^{-2} resulted in higher weight per head and higher total yield than the low rate of NPK in 2013, even though the low rate of NPK provides the same amount of these nutrients as in the 2.4 kg m^{-2} rate of biochar.

Insect damage and disease incidence

Insect and disease assessments were only done at the HM location. There were no differences in insect damage among any of the treatments (Table 4). Some differences in percent leaf area diseased were observed. Cabbage grown in plots treated with NPK and biochar at 2.4 kg m^{-2} + NPK in 2014 had significantly less leaf area diseased than the other treatments. In 2015, these treatments and the low rate of biochar had less leaf area diseased than the compost treatment (Table 4).

Chlorophyll content

In 2013, visual differences in chlorophyll content were observed among the treatments at HM (Table 5). Soil–plant analyses development (SPAD) readings were significantly higher in the biochar 2.4 kg m^{-2} + NPK and NPK fertilized treatments compared with the biochar treatments and the check (Table 5). Like the SPAD values, greenness ratings were significantly higher in the biochar 2.4 kg m^{-2} + NPK and NPK fertilized treatments compared with the other treatments (data not shown). There were also significant differences in SPAD readings among the treatments in all years at SRS (Table 5). The SPAD values were highest in the standard NPK fertilizer plot in all rating dates of all years. The application of biochar, regardless of application rate, did not affect SPAD readings compared with the untreated check in any of the years, except for the 11 Sept. assessment in 2014. On this assessment date, cabbage grown with the biochar 2.4 kg m^{-2} rate had a higher SPAD value than the low rate of NPK and the untreated check, but still lower than the standard NPK treatment.

Nutrients in plant tissue

Foliar nutrient levels were measured in 2015 in cabbage at HM and SRS. Results varied between the two locations. At the HM site, no significant differences were observed in K, Ca, and Fe levels in cabbage leaves among the treatments (Table 6). Cabbage grown with standard NPK fertilizer had significantly higher levels of N, P, Cu, Zn, Mn, and B compared with cabbage grown on soil treated with biochar alone or the untreated check (Table 6). In contrast, levels of Mo were higher in untreated cabbage and cabbage grown with biochar at 2.4 kg m^{-2} than for treatments that included the standard NPK. Cabbage grown with standard NPK alone or with biochar had lower levels of Mg than biochar alone (Table 6). There were no differences in foliar concentrations of K, Ca, or Fe. At the SRS, cabbage grown with standard NPK treatment had significantly higher levels of N, P, K, Mg, Zn, Mn, and Fe and the lowest levels of S in 2015 (Table 6). All other treatments recorded identical lower levels of N, P, K, Mg, Zn, Mn, and Fe. There were no differences in Ca, Cu, and B levels in cabbage leaves among the treatments.

Table 5. SPAD chlorophyll values of cabbage grown with compost, biochar, and NPK fertilizer at SRS in 2013, 2014, and 2015.

	SPAD value[a]								
	2013		2014				2015		
Treatment	9 Aug.	4 Sept.	9 July	28 July	11 Sept.	8 Oct.	11 Aug.	15 Sept.	13 Oct.
Untreated check	60.2bc	69.8b	53.1b	56.6b	67.2c	64.8b	68.7b	77.4b	75.4b
Compost	59.7bc	69.1b	59.2a	55.5b	70.8bc	67.7b	67.2b	78.1b	74.1b
Biochar 0.6	58.9c	67.9b	58.3a	55.6b	68.7c	66.2b	66.5b	78.7b	74.0b
Biochar 2.4	59.4bc	68.4b	58.6a	55.1b	73.4b	68.1b	66.8b	76.9b	76.6b
Low rate NPK[b]	62.0b	63.1c	52.8b	55.5b	67.9c	65.3b	69.8b	79.8b	75.8b
Standard NPK[c]	65.7a	79.5a	55.0b	61.0a	80.5a	82.8a	79.6a	85.5a	86.7a
Standard error	1.3	1.9	1.2	1.6	1.9	1.7	2.3	1.6	1.3

Note: Means followed by the same lowercase letters are not significantly different at $P < 0.05$ according to Fisher's protected least significant difference test.

[a]SPAD value is a measure of chlorophyll or leaf greenness.

[b]N, P, and K applied as conventional fertilizers at a rate equivalent to the N, P, and K contained in the 2.4 kg m^{-2} biochar + compost treatment at SRS: 9.5 kg ha^{-1} N, 9.1 kg ha^{-1} P, and 80.7 K all applied pre-plant.

