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Temporal Effects of Biochar and Dairy Manure on Physicochemical Properties of Podzol: Case from a Silage-Corn Production Trial in Boreal Climate

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Abstract: A field experiment was conducted to evaluate the effects of biochar and dairy manure (DM) on physicochemical properties of podzolic soils, as well as to establish the relationships between selected physicochemical properties and soil electrical conductivity (EC) in a silage-corn production system. Nutrient requirements of the crop were met through different nutrient sources considering soil nutrient status, nutrient availability from DM (DM, DM + biochar) and regional crop nutrient recommendations. Experimental treatments included control, inorganic nitrogen (IN), IN + biochar, IN + DM, and IN + DM + biochar. DM was applied at 30,000 L ha^{-1}, whereas biochar was applied at 20 Mg ha^{-1} and mixed within the top 20 cm of the soil. Disturbed soil samples as well as time domain reflectometry (TDR) measurements were collected from treatment plots on four field days. Results showed no significant ($p > 0.05$) treatment effects on soil pH and cation exchange capacity (CEC) within each field day. However, significant temporal effects were recorded for pH, EC, apparent electrical conductivity (EC_a) and electrical conductivity of the soil solution (EC_w). Soil depth (0–10 cm and 10–20 cm) had no significant effect on treatments. Significant positive correlations were recorded for EC with soil organic carbon and CEC (EC_a, EC_w 0–10 cm, & 10–20 cm, $p = 0.000$). Correlation results show that EC_a measurements as a proxy to investigate the variability of key soil properties over large areas, but further investigation between EC_a data and soil properties should be carried out to address uncertainties associated in predicting these properties.

Keywords: biochar; dairy manure; pH; soil organic carbon; cation exchange capacity; electrical conductivity

1. Introduction

The Government of Newfoundland and Labrador (NL) recognized that local food production needs to be increased from its current 10% to 20% by 2022 [1] in an attempt to improve the food security by supporting the advancement and development of management decisions to increase the productivity and sustainable growth. NL farmers use different agronomic practices to increase land productivity to contribute to food security. These include adding inorganic fertilizer or dairy manure (DM) alone or in various combinations to meet the crop nutrient requirements. It is important, however, to use the beneficial management practices that not only enhance the crop production, but also minimize the negative impacts on soil, water, and the environment. If excessive inorganic fertilizer or DM is applied to the soil, mineral nutrients can leach into groundwater, potentially leading to water contamination and eutrophication or emission to the atmosphere as greenhouse gases (GHGs), a major driver of global warming [2,3]. Therefore, it is important to investigate the effects of such management practices on podzol soils in boreal ecosystem prone to nutrient leaching and GHGs emissions. Boreal soils, podzols, in nature are known to have high hydrogen (H^+) and aluminum (Al^{3+}) ion levels leading to low soil pH characteristics [4]. The low soil pH limits the nutrients uptake, thus limiting crop yields in podzols. Biochar, a recalcitrant black carbon (C) material produced by the baking of organic matter under low oxygen conditions, when applied as an amendment to acidic soils, showed positive effects on soil pH [5,6]. This can in turn reduce the concentration of H^+ and Al^{3+} ions, since Al^{3+} precipitates as hydroxy-Al polymers at higher pH, increasing essential nutrient availability and crop yield [5,7].

Biochar is very stable due to the aromatic C structure [8] and can alter the physicochemical properties of soil. Biochar has multifaceted benefits including reduction of GHGs emission, soil compaction [9], increased soil pH, and the aggregate stability [10]. It also resulted in enhanced soil permeability, porosity and water holding capacity leading to better nutrient availabilities in plant root zones [11,12]. Furthermore, biochar increases the C sequestration and soil organic matter [13–15]. Cation exchange capacity (CEC) is also reported to increase as a result of biochar amendments along with pollutant degradation whereas microbial growth as well as optimum microbial activities are enhanced [16–18]. Recent studies have shown that biochar increases cation exchange capacity (CEC) of soils [5,19]. When biochar is exposed to oxygen and water (i.e., when added to the soil) spontaneous oxidation reactions take place, most likely enhanced through microbial activity, resulting in high CEC [20]. As biochar ages, CEC increases due to increase oxygenated functional groups attached to the biochar [20], therefore contributing to higher absorption capacity of cations perhaps even better than soil organic matter (SOM) [19].

