Biochar application on commercial field crops using farm-scale equipment

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ABSTRACT

Commercial growers who wish to apply biochar to their field crops will need to use conventional agricultural machinery to amend large field areas. Biochar produced by fast pyrolysis of hardwood was applied at a target rate of 5.6 t ha^{-1} to a single swath (10 m x 100 m) in an agricultural field in Quebec, Canada, using a commercial lime spreader. Windborne losses of up to 30% biochar occurred during handling, transportation, and application. We recommend covering and moistening the biochar before spreading, avoiding surface application on windy days, or mixing it with other materials (e.g., compost, manure) to reduce biochar loss. The biochar-amended swath and an adjacent equally sized swath that received no biochar were harrowed. The entire field was seeded with soybean in the first season, followed by an oat-forage mixture in the second season, and forage in the third season. Soybean and oat yields increased by up to 20% with biochar. In the third season, forage in the biochar-amended swath had greater nutrient concentration and higher projected milk production when used as feed for dairy cattle, based on near-infrared spectroscopy analysis. The variable cost of applying biochar was an estimated CA$2,285 ha^{-1}, indicating the need for a complete cost-benefit analysis of farm-scale biochar applications.

RÉSUMÉ

Les producteurs commerciaux qui souhaitent appliquer du biochar à leurs cultures en plein champ devront utiliser des machines agricoles conventionnelles pour amender de grandes surfaces. Du biochar, produit par la pyrolyse rapide de bois dur, a été appliqué à un taux cible de 5,6 t ha^{-1} à un seul andain (10 m x 100 m) dans un champ agricole au Québec, Canada, en utilisant un épandeur de chaux commercial. Des pertes éoliennes de biochar allant jusqu'à 30 % se sont produites pendant la manutention, le transport et l'application. Nous recommandons de couvrir et d'humidifier le biochar avant de l'épandage, d'éviter l'application les jours de grand vent ou de le mélanger à d'autres matières (p. ex., compost, fumier) pour réduire les pertes éoliennes. L'andain amendé au biochar et un andain adjacent de taille égale qui n'a pas reçu de biochar ont été hersés. Le champ entier a été ensemencé de soja la première saison, d'un mélange avoine-fourrage la deuxième année, puis de fourrage la troisième saison. Les rendements de soja et d'avoine ont augmenté jusqu'à 20 % avec le biochar. Au cours de la troisième saison, le fourrage de l'andain amendé au biochar présentait, d'après l'analyse par spectroscopie dans le proche infrarouge, une plus grande concentration en nutriments qui entrainerait une production laitière plus élevée si ce fourrage était utilisé comme aliment pour les vaches laitières. Le coût variable de l'application du biochar a été estimé à 2 285 $ CA ha^{-1}, ce qui indique la nécessité d'une analyse coûts-avantages complète de l'application du biochar à l'échelle de la ferme.

KEYWORDS

Applicator machine, biochar economics, farm equipment, farm-scale, fine particulate, lime spreader.

MOTS CLÉS

Application mécanisée, aspects économiques du biochar, équipement agricole, échelle de la ferme, particule fine, épandeur à chaux.

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INTRODUCTION

Biochar is a carbonaceous residue obtained when biomass undergoes pyrolysis under low or no oxygen conditions. In laboratory and field studies, biochar improves soil structure, water retention (Karer et al. 2013; Ramlow et al. 2019) and soil nutrient availability (Sänger et al. 2017) in temperate agroecosystems and sometimes increases crop yields (Medynska-Juraszek et al. 2021). However, for biochar to be an attractive and feasible option for commercial field and forage crop production, there must be tangible economic benefits, such as reducing the cost of other agronomic inputs by improving soil quality and/or raising yield. Biochar use may also allow farms to qualify for carbon offset credits, either because biochar increases the soil carbon pool and is counted as part of the carbon sequestration on the farm or because biochar modulates the carbon and nitrogen biogeochemical cycles in a way that reduces greenhouse gas emissions (Sorensen and Lamb 2018). These are essential considerations because applying biochar on farms may cost thousands of dollars per hectare (Dickinson et al. 2015; Homagain et al. 2016; Sorensen and Lamb 2018).