[c]Standard NPK is pre-plant 130 kg ha^{-1} N, 50 kg ha^{-1} P, and 50 kg ha^{-1} K, and side-dressed 40 kg ha^{-1} N, consisting of ammonium nitrate, triple super-phosphate, and muriate of potash.

Table 6. Foliar nutrient levels for cabbage grown on mineral soil treated with biochar in 2013 at HM and SRS in 2015.

	Nutrient (%)						Nutrient (ppm)					
Treatment	N	P	K	Mg	Ca	S	Cu	Zn	Mn	B	Fe	Mo
Holland Marsh												
Untreated check	2.1c	0.2b	2.4ns	0.23ab	2.8ns	—	1.4b	8.9b	13.8b	32.5b	88.5ns	7.1b
Biochar 2.4	2.0c	0.2b	2.4	0.24a	2.6	—	1.3b	8.5b	11.8b	28.0b	64.0	8.8a
Biochar 2.4 + NPK[a]	2.8b	0.3a	2.2	0.17c	2.4	—	1.7a	10.9a	14.3b	41.5a	72.8	3.0c
Standard NPK[a]	3.0a	0.3a	2.3	0.21bc	2.7	—	1.7a	11.0a	19.5a	43.5a	78.0	2.4c
Standard error	0.083	0.013	0.15	0.014	0.29	—	0.082	0.59	1.2	3.1	8.0	0.71
Simcoe												
Untreated check	1.2b	0.26b	2.4b	0.11b	0.34ns	0.45a	1.8ns	0.3c	13.2b	13.2ns	22.5b	—
Compost	1.2b	0.25b	2.3b	0.11b	0.36	0.42a	1.8	10.7bc	12.3b	12.1	21.3b	—
Biochar 0.6	1.2b	0.25b	2.4b	0.12b	0.37	0.45a	1.8	12.8b	12.8b	12.9	22.1b	—
Biochar 2.4	1.2b	0.26b	2.4b	0.12b	0.39	0.46a	2.0	11.5bc	12.6b	13.1	23.2b	—
Low rate NPK[b]	1.2b	0.25b	2.5b	0.11b	0.37	0.44a	1.4	9.1c	12.4b	11.5	21.7b	—
Standard NPK[a]	1.8a	0.30a	2.8a	0.14a	0.43	0.32b	1.8	17.2a	23.0a	13.7	34.3a	—
Standard error	0.13	0.013	0.11	0.0059	0.033	0.025	0.34	1.2	0.74	0.95	2.1	—

Note: Means in a column for the same location followed by the same lowercase letters are not significantly different at $P < 0.05$ according to Fisher's protected least significant difference test. ns, not significant.

[a]Standard NPK is pre-plant 130 kg ha^{-1} N, 50 kg ha^{-1} P, and 50 kg ha^{-1} K, and side-dressed 40 kg ha^{-1} N, consisting of ammonium nitrate, triple super-phosphate, and muriate of potash.

[b]N, P, and K applied as conventional fertilizers at a rate equivalent to the N, P, and K contained in the 2.4 kg m^{-2} biochar + compost treatment at SRS: 9.5 kg ha^{-1} N, 9.1 kg ha^{-1} P, and 80.7 K all applied pre-plant.

Soil moisture and water-holding capacity

The water-holding capacity of the soil was assessed by determining the percent soil moisture by weight at the HM site and volumetric water content at the SRS site. At the HM mineral soil site, in the first year of the trial, soil treated with biochar at 2.4 kg m^{-2} had a higher water-holding capacity (>19%) than all other treatments (Table 7). In the following year, only soil treated with compost alone had a higher water-holding capacity than the untreated check (Table 7). By the third year of the trial (2015), 2 yr after the biochar and compost treatments had been applied, there were no differences in water-holding capacity among treatments (Table 7). The water-holding capacity of the muck soil was high and similar among treatments, as expected. The volumetric water content was not different from the untreated check in any year at SRS (Table 7). The percent moisture by volume was low at SRS in 2015, but this

Table 7. Soil moisture assessments for soil treated with compost, biochar, and NPK fertilizer at HM and SRS in 2013, 2014, and 2015.

