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Impact of Soil Amendments on the Hydraulic Conductivity of Boreal Agricultural Podzols

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Abstract: Hydraulic properties of soil are the basis for understanding the flow and transport through the vadose zone. It has been demonstrated that different soil amendments can alter the soil properties affecting soil hydrology. The aim of this study was to determine the effect of soil amendments on hydraulic conductivity (K) of a loamy sand podzolic soil under both unsaturated (K_{unsat}) and near-saturated (near K_{sat}) conditions in an agricultural setting. A field experiment was conducted with two common soil amendments: Dairy manure (DM) in 2016 and 2017 and biochar (BC) once only in 2016. DM and BC were incorporated up to a depth of 0.15–0.20 m at a rate of 30,000 L ha^{-1} and 20 Mg ha^{-1}, respectively. A randomized complete block experimental design was used and the plots planted with silage corn (*Zea mays* L.) without irrigation. The treatments were: Control without amendment (0N), inorganic N fertilizer (IN), two types of DM (IN+DM1 and IN+DM2), and two treatments with BC (IN+BC and IN+DM1+BC). Infiltration data were collected using a mini disk infiltrometer under three tension levels in which −0.04 and −0.02 m was ascribed as unsaturated (at the wet end) and −0.001 m as near-saturated condition. Based on the measured infiltration rates, K_{unsat} and near K_{sat} hydraulic conductivities were calculated. There were no significant effects of DM and BC on bulk density and near K_{sat}. Treatments IN+DM1, IN+DM2, and IN+DM1+BC significantly reduced the K_{unsat} compared to the control. Since these soil amendments can influence soil hydrology such as reduced infiltration and increased surface runoff, carefully monitored application of soil amendments is recommended.

Keywords: biochar; dairy manure; hydraulic conductivity; infiltration; podzols; soil amendments

1. Introduction

The soil unsaturated zone, also called zone of aeration or vadose zone, is the soil layer above the groundwater table. In agricultural and arable soils, the unsaturated zone provides air, water, and nutrients to plants and soil organisms [1,2]. Hydrologically, the vadose zone controls water and contaminant entry, storage, and movement from the soil surface to the groundwater [3]. Thus, understanding the dynamics of the unsaturated zone is critical for the use and sustainable management of groundwater. Hydraulic properties of soils such as hydraulic conductivity (K) and the moisture retention function are critical for understanding flow and transport through the soil matrix and are important inputs in vadose zone simulations [4,5]. In addition, saturated and unsaturated hydraulic properties of any soil will influence the separation of input water (i.e., precipitation/irrigation) into runoff and infiltration [6]. Unsaturated (K_{unsat}) and saturated (K_{sat}) hydraulic conductivity is a measure of how water flows through unsaturated and saturated soil profiles, respectively [7], and K_{sat} is often used as an indicator of how water flows through unsaturated soils, which is generally overestimated [1,5].

Synthetic fertilizers are added solely to improve soil fertility; however, the main purpose of using natural soil amendments such as manure and biochar (BC) is to improve overall physical, chemical, and biological properties of soils [8–10].

Dairy manure (DM) and BC are commonly used by farmers worldwide, thus physicochemical and hydraulic properties of agricultural soils are continuously being altered by the use of amendments and other management practices. Previous studies have reported that DM amendments improved the soil tilth and porosity [11], increased soil infiltration rates, K_{sat} [12,13] crop yields [14], soil organic matter (SOM), and aggregation as well as decreased the soil bulk density [15,16]. The addition of BC improved soil chemical properties such as pH and cation exchange capacity (CEC) due to higher surface area [17], physical properties such as porosity and bulk density [18–21], and provided suitable habitats for microorganisms [22]. Both DM and BC facilitate soil aggregate formation by stimulating microbial and fungal activity, increasing their exudate production, and providing greater binding agents between soil particles [23]. In addition, aromatic components in BC can also contribute to the stabilization of microaggregates when compared to DM [24,25]. Earthworms mix soil amendments such as BC and DM throughout the soil profile and further assist in aggregate stabilization [26]. Soil aggregates are very important in soil property determinations because they prevent rapid biodegradation of SOM, thus enhancing the soil structure and porosity [27,28].