Biochar application on commercial farms may require farmers to modify their agricultural equipment. Most examples of biochar application for agronomic purposes in temperate regions come from controlled experiments (e.g., with <1 kg of soil in the lab or greenhouse) or small-scale field plots where biochar was applied by hand (for example, Rondon et al. 2007; Karer et al. 2013; Borchard et al. 2014; Ahmed and Schoenau 2015; Brantley et al. 2015; Medynska-Juraszek et al. 2021), as opposed to commercial farming machinery that spreads biochar across larger field areas. Little guidance exists on how to apply biochar using standard farming equipment, such as how to avoid biochar loss during its transport, handling, and field application. Therefore, methods for handling biochar on commercial farms must be tested if biochar application is to be a routine agronomic practice.

The objectives of this field study were to: (i) observe the suitability of commercial farming equipment (a lime spreader) to broadcast biochar on an agricultural field, (ii) determine if the target biochar applications by commercial equipment were sufficient to detect crop responses in growth, yield, and nutrient content in the next three growing seasons, and (iii) discuss the cost-benefit analysis of applying biochar using the commercial lime spreader.

MATERIALS AND METHODS

Site description

The experiment occurred over three growing seasons from 2008 – 2010 at a large field located at Ferme Ridelo (N 45º32.598, W 72º02.237) in Saint-François-Xavier-de-Brompton, Quebec, Canada. Mean monthly temperatures in this region range from -10.6°C in January to 19.6°C in July, based on average data from Environment Canada (2019). The valley landscape is dominated by commercial farms that produce field crops such as corn, soybean, and forages for dairy operations in the region. The soil at the field site is a clay loam with approximately 190 g kg^{-1} of clay, 380 g kg^{-1} of sand, 33 g total C kg^{-1}, 2.3 g total N kg^{-1}, 5.2 g total P kg^{-1} and a pH of 5.9, based on data from Sachdeva et al. (2019) and Whalen et al. (2021). Soil is in the Brompton stony loam series and is classified as a poorly drained Podzol (Lamontagne and Nolin, 1997). The field was managed according to local agronomic practices, which include periodic liming based on field-scale soil testing and dairy manure applications once every 1 to 2 year.

Biochar

Biochar used in this trial was manufactured and supplied by DynaMotive Energy Systems Corporation (West Lorne, Ontario, Canada) using fast pyrolysis technology at a temperature of approximately 700°C to convert hardwood waste biomass into biofuel and biochar. The biochar was produced in 2007 and kept in storage by the producer until shipment to the trial site on 16 May 2008. The biochar was packed at the production facility in 200 L (55 US gallon) steel drums containing approximately 55 kg of product and shipped by truck to the farm trial site. Characteristics of the material, as analyzed by SGS Canada Inc. and supplied by the manufacturer, are provided in Table 1.

Plot establishment and treatments

The treatment plot received biochar in a single swath of 10 m x 100 m (1,000 m^2), and an identically sized unamended plot directly adjacent to the treatment plot was used as the control. The experiment was not randomized or replicated. Spreading occurred on 28 May 2008, beginning with a calcitic lime application of 3.4 t ha^{-1} on the entire experimental area (treatment plot and control). Next, biochar was applied on the same day (28 May 2008) to the treatment plot using a full-size lime spreader (Model DECE-600LF, Atelier Desprès Inc, Val-Alain, Quebec) which broadcasts lime across a 10 m wide swath. The target application rate for biochar was 5.6 t ha^{-1}. The amount of biochar necessary to cover the 1,000 m^2 treatment plot (~600 kg) at this application rate was received from the supplier and placed inside the spreader. We estimated the biochar application rate based on the guidelines for lime application provided by the spreader manufacturer. The gate opening, spreader rotation speed, and tractor driving speed were set to deliver 2.8 t ha^{-1} lime. Then we reduced the tractor speed by 50% to effectively double the application rate to the desired 5.6 t ha^{-1}. Since there is an order of magnitude difference between lime density (2,700–6,200 kg m^{-3}) and biochar density (approximately 250 kg m^{-3}), it required two passes to spread the biochar mass contained in the lime spreader. The first pass was made at the minimum programmable tractor speed of 1.9 km h^{-1}, with the spreader height set as low as possible. Approximately 30% of the initial biochar mass remained in the spreader after the first pass. The tractor speed for the second pass was set at slightly more than double that of the first pass (4.8 km h^{-1}). No biochar remained in the spreader upon reaching the end of the 100 m swath after the second pass. After the broadcasting operation was complete, biochar and lime were incorporated by one pass of a disk