Treatment		Soil moisture[a,b]						
		2013			2014		2015	
		HM		SRS	HM	SRS	HM	SRS
HM	SRS	Muck	Mineral	Mineral	Mineral	Mineral	Mineral	Mineral
Untreated check	Untreated	54.2ns	14.2b	19.6ns	20.3bc	18.7ab	23.5ns	6.6ns
Compost	Compost	52.8	14.6b	18.6	22.8a	17.8b	23.5	6.5
Biochar 0.6	Biochar 0.6	50.6	13.1b	17.0	19.7c	18.0b	23.6	6.3
Biochar 2.4	Biochar 2.4	53.1	19.2a	18.5	22.5ab	17.7b	23.3	7.1
Biochar 2.4 + NPK[d]	Low rate NPK[c]	—	—	18.8	—	17.3b	—	6.0
Standard NPK[d]	Standard NPK[d]	—	—	18.9	—	20.0a	—	8.7
Standard error	—	1.9	2.009	1.2	0.95	0.69	0.78	1.1

Note: Means followed by the same lowercase letters are not significantly different at $P < 0.05$ according to Fisher's protected least significant difference test. ns, not significant.

[a]Percent moisture holding capacity assessed after harvest at HM.

[b]Percent moisture by volume as measured by time domain reflectometry in field plots at SRS.

[c]N, P, and K applied as conventional fertilizers at a rate equivalent to the N, P, and K contained in the 2.4 kg m^{-2} biochar + compost treatment at SRS: 9.5 kg ha^{-1} N, 9.1 kg ha^{-1} P, and 80.7 K all applied pre-plant.

[d]Standard NPK is pre-plant 130 kg ha^{-1} N, 50 kg ha^{-1} P, and 50 kg ha^{-1} K and side-dressed 40 kg ha^{-1} N, consisting of ammonium nitrate, triple super-phosphate, and muriate of potash.

may be related to low monthly rainfall that year (Supplementary Table S1[1]).

Soil properties

The content of macronutrients (nitrate-N, P, and K) in the soil varied more at the HM site than the SRS site (Table 8). At the muck soil site, the high rate of biochar resulted in higher levels of nitrate-N and K than the untreated check, while levels of P were lower than the check in the low biochar treatment and the K concentration was higher than the check in the compost and biochar at 2.4 kg m^{-2} treatments (Table 8). At the mineral soil site at HM, nitrate-N levels were not different from the check in 2013. Levels of P were higher than the check in 2013 and 2014, while levels of K were higher in 2014 and 2015 (Table 8). There were no differences in macronutrient levels at SRS except that the standard NPK treatment had the highest nitrate-N in 2013 and the highest K concentration in 2014 (Table 8).

There were no differences in soil organic matter content at either location for any year. The organic matter content at the SRS site ranged from 1.3% to 2.0%. The organic matter at the mineral soil HM site ranged from 2.1% to 3.4% (Supplementary Table S2[1]). A difference in soil pH was only seen in 2015 at HM. Soil fertilized with NPK had lower soil pH (6.5) than all other treatments (7.2–7.5) (Supplementary Table S2[1]). None of the other treatments differed from the untreated check. At SRS, there were differences in soil pH among treatments at harvest in all years (Supplementary Table S2[1]). No treatments were different from the untreated check in 2013 (5.9–6.7). In 2014 and 2015, the treatments with compost and biochar alone had higher pH (6.8–7.0) than the untreated check (6.2–6.4); the standard NPK treatment had the lowest pH in 2015 (5.6) (Supplementary Table S2[1]).

Total salts, as indicated by electrical conductivity (EC), were measured in 2013 at SRS and in 2015 at HM (data not shown). The EC in the untreated check was the same in both assessments (0.04 mS cm^{-1}), and the compost and 0.6 kg m^{-2} biochar treatments were not different from the untreated check. At SRS, the 2.4 kg m^{-2} biochar treatment had the highest EC (0.08 mS cm^{-1}), while this treatment had low (0.04 mS cm^{-1}) EC at HM. The treatments that included NPK had similar EC readings (0.06–0.07 mS cm^{-1}). There were no significant differences in cation-exchange capacity (CEC) among any treatments for any years at HM. The CEC ranged from 51.4 to 53.1 meq 100 g^{-1} for the muck soil site and from 9.7 to 11.8 meq 100 g^{-1} at the mineral soil site (Supplementary Table S3[1]). There were differences in CEC at harvest each year at SRS. In 2013, the application of compost resulted in a higher CEC in the soil at harvest (6.1 meq 100 g^{-1}) compared with the untreated check (4.5 meq 100 g^{-1}; Supplementary Table S3[1]). In 2014, the compost and high rate of biochar treatments had higher CECs at harvest (6.7–8.1 meq 100 g^{-1}) than the untreated check (6.2 meq 100 g^{-1}), while in 2015, compost and both biochar treatments had higher CECs (7.9, 7.4, and 8.3, respectively) than the untreated check (6.3 meq 100 g^{-1}; Supplementary Table S3[1]).