Electrical conductivity (EC) is a measurement that correlates with properties of the soil affecting crop productivity [21]. Soil physicochemical properties, including CEC, soil salinity, subsoil characteristics, soil texture, clay content, bulk density (BD), and SOM content, all influence the soil EC [21,22]. Another measurement, the apparent electrical conductivity (EC_a) is often easy to measure, but does not always relate to the crop production [22]. Ristolainen et al. [23] discussed how EC_a has mostly been correlated with soil salinity and water content of saline soils, while in non-saline soils, EC_a depends mostly on the SOM content, soil texture—especially clay content and plant available nutrients. It is assumed that NL's soils are non-saline, due to high leaching potentials with high amounts of well-distributed precipitation received each year. Therefore, it would be expected that the EC_a measurements obtained will depend on the non-saline soil properties discussed above. Various studies have shown that biochar can also influence soil EC by increasing the EC values through holding more soluble salts [5,6]. Efficient use of inorganic fertilizer, DM, and biochar will maintain soil health, reduce GHGs emissions, as well as increase crop productivity. Effects of DM, and biochar as soil amendments and agronomic practices to enhance crop productivity as well as to minimize the environmental damage are important considerations particularly on podzols used for agriculture in boreal ecosystems [24–27].

Soil organic C (SOC) is known to be the largest C stock in the terrestrial ecosystems [28,29]. Soils store three times more organic C than the plants [30]. The soils of Canada's boreal region contain large C reservoirs [31]. Owing to this high C storage, it is important to ensure that agricultural practices do not release this stored C as CO_2 into the atmosphere, considering this could increase the risk of global temperature rise. Decomposition of these large stocks of SOC in ecosystems of northern latitudes in response to rising temperatures may be one of the largest feedbacks with respect to climate change [32]. Thus, it is important to investigate whether the effects of using these soils for agriculture purposes would affect its C storage, since biochar has been shown to be a good soil amendment for sequestering C [33,34].

Currently, very little is known concerning how intensive agriculture as well as the use of DM and biochar affects the physicochemical properties and productivity of podzols in boreal climates. The objectives of this research are therefore: (i) to evaluate the effect of different soil amendments on physicochemical properties of a loamy sand podzolic soil, and (ii) to test if a relationship for EC_a and electrical conductivity of soil solution (EC_w) can be obtained with the other tested soil properties. The long-term goal of our research group is to map the spatio-temporal variability of soil's physicochemical properties over larger agricultural fields by using the proxy parameters such as ECa through the electromagnetic induction (EMI) method in support of precision agriculture on podzolic soils in boreal ecosystems.