Table 1. Typical characteristics of DynaMotive biochar, as provided by the manufacturer. Data are based on the analysis of one biochar sample in March 2006, unless otherwise specified. ASTM methods used are for coal analysis.

Characteristic	Unit	Value	Analytical method	Range[a]
Moisture	%	2.0	ASTM D3173	
Ash	%	10.9	ASTM D3174	1–25
Volatile matter	%	23.9	ASTM D3175	18–30
Fixed carbon (C)	%	65.0	ASTM D3172	
Total C	%	72.5		60–75
Total nitrogen (N)	%	0.5		
C/N		161		
H/C		0.04		
O/C		0.15		
Sulfur (S)	%	0.02		
Aluminum (Al)	mg/kg ash	300	OES-ICP	
Calcium (Ca)	mg/kg ash	6460	OES-ICP	
Phosphorus (P)	mg/kg ash	180	OES-ICP	
Potassium (K)	mg/kg ash	6080	OES-ICP	
Bulk density	kg/m^3			250–350
Particles < 2 mm	Typical %	100		
Particles < 1 mm	Typical %	95		
Particles < 0.5 mm	Typical %	60		

[a]As supplied by the manufacturer in the Material Safety Data Sheet

harrow at approximately 0.1 m depth. The control plot was harrowed at the same depth to incorporate the lime.

In 2008, the entire field was seeded with Roundup Ready® soybean (*Glycine max* (L.) Merr.) variety 2590R (Pro Seeds of Canada, Woodstock, Ontario) during the first week of June. The crop was managed according to local agronomic practices for nutrient, weed, and pest management. Soybean was harvested on 20 October 2008, followed by an application of dairy manure a few weeks later at a rate of 22.4 t ha^{-1}. In spring 2009, plots were tilled and rolled, lime was applied at 3.4 t ha^{-1}, and synthetic fertilizer (6-25-30 MAP) was broadcast at 112 kg ha^{-1}. On 8 June 2009, a mixture of annual ryegrass (*Lolium multiflorum* Lam.), red clover (*Trifolium pratense* L.) and timothy (*Phleum pratense* L.) was broadcast seeded at a rate of 17 kg ha^{-1}, and oats (*Avena sativa* L.) were seeded at a rate of 78 kg ha^{-1} using a seed drill. Forage was harvested once during the growing season on 20 August 2009, and 20 cm of stubble was left behind. The spring was very wet in 2009, and forage was seeded late, resulting in the slow establishment of the stand, which improved throughout the season. Oats were not re-seeded in 2010, but the forage mixture was established in the field without replanting.

Plant sampling and analysis

No samples were taken from the 5 m adjacent to the biochar-amended plot to avoid sampling areas of the control plot possibly being contaminated with biochar. Plant density of the soybeans in 2008 was assessed in each plot on 11 and 15 October by measuring the length of one row that encompassed 100 plants and the length of two adjacent rows that contained 50 plants. The number of plants was also counted in four 1 m^2 quadrats. Plant samples were taken on 15 October by harvesting 50 whole soybean plants from two adjacent rows in the middle of each plot (total=100). These plants were measured individually for above-ground height, taproot length, total pod weight, and total seed weight. Soybean yield was evaluated on 20 October 2008 using a New Holland® self-propelled combine harvester (model CR9070) equipped with a Precision Land Management® yield and moisture monitor. Before harvest, the crop yield monitor for soybean was calibrated for moisture content and the speed of the harvester. Once calibrated, the yield monitor for this equipment was accurate to ± 5%.