There were some differences in base saturation. In muck soil at HM in 2013, soils amended with biochar 2.4 kg m^{-2} had a higher percent of K (1.3%) and Mg (8.1%), and a lower percent Ca (88.3%) than the untreated check

Table 8. Nitrogen, phosphorus, and potassium concentration in muck and mineral soil treated with biochar, compost, and NPK fertilizer after harvest at HM and SRS in 2013, 2014, and 2015.

	NO_3 (ppm)		P (ppm)				K (ppm)			
	2013		2013		2014	2015	2013		2014	2015
Treatment	Muck	Mineral	Muck	Mineral	Mineral	Mineral	Muck	Mineral	Mineral	Mineral
Holland Marsh										
Untreated check	73.2a	4.6ab	144.2a	32.6c	34.3c	35.5c	126.1c	48.3ns	49.8b	62.7c
Compost	67.1ab	4.9a	156.0a	47.4a	46.0a	45.9ab	188.1b	81.4	79.0a	96.7a
Biochar 0.6	62.8b	5.1a	109.2b	38.5bc	41.0b	40.7bc	148.1bc	59.3	56.3b	84.7ab
Biochar 2.4	61.0b	3.5b	163.0a	43.2ab	47.8a	42.9abc	279.0a	80.6	96.0a	89.2ab
Biochar 2.4 + NPK[a]	—	—	—	—	—	50.1a	—	—	—	76.0bc
Standard NPK[a]	—	—	—	—	—	47.2ab	—	—	—	59.4c
Standard error	3.2	0.44	13.9	3.4	2.9	3.5	22.3	14.1	7.6	9.7
Simcoe										
Check	—	2.2b	—	75ns	77ns	90ns	—	185ns	156a	182ns
Compost	—	2.4b	—	71	92	98	—	205	168a	182
Biochar 0.6	—	2.0b	—	66	70	78	—	185	152a	185
Biochar 2.4	—	2.6b	—	71	77	86	—	210	180a	194
Low rate NPK[b]	—	2.0b	—	71	93	87	—	198	181a	240
Standard NPK[a]	—	5.7a	—	71	93	104	—	158	106b	190
Standard error	—	0.9	—	7.2	10.1	12.2	—	23.4	18.2	24.6

Note: In 2013, NH_4-N in both muck and mineral soil ranged from 2 to 3 ppm and was non-significant among the treatments. Means in a column for the same location followed by the same lowercase letters are not significantly different at $P < 0.05$ according to Fisher's protected least significant difference test. ns, not significant.

[a]Standard NPK is pre-plant 130 kg ha^{-1} N, 50 kg ha^{-1} P, and 50 kg ha^{-1} K, and side-dressed 40 kg ha^{-1} N, consisting of ammonium nitrate, triple super-phosphate, and muriate of potash.

[b]N, P, and K applied as conventional fertilizers at a rate equivalent to the N, P, and K contained in the 2.4 kg m^{-2} biochar + compost treatment at SRS: 9.5 kg ha^{-1} N, 9.1 kg ha^{-1} P, and 80.7 K all applied pre-plant.

(K: 0.61%, Mb: 7.7%, and Ca: 89.4%) (Supplementary Table S4[1]). The base saturation data for mineral soil at the HM site were not available in 2013. There were no differences in percent base saturation between any of the treatments compared with the untreated check in 2014 or 2015 at the mineral soil site, except that percent K (2.4%) was higher than the check (1.5%) in 2014.

Base saturation data for the SRS site were only available for the 2015 season. Percent Ca, Mg, and H^+ were lower in the standard NPK treatment (46.9%, 8.8%, and 8.8% for Ca, Mg, and H^+, respectively) than the untreated check (60.4%, 12.8%, and 12.8% for Ca, Mg, and H^+, respectively), while the low rate of NPK had a higher percent K (9.2%) than any other treatment (5.8%–7.4%; Supplementary Table S4[1]).