2. Materials and Methods

2.1. Field Experiment

An agronomic field experiment was established at the Pynn's Brook Research Station (PBRS), Pasadena (49°04′21″ N; 57°33′36″ W), western NL, Canada to evaluate the production potential of five silage corn genotypes using different nutrient management practices [35]. Experimental soil was a loamy sand (sand 82.0% ± 3.4, silt 11.6% ± 2.4 and clay 6.4% ± 1.2) with an average bulk density of 1.31 (± 0.07) g cm^{-3} [26] and measured soil organic matter and CEC were of 3.10% and 12 cmol kg^{-1}, respectively. Experimental treatments were: (1) T_1—control with no inorganic fertilizer or soil amendment; T_2—inorganic N (IN); T_3—Biochar + IN; T_4—DM + IN; T_5—DM + biochar + IN.Treatment details can be found in Table 1. Each experimental plot was 1.5 m × 6 m, with all plots arranged in a randomly distributed order with four replicates. DM was applied at the rate of 30,000 L ha^{-1} according to local farmer's practice. Nutrients from DM (0.6 kg P, 1.5 kg N, 4.1 kg K per 1000 L of DM) were supplemented with inorganic fertilizer to meet the crop nutrient requirements. Each plot (except controls) received equal amounts of nutrients (225 kg ha^{-1} N, 225 kg ha^{-1} K and 110 kg ha^{-1} P) after considering nutrient availability from DM, inorganic fertilizer, initial soil nutrient status and regional recommendations for silage-corn. Biochar used in this experiment was produced from Yellow Pine Wood by slow pyrolysis at 500 °C for 30 min and obtained from AirTerra Inc. (Alberta, Canada) and basic properties of biochar are given in Table 2. Biochar (with pH = 9; H = 0.68%; O = 7.84%; N = 0.22%; N, total ash = 7.1%; recalcitrant C = 7.1%; bulk density = 0.19 Mg m^{-3}; and particle density 1.57 Mg m^{-3})was applied @ 20 t ha^{-1} and mixed within the top 20 cm of the experimental plots [36]. DM and biochar were added to soil on May 23, 2016—approximately two months before the first sampling day.

Table 1. Experimental treatments including different nutrient management practices to produce silage-corn in Newfoundland, Canada.

Treatments	Soil Amendments
T_1	Control—no fertilization or soil amendment
T_2	Inorganic nitrogen @ 225 kg ha^{-1}
T_3	Inorganic nitrogen + biochar @ 20 t ha^{-1}
T_4	Inorganic nitrogen + dairy manure @ 30,000 L ha^{-1}
T_5	Inorganic nitrogen + dairy manure + biochar

Table 2. Properties of biochar used in current study obtained from AirTerra Inc. (Alberta, Canada).

Parameter	Details
Bulk density (BD)	0.23 g cm^{-3}
pH	9.4
Electrical conductivity (EC)	0.43 dS m^{-1}
Total organic carbon	88.6%
Void space	87.50% (dry weight basis)
Solid space	12.50% (dry weight basis)
Water holding capacity	74.90 mL 100 g^{-1} dry biochar
Moisture	15.20%
Total volatile fractions	78.70%
Total ash	6.00%

For the current study, four field days (FDs) were selected including July 28 (65 days after sowing silage corn [DAS]), August 4 (72 DAS), September 30 (129 DAS) and October 6, 2016 (135 DAS). On each FD, soil sampling and in-situ measurements of soil moisture, EC_a and temperature were carried using a portable time domain reflectometry (TDR) sensor (HD2 Imko GmbH, Germany). Composite soil samples were made by mixing soil collected from three sampling locations from 0–10 cm (D1) and 10–20 cm (D2) depths in each treatment plot. Soil samples were transported to Boreal Ecosystem Research Facility (BERF), Grenfell Campus, Memorial University of NL to measure further soil physicochemical properties (pH, SOC, CEC, and EC_w).

2.2. Laboratory Analysis

EC_w was measured using air-dried soil samples diluted in a 1:2 soil to distilled water ratio as suggested by Brady and Weil [37]. A portable pH/EC/TDS/Temperature meter (HANNA—HI9813–6 with CAL Check) was used to measure EC_w, pH, TDS and temperature of soil solution. For SOC analysis, the Walkley-Black chromic acid wet oxidation method [38] was followed using the automatic titrator (Mettler Toledo G20 compact Titrator). At the same time, 20 mL of sulfuric acid (H_2SO_4) at 95–98% purity was added to the solution. The titrant used in this method was ferrous sulfate solution ($FeSO_4$) and SOC was calculated using the following Equation (1).

$$\text{SOC\%} = \frac{3\left(1 - \frac{T}{S}\right)}{W} \quad (1)$$

where T is the volume of the $FeSO_4$ used in titrating the sample (mL), S is the volume of $FeSO_4$ used in the blank titration (mL), and W is the soil sample weight used for titration, corrected for oven-dried weight (g) [38].