Plant samples (oat) were taken in 2009 on 20 July, 17 August, and 20 September by harvesting one whole oat plant along a transect positioned diagonally at 45° to 32 rows in each field plot (32 plants in biochar plot, 32 plants in control plot). Oat samples were assessed for root length, above-ground plant height, and total length. On 1 August 2009 (before harvesting the forage), the number of oat plants were counted in three 1 m^2 quadrats, and above-ground oat biomass was collected from the quadrats to determine the fresh weight. Oat and forage samples were sent to a forage analysis laboratory (Agri-Analyse Agricultural Laboratory, Sherbrooke, Quebec, Canada) for analysis of plant nutrients (protein, fat, starch, fibre, and minerals) by near-infrared (NIR) spectroscopy. The lab also entered the NIR results in software developed specifically for the dairy industry (MILK2006, R. Shaver et al., University of Wisconsin) to project dairy cattle milk production potential based on the forage quality, quantity, and dry matter intake (Schwab et al. 2003).

Fig. 1. Clockwise from top left: Biochar losses during handling, transportation, application with a commercial lime spreader, and incorporation at a field site in Quebec, Canada.

In 2010, above-ground forage biomass was harvested from five 1 m^2 quadrats on 11 June, 22 July, 17 September, and 6 October. Fresh weight was the cumulative total from all four sampling dates. Forage samples were sent to the same analysis lab that was used in 2009 (Agri-Analyse Agricultural Laboratory) for NIR-based plant nutrient analysis and projected milk production from forage.

Statistical analysis

Since the experiment was not replicated, no statistical analyses were done. Averages and standard deviations illustrate the variability in the repeated measurements made within each field plot (biochar-amended vs control).

RESULTS AND DISCUSSION

Biochar application and losses

Biochar was broadcast applied with the commercial lime spreader, but some losses occurred when it was transferred into the spreader, and not all of the particles were deposited in the field area. Visually, we estimated biochar losses of 2% (by mass) during handling and loading, 3% during transport to the field, and 25% as windborne losses during the broadcast application, for a total of 30% mass loss of biochar (Fig. 1). Thus, the actual application rate is estimated to be 70% of 5.6 t ha^{-1} (i.e., 3.9 t ha^{-1}). Biochar used in this study was composed of small particles (approximately 60% passed through a 0.5 mm sieve, Table 1) that were not moistened before handling and application, making them susceptible to dust production and windborne losses. Page-Dumroese et al. (2016) demonstrated that bulk and pelleted biochar could be successfully applied to forest soils by modifying existing logging equipment. They also noted that excessive dust was produced during broadcast application because the biochar was not moistened before application. This poses an occupational hazard that may require operators to use personal protective equipment such as masks or respirators when handling biochar. Although windborne loss is likely when fine biochar particles are spread on fields by broadcasting, it is not the only way surface-applied biochar can be transferred from agricultural fields to adjacent environments. Major et al. (2010a) inferred biochar losses of up to 53% after spreading on coarse soil, which they attributed to the waterborne runoff of biochar remaining on the soil surface during intense rain events.

It seems inevitable that some biochar particles will be lost when biochar is transferred from storage containers into farm equipment. However, we could minimize dust emitted from the equipment by covering the loaded lime spreader with a tarp or impermeable plastic when it is driven from the loading area to the agricultural field. Avoiding biochar application on windy days and moistening the material before application may also help prevent windborne loss of biochar particles. This is especially important when spreading finely-ground biochar, as was used in our study. Another option is to mix biochar with compost or manure, which would retain the fine particles in a moist, dense matrix to physically protect the biochar from windborne and waterborne losses. A biochar-compost mixture provides the greatest flexibility for agronomic use since it could be broadcast and incorporated or top-dressed and left without incorporation on the soil surface. In contrast, manure should

Table 2. Soybean yield data from the mechanical harvester in the 2008 season.