The concentrations of other plant nutrients in soils varied at the two sites, and no particular patterns were obvious. At the HM site, no significant differences were found in soil concentrations of Ca (1267–1899 ppm), Cu (0.61–0.87 ppm), or B (0.40–0.58 ppm) among the treatments in 2014 and 2015, and Fe concentration (29–36 ppm) in 2014 (Supplementary Table S5[1]). There were higher levels of soil Mg in the compost and biochar 2.4 kg m^{-2} treatments (85.5–92.6 ppm) compared with the check in 2013 (66.0 ppm) and 2014 (64.0 ppm). In 2015, only the compost alone treatment had more Mg (86.8 ppm) than the check (68.0 ppm). Also in 2015, the NPK treatment had higher Fe (55.1 ppm) than the check (33.9 ppm). Soil analyses for these nutrient elements were available for 2014 and 2015 at SRS, with samples taken before planting and at harvest. Biochar at 2.4 kg m^{-2} had higher Ca at all sample times (812–1135 ppm) and higher Mg at harvest (110 ppm) compared with the untreated check (Ca: 610–766 ppm; Mg: 96–97 ppm; Supplementary Table S6[1]), while the standard NPK treatment (Ca: 583–735 ppm; Mg: 67–89 ppm) was not different from the check. There were no differences in SO_4 (1.5%–5.7%) or Al (955–1091 ppm) at SRS. Boron was higher in the biochar 2.4 kg m^{-2} treatment at harvest (0.26 ppm) compared with the check (0.20 ppm; Supplementary Table S7[1]). There were no differences in Cu (1.7–2.0 ppm) or Fe (23.2–45.3 ppm) compared with the untreated check at SRS, except for higher Fe in the standard NPK treatment at harvest (50.0 ppm) in 2015 (Supplementary Table S7[1]). There were few differences in Zn, Zn index, Mn, or Mn index at either location (Supplementary Tables S8 and S9[1]), except that Zn (0.89–1.6 ppm) and Mn (11.8–12.8 ppm) were generally higher in the biochar 2.4 kg m^{-2} treatment at HM (Supplementary Table S8[1]). There were no differences in Al at the HM mineral soil site (653.5–765.7; Supplementary Table S8[1]).

Discussion

The yield of cabbage was closely related to the plant nutrients that were applied at both sites and all years, as expected. The application of fertilizer resulted in typical commercial yields (48.6–99.5 t ha^{-1}) for all site years on mineral soil. In five of the six site–years, there was no increase in yield in treatments where compost or biochar had been applied compared with standard commercial fertilizer at the recommended rate. An exception was the 2013 trial on mineral soil at HM, where the biochar + NPK treatment had a higher total yield than cabbage that received NPK alone. The trial at the SRS site compared cabbage yield with biochar at a rate of 2.4 kg m^{-2} (24 t ha^{-1}), as compared with applying NPK to provide the same nutrients (9.5 N, 9.1 P, and 80.7 K kg ha^{-1}). The biochar application resulted in higher weight per marketable head and higher total yield in the first year of the trial. Three years after the application of biochar treatments, cabbage grown without the addition of NPK fertilizer had pale leaves and small heads, resulting in few marketable heads. Cabbage yield was appreciably higher at SRS than HM regardless of treatments or year. This was possibly due to the application of irrigation water when rainfall was low throughout the growing season at SRS. Irrigation was not available at the HM mineral soil site. McKeown et al. (2010) have documented a positive correlation between the yield of cabbage and combined nitrogen fertilization and irrigation.

Previous studies have reported a significant enhancement in the growth and yield of several crops with the incorporation of a wide range of biochars (Gaskin et al. 2010; Hossain et al. 2010; Major et al. 2010; Uzoma et al. 2011). The greatest yield increase relative to the control was 903% with the addition of 50 g kg^{-1} biochar to nonfertilized soil in pot-grown lettuce (Carter et al. 2013). In another report, the addition of 50 t ha^{-1} of biochar also increased the total yield by 30% when high levels of N were used on oats in the United Kingdom (Alfred et al. 2009). Olaniyi and Ojetayo (2011) and Sarker et al. (2003) reported that differences in cabbage head weight and yield depended on fertilizer type. Westerveld et al. (2003) and McKeown et al. (2010) have shown that desirable head parameters and total yield increased with higher N rates. Biochar applied together with mineral fertilizer has increased yield in trials in the tropics, probably as a result of increased CEC due to the biochar (Lehmann and Joseph 2009). In fertilized soils, the addition of biochar led to a smaller increase in plant growth compared with when biochar was added to nonfertilized soils (Carter et al. 2013). Van Zwieten et al. (2009) found little responses of crop yield and nutrient status associated with the sole use of biochar, which the authors attributed to its nature: a carbon-rich but nutrient-poor material. Most studies have shown that the beneficial effects of the addition of biochar on crop production are most evident when biochar is combined with mineral fertilizers (Lehmann et al. 2003; Chan et al. 2007; Asai et al. 2009; Van Zwieten et al. 2009; Schulz and Glaser 2012). The current research did not find an improvement in yield when biochar was combined with mineral fertilizers, except in one of six site–years on a mineral soil.