CEC of soil samples were measured by exchanging soil's cations with sodium acetate [38]. CEC was estimated using 100 soil samples from both depths on the first (65 DAS) and the last FD (135 DAS), and only from 0–10 cm soil depth on the third FD (65 DAS). Samples were analyzed for sodium concentration using ion chromatography (Dionex ICS-5000$^+$ DC-5 detector/chromatography module). No interference was observed among sodium and ammonium peaks (Figure 1), and values were corrected for actual concentration (cmol kg^{-1}) by the following Equation;

$$\text{Exchangeable sodium} = \frac{a \times b \times mcf}{(d) \times (23) \times s} \quad (2)$$

where a is sodium concentration in ppm, mcf is the moisture correction factor for oven-dried weight of soil, s is the air-dried sample weight (g), b is the ammonium acetate solution (33 mL), d is the conversion factor (10) from ppm to cmol kg^{-1}, and 23 is the molecular weight of Na [39].

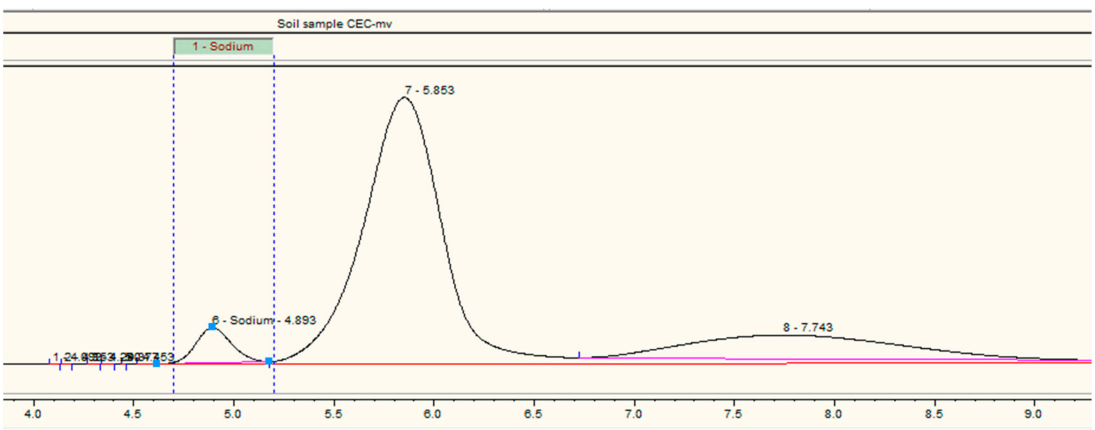

Figure 1. Ion chromatography peaks showing clearly separated sodium and ammonium.

2.3. Statistical Analysis

Data were analyzed using Microsoft Excel. Treatment effects were analyzed by grouping all five treatments into two main groups representing two soil depths. The analyses were done, after verifying the data normality, within each field day using ANOVA technique whereas treatment means were tested by Minitab using Tukey's Honesty Significant Difference (HSD) at 5% confidence level. Correlation analyses between EC (EC_w and EC_a) and SOC and CEC were also carried out.

3. Results and Discussion

3.1. Climatic Conditions and Soil Gravimetric Moisture Contents

Significant temporal changes have been observed in average air temperature and rainfall during the study period (Figure 2). The observed average air temperature was higher on FD_1 (23.5 °C) compared to lowest on FD_4 (10.8 °C), whereas the temperature varies in order of FD_1 > FD_2 > FD_3 FD_4 (Figure 2). Overall, 444 mm rainfall was received on the experimental site from FD_1 to November 8, where significantly higher rainfall was recorded on September 8 (42 mm) and October 10 (70 mm) as depicted in Figure 2. However, the rainfall was <1 mm on the observed FDs during the study period (Figure 2).