Parameter	Unit	Control	Biochar
Harvested surface area	ha	2.46	0.18
Dry weight	kg	2640	93
Moisture content	%	13.8	13.7
Average dry yield	kg ha^{-1}	1073	1283
Yield increase with biochar	**%**		**20**

Table 3. Percent increase in soybean plant density with biochar application in the 2008 season.

Method	Increase with biochar
100 plants on a single row	25%
50 plants on 2 adjacent rows	68%
One 4 m^2 quadrat	11%
Average	**35%**

be incorporated as soon as possible after spreading to minimize ammonia volatilization (Whalen et al. 2019). Adding biochar to compost increases the N retention in the biochar-compost mixture, reduces odours, and speeds up the composting process (Dias et al. 2010; Steiner et al. 2010). However, a mix of biochar with manure or compost may be challenging to apply using a lime spreader. It would likely require using other types of application equipment (e.g., manure spreader). Since we expect fine biochar particles to drift outside of the target field during land-spreading operations, we need to identify the optimal practices that minimize biochar losses, and these will likely depend on site-specific soil and environmental factors, as well as daily conditions. The actual biochar application should be quantified in future studies using a standardized procedure, such as ASABE Standard S573.

Plant responses to biochar application

There was no effect of biochar application on measured soil properties (soil respiration, temperature, pH, moisture, carbon content) during this 3 year study (data not shown). Still, several plant responses to biochar were observed in some seasons and crops. Plant responses were more apparent in 2009 and 2010 when forage was planted than in the first year of application (2008) when soybean was planted. This may be because forage is more responsive to biochar applications. It may also be because it takes time for biochar to be weathered and contribute to soil fertility, meaning that the biochar effects would increase with time. For example, Major et al. (2010b) found no difference in maize yield in the first year following biochar application, but significant increases in yield were observed in the second, third, and fourth years. In our work, the notable difference in the soybean planted in 2008 was a 20% increase in yield (Table 2). However, we are aware that the calculated yield from the machine harvester could be biased by the different harvest areas of the biochar-amended plot (0.18 ha) and control plot (2.5 ha) in this field. Still, soybean plant densities were greater in the biochar-amended plot than in the control plot (Table 3). In 2008, taproot length increased, but soybean had a shorter above-ground height with biochar addition. Individual seed pods and seeds had similar weights in the biochar-amended and control plots (data not shown).

Oat morphology responded to biochar application before forage was harvested on 20 August 2009. Oat shoots were taller, while root length and total plant length tended to be longer with biochar application, although there was no difference in root length between control and biochar-amended plots on 17 August (Table 4). At forage harvest (i.e., sampling on 28 September), oat morphology was similar in the control and biochar-treated plots (Table 4). Oat plant density and fresh weight were more than double in the biochar-amended plot than in the control plot in 2009. The total fresh weight of above-ground forage biomass was 4.1% greater in the biochar-amended plot than in the control plot in 2010 (data not shown).

Forage nutrient analysis by NIR and projected milk production tended to be similar in the biochar-treated and control plots in 2009 but differed more in the 2010 season (Table 5). Protein, fat, starch, total minerals, and energy – measured as Total Digestible Nutrients (TDN) – were 3–13% greater in forage collected from the biochar-amended plot than in the control plot in 2010 (Table 5). Projected milk production from forage was 16–44% greater in the biochar-amended plot than in the control plot in 2010. We are not aware of other studies that have evaluated the projected milk production of dairy cattle that are fed forage grown on biochar-amended soil. Our results suggest that improved forage quality and yield following biochar application to commercial fields may be economically advantageous for dairy producers. This needs to be confirmed with additional studies. Biochar application produces a variable growth response and nutrient composition in perennial forages. For example, Lu et al. (2020) found that adding biosolids increased the crude

Table 4. Oat morphological parameters on 20 July, 17 August, and 28 September in the 2009 season. Values are mean ± standard deviation of 32 plants taken from transects angled at 45° to the row length within each field plot (biochar and control).