Increased surface area of the solid phase and porosity of soil has been shown to influence the soil structure through changing the overall surface area, amount, size, and distribution of soil pores, and bulk density thus improving soil aeration and soil strength [29,30]. Additional advantages of BC application to agricultural soils are the reduction in greenhouse gas emissions [31–33] and carbon sequestration [34–36].

Studies reporting the effects of BC and DM on K_{sat} vary in the literature and those reporting the effects on K_{unsat} are very limited and inconclusive, particularly relating to podzolic soils common in boreal ecosystems [37,38]. Generally, podzolic soils are formed from coarse- to medium-textured, acidic parent materials under forest or health vegetation in cool climates. However, these soils can occur in wet sandy sites in areas of subhumid climates and can also be formed from calcareous parent materials. Podzols are distinctively characterized by illuviated B horizons where humified organic matter combined with Al and Fe accumulation, often overlaid by a light colored eluviated (Ae) horizon [39]. Despite the growing need for food production in cool climatic regions globally and the expansion of agriculture and human population in boreal environments containing podzolic soils, there is limited information available on hydraulic properties and water management of podzolic soils for effective agricultural production in these environments [40].

Amending the soil with different types and rates of DM and BC may have varying and specific influences on soil properties due to the composition and inherent properties of DM and BC amendments. The age and health conditions of the herd and feeding practices can influence the quality and quantity of DM as can the type of bedding, amount of water used in the barn or added to DM, and the type and duration of storage can affect DM composition and properties [41]. The type of biomass used as the feedstock and pyrolysis conditions such as temperature and charring time can affect BC properties as well. Organic soil amendments such as BC and DM may alter the soil properties according to the type of soil and climatic conditions [19,22,42]. Additionally, the aging of these amendments may have different and complex effects on soil properties [43,44]. Since high DM application rates can potentially increase water repellency, localized patches with higher water infiltration potential can also be formed resulting in selective water entry into the soil, stimulating preferential flow paths. Hence, water repellency may bypass the complete wetting of the soil matrix, causing microbial, nutrient, and agrochemical leaching or runoff, subsequently increasing groundwater contamination [45,46].

Moreover, this localized wetting, leaching, and runoff can cause nutrient deficiency in crops and decreased availability of soil moisture in the rhizosphere [47,48].

Knowledge of the K_{unsat} and K_{sat} and its variability is essential for describing the infiltration capacity, flow, and solute transport in such soils where soil amendments are added. The main objective of this study was to evaluate the effect of the application of DM and BC as soil amendments on infiltration capacity under both unsaturated and near-saturated conditions in agricultural podzols in a boreal climate. In order to achieve this objective, K_{unsat} (at −0.04 and −0.02 m tension) and near K_{sat} (−0.001 m tension) were estimated using a mini disk infiltrometer with an emphasis on amending agricultural podzolic soil with DM and BC.

2. Materials and Methods

The study was conducted at Pynn's Brook Research Station (PBRS) operated by the Department of Fisheries and Land Resources, Government of Newfoundland and Labrador, Pasadena (49°04′22.6′′N 57°33′38.9′′W), Canada. Data collected during 30-years (1986–2016) by the Deer Lake weather station and obtained from Environment Canada (http://climate.weather.gc.ca/) shows that the area receives an average precipitation of 1113 mm per year with less than 410 mm falling as snow, and has an annual mean temperature of 4 °C. Handheld GPS measurements have indicated an elevation between 43 and 50 m a.s.l. The reddish brown to brown podzolic soil developed on a gravelly sandy fluvial deposit with >1.0 m depth to bedrock with an average slope of 2% to 5% [49]. The soil tested is classified as a loamy sand podzol (73.7 ± 4.1% sand + 23.0 ± 3.8% silt + 3.3 ± 0.3% clay) with an average bulk density of 1.31 g cm^{-3} (± 0.07) and porosity of 51% (±0.03) [40]. The area was tile drained (at 0.75 m depth) and the depth to the water table (2017 and 2018) varied between 1.58–2.98 m with an average of 2.48 m.