Biochar application increased vegetable yields by 4.7%–25.5% as compared with farmers' practices in Vietnam (Vinh et al. 2014). The yield of French bean was increased by the application of biochar compared with no biochar (Saxena et al. 2013). Biochar treatment in a lettuce–cabbage–lettuce cycle increased final biomass, root biomass, plant height, and nthe umber of leaves in comparison to no biochar treatments (Carter et al. 2013). The increased productivity is likely a result of direct mitigation of acid soil conditions and Al toxicity caused by the direct application of ash in the biochar. Others have concluded that the response of biochar amendment on crop productivity depends on the particular soil characteristics and application may or may not bring positive effects on crop yields (Lehmann and Joseph 2009). A recent meta-analysis of the literature on biochar concluded that biochar application is often beneficial for the low-nutrient, acidic soils of the tropics. In contrast, no yield increases were found (on average) as a result of biochar application to soils in temperate regions of the world (Jeffery et al. 2017).

Visual differences among the treatments became apparent several weeks after planting, with all treatments except for the standard NPK showing pale green leaves and smaller plants that are typical signs of nitrogen deficiency. This was validated using a SPAD chlorophyll meter. Leaf SPAD values decreased after biochar addition in clay soil for rice production, which was likely as a result of a decrease in soil N availability, as this parameter is highly correlated to the nitrogen nutritional status of the leaf (Asai et al. 2009). Another report found that leaf chlorophyll content was not significantly affected by the application of biochar (Chintala et al. 2013*a*).

In this study, an increase in water-holding capacity compared with the untreated check was seen at HM in one out of three years. There were no differences in volumetric water content at SRS in any year, even though the soil at SRS had lower organic matter content. An increase in water-holding capacity is often seen following the application of biochar. Water-holding capacity doubled with around a 9% biochar amendment of an infertile sandy soil, which increased the potential to mitigate drought and increase crop yields in a loamy sand soil (Yu et al. 2013). An agriculturally relevant biochar amendment of 5% biochar (100 t ha^{-1}) resulted in a water-holding capacity of 24%, that is, a 50% increase over unamended soil (Novak et al. 2009). The rate of biochar used in the current experiment was 24 t ha^{-1}, which may not have been enough to affect the water-holding capacity of the sandy soils of SRS. Soils with a high water-holding capacity produce higher crop yields with a decreased need for irrigation in many production areas (Sohi et al. 2009). Others have also found inconsistencies in the effect of biochar on moisture-holding capacity. Singh et al. (2010) stated that the increased porosity of biochar increases water retention in soils, but the enhancement depends on biochar feedstock, soil type, and mixture rates. Increased moisture-holding capacity has the potential advantage that nutrients dissolved in the water may be retained in the root zone of the soil, so plants may be better able to access the nutrients (Lehmann and Joseph 2009), while poor water-holding capacity plays a major role in nutrient loss in sandy loam soil (Major et al. 2009; Novak et al. 2009; Sohi et al. 2009).

The application of biochar or compost did not affect soil pH at the HM site but did increase pH by 0.2–0.6 units at the SRS site when soil was assessed at harvest. Soils treated with just the standard NPK fertilizer over 3 yr had a significantly lower pH than all other treatments in 2015 at HM (the only year this was assessed) and in 2014 and 2015 at SRS. This was probably due to the acidifying effect of ammonium nitrate fertilizer, which is a product of the proton-generating reaction of ammonium ions (Gaskin et al. 2010; Chintala et al. 2013*b*). Optimal soil pH for cabbage growth is 6.0–7.5, and the absolute minimum and maximum growing conditions are pH 4.2–7.5 and 5.3–8.0, respectively (FAO 2010). Therefore, the effect of biochar on pH could increase the growth of crops such as cabbage in low pH soils (FAO 2010). The pH of the soil at HM was 7.4 at the start of the trial, while the soil as SRS had a pH of 6.3, so the increase in pH at this site is consistent with adding a higher pH material such as biochar. An increase in pH by 0.5–1.0 units with the application of 30 Mg ha^{-1} of biochar occurs in most cases (Shackley et al. 2012). Chan et al. (2007) found significantly higher soil pH, organic carbon, and exchangeable cations at higher rates (>50 t ha^{-1}) of green waste biochar in alfisol soil.