	20 July 2009		17 August 2009		28 September 2009	
	Control	Biochar	Control	Biochar	Control	Biochar
Above-ground plant height (m)	0.22 ± 0.06	0.28 ± 0.05	0.44 ± 0.08	0.50 ± 0.10	0.23 ± 0.06	0.23 ± 0.06
Root length (m)	0.09 ± 0.02	0.11 ± 0.02	0.10 ± 0.02	0.10 ± 0.03	0.08 ± 0.02	0.10 ± 0.02
Total length (m)	0.31 ± 0.07	0.39 ± 0.06	0.53 ± 0.09	0.60 ± 0.11	0.32 ± 0.07	0.33 ± 0.07

Table 5. Near-infrared (NIR) nutrient analysis (% dry matter basis) and projected milk production from forage samples collected in 2009 and 2010.

	9 August 2009		7 October 2009		17 September 2010	
	Control	Biochar	Biochar	Biochar	Control	Biochar
Crude protein (%)	12.8	11.3	16.6	16.1	12.7	14.0
Fat (%)	2.2	2.1	3.1	3.0	2.5	2.6
Starch (%)	3.1	3.0	4.1	3.8	4.5	4.7
Fibre						
Acid detergent (%)	34.1	34.8	26.5	28.1	38.0	36.0
Neutral detergent (%)	56.9	58.5	44.5	48.0	57.1	53.8
Minerals						
Calcium (%)	0.5	0.5	1.0	0.8	1.0	1.1
Phosphorous (%)	0.3	0.3	0.3	0.3	0.2	0.3
Potassium (%)	1.4	1.2	1.3	1.2	1.0	1.0
Magnesium (%)	0.2	0.2	0.2	0.2	0.3	0.3
Sulfur (%)	0.1	0.1	0.2	0.2	0.2	0.2
Chloride (%)	2.2	1.9	2.4	2.6	1.1	1.2
Sodium (%)	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
TDN[a]	57.4	57.4	65.4	62.6	48.4	51.4
Milk production from forage						
kg d^{-1}	4.57	4.09	4.03	3.22	4.10	5.90
kg MT^{-1}	346	334	292	269	796	927

[a]TDN = total digestible nutrients (Weiss)

protein content of perennial bahiagrass (*Paspalum notatum* Flügge) by up to 39% compared to the unamended control. Still, crude protein values of this forage were the same in biochar and inorganic fertilizer-treated plots in their experiment. Biochar application to bahiagrass had no effect on plant nutrient and mineral content (N, P, K, S, Ca, Mg, Fe, Mn, Zn, and Cu) (Lu et al. 2020). However, Mclennon et al. (2022) found that those forage tissue concentrations of P, K, S, and Mn were significantly higher in forage plots treated with biochar than in unamended plots. A meta-analysis of 114 studies found an increase in plant tissue K with biochar application but no effect of biochar on plant N concentration (Biederman and Harpole 2013). These inconsistent results are explained by the fact that biochar is a heterogeneous material and its performance as an agricultural soil amendment depends upon its physicochemical properties resulting from the type of feedstock material, pyrolysis temperature, particle size, surface area, application rate and method, as well as site-specific soil and field conditions.