2.1. Experimental Design and Land Preparation

The experiment was conducted using a randomized complete block design containing 32 experimental plots each having dimensions of 1 m width and 5 m length.

This study was part of a silage-corn (*Zea mays* L.) varietal trial (2015 to 2017) evaluating the effect of soil amendment on nitrogen (N) losses and greenhouse gas emission. There were eight treatments within the main experiment and each treatment was replicated four times. However, only six treatments were considered for this study and included amendments using two types of DM according to their total N and total phosphorous (P) contents [DM1 with high N (0.44%), P (0.08) and DM2 with low N (0.12%), P (0.01%)] and granular BC produced by slow pyrolysis at 500 °C for 30 min of Yellow pine wood (*Pinus taeda*). The six treatments used in this study were: N0 (no N-control), IN (inorganic N), IN+DM1, IN+DM2, IN+BC, and IN+DM1+BC. Tables 1 and 2 show the basic properties and characteristics of BC and DM used in this study. The field was ploughed with a spring disc for seed bed preparation. DM (in both 2016 and 2017) was applied at a rate of 30,000 L ha^{-1} according to local agricultural practice (surface broadcasting of a liquid slurry) and additional inorganic N was applied to fulfill the N requirements of the crop. BC (only once in 2016) was incorporated at a rate of 20 Mg ha^{-1} and thoroughly mixed within the top 0.15–0.20 m of the soil. Silage corn was seeded (at a rate of 90,900 seeds ha^{-1}) using a SAMCO system (SAMCO Agricultural Manufacturing, Ireland). This system was also used to cover the seeded fields with plastic sheets. The plastic sheet provided additional heat units to enhance seedling germination and establishment during early growth stages of silage corn in cool climate production systems [50]. The field was not irrigated, thus the crop relied solely on seasonal precipitation. The infiltration tests were carried out in the middle of the growing season when the crop was at the tasseling stage (4–22 August 2017).

Table 1. Basic properties of biochar used in the study.

Feedstock	Unit	Yellow Pine Wood (*Pinus taeda*)
Particle size	mm	1–6
Bulk Density	(g cm^{-3})	0.20
Moisture	%	15.2
pH (1: 10 BC: Water)	–	9.0
EC (1:10) at 21–22 °C	(dS m^{-1})	5.2
Fixed carbon	%	87.3
Volatile Carbon (600 °C)	%	12.7
Ash	%	6

Table 2. Basic characteristics of two types of dairy manure used in the study [51].

Characteristic (as Received Basis)	DM1	DM2
Dry matter (%)	10.90	1.70
pH	6.80	7.10
Total Nitrogen (%)	0.44	0.12
Total Phosphorus (%)	0.08	0.01
Total Potassium (%)	0.37	0.12
Total Calcium (%)	0.19	0.04
Total Magnesium (%)	0.07	0.01
Total Iron (mg kg^{-1})	68.00	7.00
Total Manganese (mg kg^{-1})	21.00	5.00
Total Copper (mg kg^{-1})	4.50	20.00
Total Zinc (mg kg^{-1})	21.00	5.00
Total Boron (mg kg^{-1})	3.40	0.50
Total Sodium (mg kg^{-1})	904.00	241.00

2.2. *Infiltration Tests and Measurements*

There are a number of experimental and empirical methods used on both field and laboratory scales to determine the soil K. The use of the mini disk infiltrometer (a tension infiltrometer) is one such method that has been developed to measure field K [52,53].