The high surface area and porous nature of biochar increases the CEC of the soil (Abebe et al. 2012). In this study, the application of compost and biochar did not affect the CEC of the mineral soil at the HM site but did increase the CEC by up to two units compared with the untreated check at the SRS site. Cation-exchange capacity is important for the retention of plant-essential cations (Liang et al. 2006; Chan and Xu 2009).

The soil analysis for nitrogen and phosphorus content showed no significant differences among treatments at SRS in 2014 and 2015. The content of nitrogen and phosphorus in biochar varies depending on the pyrolysis process (Lehmann and Joseph 2009). The biochar compost mixture used in the current trial contained 188 mg kg^{-1} nitrate N, 180 mg L^{-1} P, and 1600 mg L^{-1} K. The phosphorus level in the mineral soil site at HM was 36 ppm, which is considered medium and warrants the application of P fertilizer. The P content of the SRS soil was 76 ppm at the start of the trial, and the recommendation would be for no added P (OMAFRA 2000). Similarly, pre-treatment levels of potassium were very high in the SRS soil, and no K application would be recommended. Magnesium levels ranged from 66 to 88 ppm and fall into the medium response category (OMAFRA 2012). In 2015, potassium levels in the HM soil were lowest in plots fertilized with standard rates of NPK, likely reflecting increased plant uptake. An increase in soil pH and CEC, which reduces the activity of Fe and Al, can also contribute to higher values of available phosphorous in soils treated with biochar (Abebe et al. 2012). However, changes in pH were small in the current trial, and the effects of pH or CEC were not expected to be a factor in the current trial.

Conclusions

It was difficult to identify specific benefits of biochar application to the relatively fertile soils where vegetables are grown in southern Ontario. Cabbage produced the highest total and marketable yields when fertilized with the standard NPK fertilizer at both locations. An increase in yield related to biochar application was identified once, at each location, in 2013, the year that biochar was applied. The high rate of biochar + NPK treatment resulted in the highest total yields at the HM mineral soil site in 2013, which was also higher than the standard NPK treatment. At the SRS site in 2013, total yield and weight per head were higher with the high biochar rate compared with the NPK fertilizer that provided the same level of NPK as the biochar. However, these yields were not different from the untreated check, and the standard rate of NPK produced the highest yields at the SRS location. Except for these examples, there was no benefit to applying biochar as opposed to commercial NPK fertilizer, and there were few differences between the biochar–compost mixture as compared with compost alone.

Standard NPK fertilizer at the recommended rate resulted in a typical commercial yield at both locations. Soil treated with 2.4 kg m^{-2} biochar or compost did not provide adequate nutrients to produce marketable cabbage yield over the 3 yr of the trial following a single application in the first year (2013). The application of ammonium nitrate lowered soil pH; however, the pH was still within the optimum range and did not affect yield. The addition of biochar and compost increased the soil nutrient concentrations of several elements. In general, P and K concentrations were high in the post-trial soil analysis and were within or above recommended levels. Insect damage was low in the trial, and there were no differences in disease severity related to biochar application. It is not clear if the appropriate rate of biochar was applied. Some trials have been conducted with 100 or over 100 t ha^{-1}. However, the rate used in this study was considered high in terms of the need to transport large amounts of material and the difficulty of spreading and incorporating that amount of material into the soil. In conclusion, there were few benefits from the application of biochar to these soils for cabbage production and no consistent increase in yield. These results are consistent with those of Jeffery et al. (2017), who found no consistent yield increase when biochar was applied to soils in temperate regions. Biochar may be a more valuable tool for the management of soils that are either degraded or have poor nutrient status. The authors suggest that biochar should be evaluated as an amendment where high quantities of biochar could be applied to small areas and where improved moisture-holding capacity would be very beneficial, such as for urban gardens and for trees in urban areas.

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