Economic considerations of biochar application

Widespread adoption of biochar application on commercial farms will only be feasible if the practice is cost-effective for farmers. The principal variable costs include purchasing the biochar material, transportation to the field location, and equipment operating costs for in-field handling and application (Sorensen and Lamb 2018). The variable costs for applying biochar in our study included CA$350 t^{-1} for purchasing the biochar, CA$50 t^{-1} for transportation to the field site, CA$100 total for equipment operating costs, and CA$150 total for labour costs. At an application rate of 5.6 t ha^{-1}, the total variable, non-recurring cost of biochar application in our study was estimated to be CA$2,285 ha^{-1} (approximately US$1,819 ha^{-1} based on an exchange rate of $US0.80). This is lower than other studies that have analyzed costs associated with large-scale biochar applications. Still, it is important to note that the biochar application rate in our study (5.6 t ha^{-1}) is much less than the typical field application rate, which ranges from 12 – 148 t ha^{-1} (Dickinson et al. 2015; Homagain et al. 2016; Sorensen and Lamb 2018). Significant costs can be associated with large-scale biochar applications at higher application rates. Dickinson et al. (2015) found the cost of applying biochar at a rate of 13 t ha^{-1} in temperate regions to be US$2,019 – 3,365 ha^{-1}. Sorensen and Lamb (2018) reported even higher costs, with the purchase and application of biochar at 25 to 148 t ha^{-1} using an on-farm manure or spinner spreader at US$7,163 – 44,277 ha^{-1}. The most efficient and cost-effective way to apply the biochar was to pay by mass and use the largest volume spreader available. This significantly decreased the unit costs associated with labour and loading time (Sorensen and Lamb 2018).

For most farmers, the high costs of biochar application must be justified by a return on investment. One way would be through increased yield, although yield benefits and increases in plant growth from biochar are more likely in tropical soils than temperate soils (Jeffery et al. 2017) or when biochar is combined with nitrogen fertilizer in temperate soils (Brantley et al. 2015; Glaser et al. 2015). Overall, the cost-benefit analysis of applying biochar in temperate regions for cereal production tends to be negative based on present total costs set against present total benefits, even under an indefinite timespan (Dickinson et al. 2015). However, another economic benefit from biochar application in temperate agroecosystems may be from carbon offset credits which represent an amount of carbon dioxide equivalent gases (tCO_2e^{-1}) removed from the atmosphere and purchased by governments, industry, or private entities as an offset to generated carbon emissions (Galinato et al. 2011; Homagain et al. 2016; Sorensen and Lamb 2018). In a hypothetical life cycle cost assessment, Homagain et al. (2016) found that biochar production and application in northwestern Ontario, Canada, is profitable only when the price of carbon credits exceeds CA$60 tCO_2e^{-1} on a 25-year revenue basis and when there is abundant feedstock biomass available within 200 km of the application site. Similarly, Field et al. (2013) and Dickinson et al. (2015) found the costs of biochar application in temperate regions were at a breakeven point when carbon credits were at least US$50 – 63 tCO_2e^{-1}. The price for carbon credits in Canada was set at CA$20 in 2019, with prices projected to reach $65 tCO_2e^{-1} in 2023 and expected to rise by $15 every year to reach $170 tCO_2e^{-1} in 2030 (Government of Canada 2021). In the U.S., carbon credits range from US$1 – 119 tCO_2e^{-1}, though half of the emissions covered by carbon credits are priced at less than US$10 tCO_2e^{-1} (World Bank 2020). Therefore, the economic incentive to apply biochar on a commercial farm scale in temperate soils may only become apparent if more beneficial agronomic uses for biochar are developed, the cost of feedstock decreases enough to reduce the costs of biochar production, or a more robust market for carbon credits is developed (see Galinato et al. 2011; Dickinson et al. 2015; Bach et al. 2016).

CONCLUSIONS

Despite windborne losses of up to 30% during its application, biochar was successfully applied on a farm scale using commercial farm equipment at a rate that could produce measurable plant responses in the first three years. Moistening the biochar before handling, covering open-top spreaders, avoiding application on windy days, and mixing with compost are practical strategies that may prevent fine biochar particles from being carried away from the application area by wind. However, we recommend further research to develop site-specific management plans for field-scale biochar applications. Plant responses to machine-applied biochar included increases in soybean yield in the first season, oat yield in the second season, and greater forage nutrient uptake in the third season. Greater forage nutritional values under biochar treatment resulted in greater projected milk production, suggesting possible economic advantages of biochar application on dairy farms. The limited yield improvement from biochar in temperate cropping systems indicates that commercial crop producers' acceptance and use of biochar will depend primarily on economic incentives realized through the sale of carbon offset credits accrued by amending the soil with this carbon-rich material with a long residence time.

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