In this study, the mini disk infiltrometer (METER Group Inc., WA, USA) was used to estimate K_{unsat} of the surface soil. This instrument has been used to determine K_{unsat} of soils in various studies including different plant covers and soil types [54,55]. The tension infiltrometer can be used to estimate the K_{unsat} by measuring the soil infiltration at different applied tension levels. These tension levels generally are in the wet end of most agricultural soils (−0.005 to 0.06 m) to measure K_{unsat} avoiding macropore (cracks or wormholes) flows. The instrument consists of a water reservoir, a mariotte tube, a bubble chamber, a tension control tube, and a porous sintered stainless-steel contact disc, 4.5 cm in diameter and 3 mm in thickness (METER Group Inc., WA, USA). The operating principle is based on releasing water from the infiltrometer to the soil surface under a controlled tension. The controlled tension in the infiltrometer is managed by the mariotte tube in the bubble chamber and the porous stainless-steel plate. Therefore, only soil pores with matric potential lower than the applied tension (or higher soil suction) can be filled. Infiltration is carried out until constant infiltration rates are achieved [56]. Using this technique, K_{unsat} in the soil matrix can accurately be estimated eliminating preferential flow caused by cracks, bio-macropores, and other structures [56,57].

After filling the bubble chamber and water reservoir with water, the mini disk infiltrometer was placed on a levelled sampling soil surface prepared with a thin layer of fine sand to facilitate good contact with the stainless-steel plate. The soil surface was cleared of vegetation and levelled to a smooth horizontal surface to ensure even contact with the infiltration disc.

The infiltration tests were carried out at the three tension levels of −0.04, −0.02, and −0.001 m in a sequence of high to low tensions. Based on the texture of the soil, the recommended tension level was

−0.02 m for K_{unsat} measurements (METER Group Inc., Pullman, WA, USA); however, −0.001 m was assumed to be close to near K_{sat} and other tension levels such as −0.06, −0.04, and −0.01 m were also tested. The initial readings were taken at all tension levels. As the water infiltrated, the water level in water reservoir was recorded at regular time intervals of 30 s, except for measurements at −0.001 m which were recorded at 15 s because of the increased rate of infiltration under −0.001 m tension. Each treatment was replicated four times, and for each treatment plot, infiltration tests were carried out in three different locations, and the average K_{unsat} and near K_{sat} was calculated. This experiment was carried out during the middle of the growing season and assumed that soil surface in each plot had settled after initial plowing and incorporation of DM and BC. We selected each location (three locations per plot) for the infiltration experiment after carefully observing the surface and selected less disturbed (well settled) surfaces. This allowed us to ensure that the infiltration was affected by the treatment only and not by other surface disturbances.

The resulting time and cumulative infiltration data were entered into a Microsoft Excel Macro Workbook provided by the manufacturer (Meter Group Inc., Pullman, WA, USA) to calculate K_{unsat} using the method proposed by Zhang [5]. Cumulative infiltration (I) was calculated using Equation (1).

$$I = C_1 t + C_2 \sqrt{t} \tag{1}$$

where C_1 is a parameter related to K (m s^{-1}) and is the slope of the relationship between I and $\sqrt{t}$ (Equation (2)), C_2 is soil sorptivity (m s$^{-1/2}$), t is the infiltration time (s). The K for the soil is then computed from Equation (2).

$$K = \frac{C_1}{A} \tag{2}$$

A is computed as in Equation (3) and is related to the van Genuchten parameters for a specific soil type to the tension rate and the radius of the infiltrometer disk,

$$A = \frac{11.65\,(n^{0.1} - 1)\,\exp[2.92\,(n - 1.9) \propto h_0]}{(\propto r_0\,)^{0.91}} \tag{3}$$

where n and α are the van Genuchten parameters [58], r_0 is the radius of the infiltrometer's disk (22.5 mm), and h_0 is the tension at the infiltrometer's disk surface.