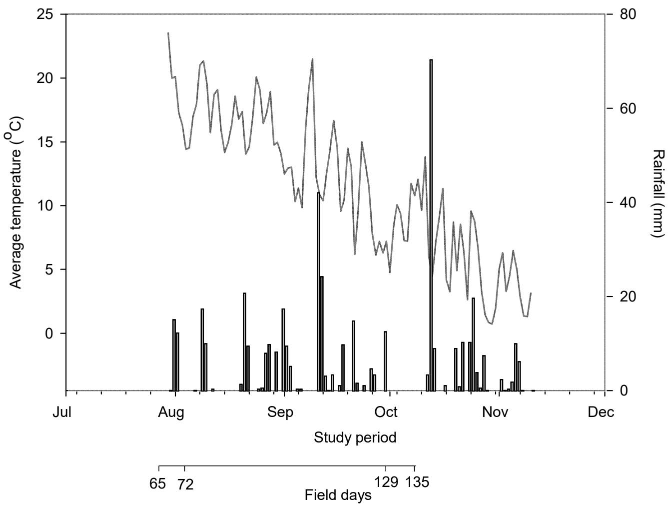

Figure 2. Mean average temperature (°C, solid line) and rainfall (mm, vertical bars) during the study period.

No significant effects of different soil amendments were recorded on gravimetric moisture contents of soil on each FD; however, the temporal variations were recorded, although non-significant at 0–10 cm (Figure 3A) and 10–20 cm (Figure 3B) soil depths. The gravimetric moisture contents varied from 12.24% to 19.12% at shallow soil depths (Figure 3A), whereas these values ranged from 13.90% to 20.48% at deep soil depth (Figure 3B).

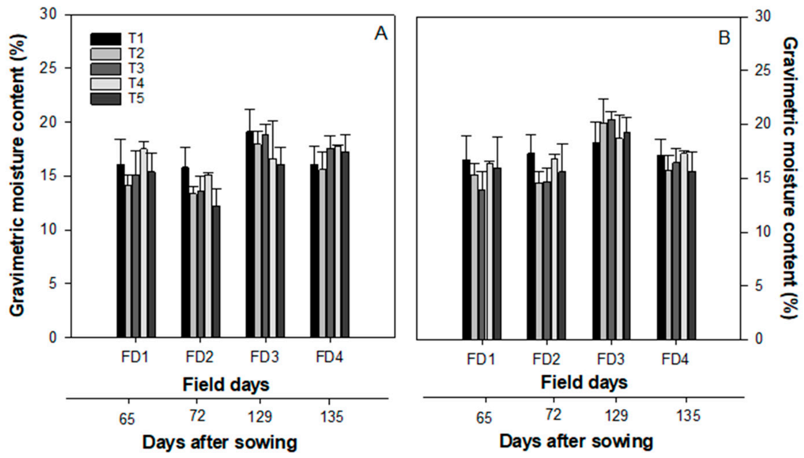

Figure 3. Temporal variations and effects of different soil amendments on gravimetric moisture content of soil at 0–10 cm (**A**) and 10–20 cm (**B**) depth in podzolic soils under various nutrient management practices. Each vertical bar represents mean whereas bar errors show ± standard error of three replications.

3.2. Effect of Soil Amendments on pH

There was no significant difference ($p > 0.05$) for soil pH among nutrient management treatments within each FD at 0–10 cm (Figure 4A), and 10–20 cm soil depths (Figure 4B). However, significant ($p < 0.05$) temporal variations were recorded in soil pH across the four FDs on both soil depths where soil pH varies in order of $FD_1 > FD_2 < FD_3 < FD_4$ (Figure 4). It is also important to note that the soil pH initially decreased non-significantly from the first to the second FD, and thereafter increased significantly for all treatments except in the control treatment (T_1—Figure 4B), reaching more favorable soil conditions for crop growth on last two FDs. Referencing the results for the soil pH, all treatments increased temporally (Figure 4A,B). Perhaps this may be attributed to the period of no rainfall from September 10 to 29. Biochar does increase soil pH, as demonstrated by the T_3 plots; however, this was not significant as suggested by Chintala et al. [5] and Molnár et al. [6]. As mentioned earlier, when soil pH increases, Al^{3+} precipitates as hydroxy-Al polymers, allowing more space for adsorption of other cations to the clay particle surfaces [7].