Soil moisture release curves were developed by collecting disturbed soil samples from IN, IN+BC, IN+DM1, and IN+BC+DM1 treatment plots. Disturbed soil samples were collected from a depth of 0 to 0.15 m at three locations for each treatment plots but only from two replicates. Samples from three locations in each plot were mixed together and a composite sample was prepared and then oven-dried at 105 °C for 24 h. After removing large stones and other inert materials, repacking of samples in pressure plate rings or tension funnels for conducting the hanging water column methods was done according to the field-measured bulk density value obtained from each treatment. Bulk density was measured by collecting undisturbed soil core samples and dividing the dry soil mass by the core volume [40]. Porosity and saturated water content were determined first by estimating the volume of water needed to saturate the air-dried samples. At lower tension levels from 1 to 8 kPa, data were collected using the hanging water column method, and from 20 to 1000 kPa, data were collected using the pressure plate apparatus. Field capacity (FC) values were obtained at 20 kPa, and permanent wilting point values (PWP) were obtained at 1000 kPa (we could not obtain values for 10 kPa and 1500 kPa using the pressure plate). Based on saturation, FC, and PWP values, macro pore volume (MPV) (drainable porosity), and available water content (AWC) were calculated.

2.3. Statistical Analysis

Statistical analyses were carried out using Minitab 17® statistical software package (©Minitab Inc. at http://www.minitab.com/en-us/). The data were checked for normality (Anderson–Darling test) and outliers (Grubb's test). To identify differences in computed K_{unsat} (cm s^{-1}) among the six treatments under three tension levels, one-way analysis of variance (ANOVA) and Tukey's tests were carried out at a 95% confidence level.

3. Results and Discussion

According to the Anderson–Darling test and Grubb's test, the data were normally distributed without outliers. The average bulk density of the field plots under different treatments ranged from 1.19–1.49 g cm^{-3} (Figure 1). Only IN+DM1 and IN+BC plots had significantly lower (p = 0.017 and p = 0.013, respectively) bulk density compared to the control. This was around a 20.0% reduction (DM1 −19.7% and IN+BC–20.3%) of the bulk density in comparison to the control treatment. On the other hand, IN+DM1+BC treatment reduced the bulk density by 11.0% but was not statistically significant (p = 0.302). Due to the significant differences in bulk density among treatments, the change in bulk density was also considered when comparing the treatment effect on K. We observed that the effect of bulk density on the K_{unsat} and near K_{sat} was not significant for all tension levels tested. Therefore, any effect among treatments could not be attributed to the bulk density ranges observed in this experiment.

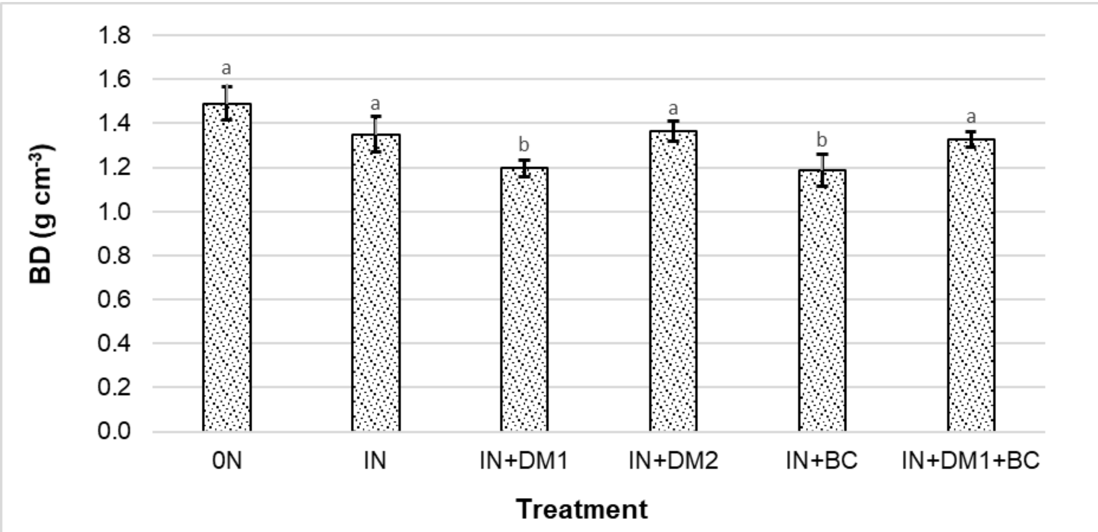

Figure 1. Average bulk density (BD) for field plots for different treatments (error bars show standard error of the mean; n = 36, alpha = 0.05). 0N: No nitrogen (control); IN: Inorganic nitrogen; DM1: Dairy manure 1; DM2: Dairy manure 2; BC: Biochar.

The K increased with decreasing tension level regardless of the treatment as expected (Figure 2). The IN+DM1 treatment showed significantly reduced K values compared to the control under −0.04 and −0.02 m tensions (IN+DM1: p = 0.005 and 0.000; IN+DM1+BC: p = 0.006 and 0.001, respectively). Moreover, IN+DM2 significantly reduced K under −0.02 m tension (p = 0.000). There were no significant changes in K under −0.001 m tension, which was assumed as the near-saturated K at field conditions. However, a relatively high variability of near K_{sat} at −0.001 tension for the IN treatment was found. The tested soil was a loamy sand podzol (high sand = 73.7 ± 4.1%) which generally has more macropores (relatively high gravitational water). The reduction in K in DM treatments might be due to liquid dairy manure clogging the soil pores or changes in soil porosity [59,60]. On the other hand, the difference in K_{unsat} values between DM1 and DM2 at −0.04 m tension could be mainly due to the difference in dry matter contents between the two DM types (Table 2). However, amended BC did not reduce K significantly, which might be due to its granular nature (1–6 mm particle size) and the soil porosity may be less affected by the BC amendment compared to when DM was applied. It is important to note that the infiltration experiments were carried out at the middle of the growing season when the soil surfaces were assumed to be well settled. Indeed, further studies should be carried out under controlled conditions to confirm these findings. Previous researchers have reported that high soil heterogeneity at field level as well as different properties of soil amendments can have mixed and complex effects on soil hydraulic properties as discussed at the end of this section.

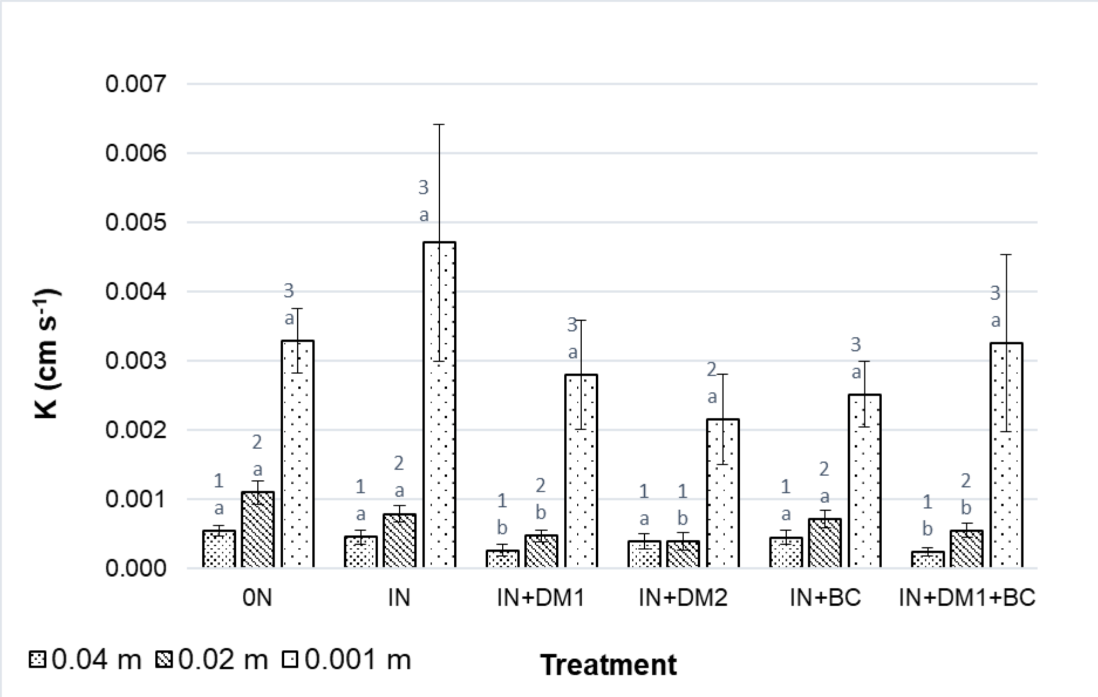

Figure 2. Average field hydraulic conductivity (K) following the addition of biochar (BC) and dairy manure (DM) as soil amendments. Error bars show the standard error of the mean (n = 12, alpha = 0.05). Letters represent significant differences between treatments for a given tension and numbers represent significant difference between tension levels in a given treatment. 0N: No nitrogen (control); IN: Inorganic nitrogen; DM1: Dairy manure 1; DM2: Dairy manure 2; BC: Biochar.

Figure 3 shows the soil moisture release curves developed for IN, IN+BC, IN+DM1, and IN+BC+DM1 plots (data are shown only for lower tension levels until 300 kPa). Saturation (sat), FC, PWP, MPV, and AWC values are shown in Table 3. The highest saturation was observed in the IN+DM1 treatment, while the lowest was found in the IN+BC treatment. The highest water content at FC and PWP was found in plots treated with both DM and BC, while the highest PAW was found in plots amended with IN. These preliminary results unique sampling indicate that DM and BC may have some effects on macro porosity and available water but cannot be fully confirmed by experimental limitations. However, a clear and systematic relationship could not be observed since we developed only one relationship per treatment. More detailed assessment using undisturbed samples representing different soil depths with replicates are needed to evaluate effects of BC and DM on soil hydraulic properties at a field level.

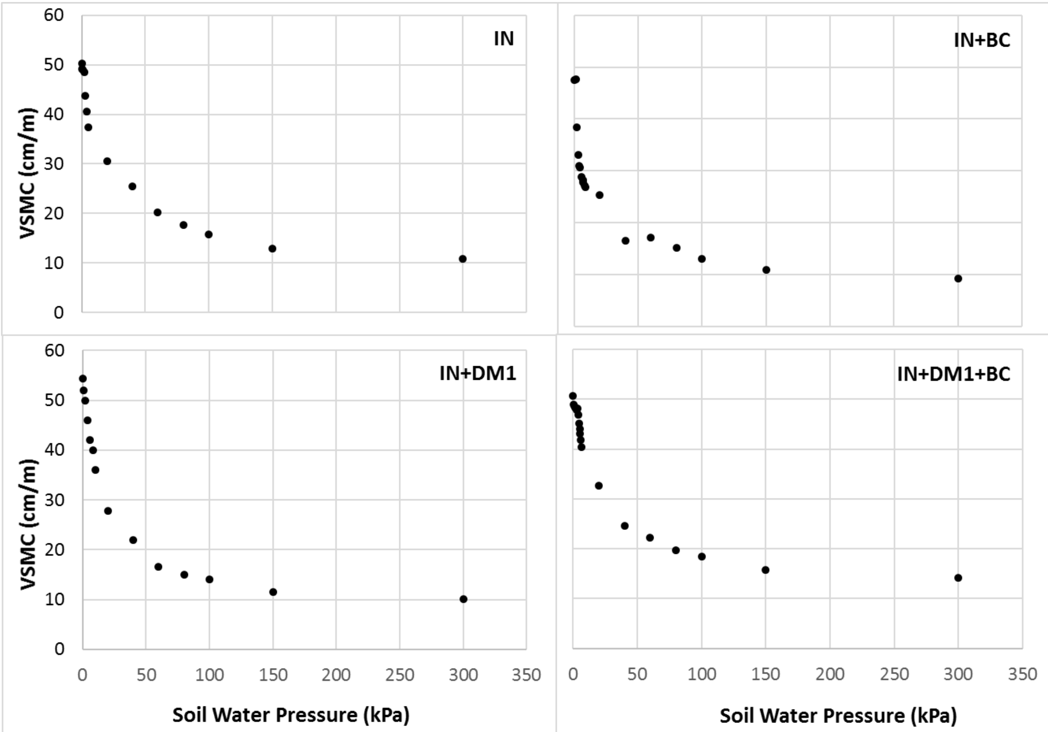

Figure 3. Soil moisture release curves developed for IN, IN+BC, IN+DM1, and IN+BC+DM1 treatments. IN: Inorganic nitrogen; DM1: Dairy manure 1; BC: Biochar.

Table 3. Summary of soil hydraulic properties (cm of water per m of soil) based on the soil moisture release curves.

Treatment	Saturation	FC	PWP	MPV	AWC
IN	50.3	30.5	7.3	19.7	23.3
IN+BC	47.4	25.3	6.6	22.1	18.7
IN+DM1	54.4	27.9	6.9	26.5	21.0
IN+BC+DM1	50.7	32.6	11.3	18.1	21.4

FC: Field Capacity; PWP: Permanent Wilting Point; MPV: Macro Pore Volume; AWC: Available Water Content.

Flow through an unsaturated soil is complex and non-linear and is strongly dependent on the pore geometry, water content, and matric potential [61,62]. Studies reporting the effects of soil amendments on K_{unsat} are very few [37,38]. According to Villagra-Mendoza [37], addition of BC enhances soil microporosity, hence enhancing K_{unsat} at higher matric potentials and rapidly decreasing towards lower potentials of sandy and sandy loam soils. Another study found that long-term manure application had little or no effect on K_{unsat} (−0.3, −0.5, −0.7, and −1.0 kPa) [38].

Previously reported effects of BC on K_{sat} vary due to the variability of soil texture, BC types, rates added, and their maturity in the field. For example, some studies reported that the addition of BC may significantly decrease [63–65] or have no effect [4,66,67] on the K_{sat} of sandy, loamy-sand, and loamy soils. Conversely, other studies have reported higher K_{sat} when BC is applied because of improvements in the structure and the porosity of the amended soil [29,42].

Furthermore, solid cattle manure amendments significantly increased K_{sat} [68] or had no effect after one soil wetting; but increased after two to five wetting and drying cycles [69]. However, it has also been found that liquid cattle manure tends to block the soil pores with fine particles of manure [59,60], thus decreasing the infiltration rates [38] and K_{sat} [70]. Moreover, the addition of high quantities (i.e., 90–360 Mg ha^{-1}) of cattle manure resulted in surface crusting and decreased

K_{sat} [60,71]. Long-term application of heavy rates of manure may cause more unfavorable hydrological conditions, such as increasing water repellency resulting in reduced infiltration and increased surface runoff. Collectively, our findings as well as those reported in the literature indicate that amendments such as DM and BC need to be applied with caution in any agricultural fields including agriculturally used podzols.

4. Conclusions

The study evaluated the effect of DM and BC incorporation on hydraulic conductivity of podzolic soils under field conditions in a boreal ecosystem. According to the study results, the treatments containing IN+DM1 and IN+DM1+BC showed significantly reduced K_{unsat} values compared to the control under −0.04 and −0.02 m tensions, while IN+DM2 significantly reduced K_{unsat} under −0.02 m tension. There were no significant changes in near-saturated hydraulic conductivity near K_{sat}) under −0.001 m tension. Based on results from the literature and this study, we can conclude that long-term and continuous application (or at higher rates) of soil amendments such as DM and BC may cause more unfavorable conditions on soil hydraulic properties, hence need to apply with caution. Further studies are recommended to identify the differences in hydrophobicity and particulate matter in different types and rates of DM and BC amendments and their effects on soil hydrology, particularly podzolic soils used for agriculture production in boreal ecosystems.

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