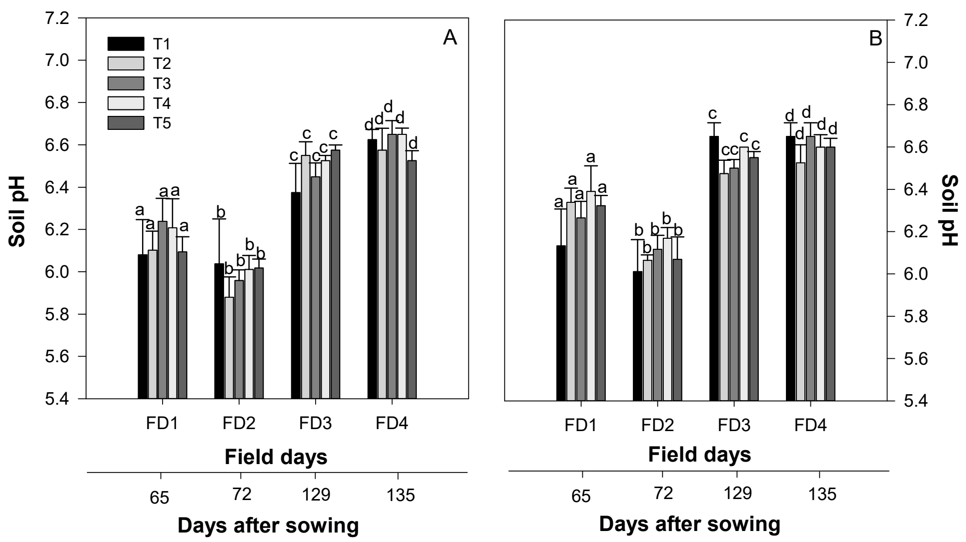

Figure 4. Effects of different soil amendments on temporal variations of soil pH at 0–10 cm (**A**) and 10–20 cm (**B**) sowing depth in podzolic soils under various nutrient management practices. Each vertical bar represents mean whereas bar errors show ± standard error for three replications. Lettering is independent of each other.

3.3. Effect of Soil Amendments on Soil Organic Carbon

SOC varied non-significantly ($p > 0.05$) among the five studied nutrient management treatments within each FD at 0–10 cm soil depth (Figure 5A). However, T_3 treatment comparatively had a higher amount of SOC on the FD_1 (65 days after treatment application) compared to the other treatments. Significant ($p > 0.05$) temporal variations were observed in SOC in order of $FD_1 > FD_2 > FD_3 > FD_4$ (Figure 5A). Significant ($p = 0.04$) differences were recorded in SOC at 10–20 cm soil depth between T_4 and T_5 on FD_2 (72 DAS) as depicted in Figure 5B. However, no-significant differences ($p > 0.05$) were found among the other treatments on FD_1, FD_3 and FD_4 (Figure 5B). There were no significant temporal variations among all nutrient management treatments across all four FDs (Figure 5B). As observed at 0–10 cm soil depth (Figure 5A), T_3 again had higher SOC values on FD_1. However, T_4 had higher SOC on all other FDs. T_5 had the lowest SOC values throughout most FDs at both soil depths. These results follow the norm and suggest that SOC does not change within short time periods. SOC content varied from 1.27% to 4.58%, with an average value of 2.85% irrespective of treatment or field day in the experimental field. These values are typical of most agricultural soils in NL. SOC remained fairly constant for all treatments temporally, as was expected over the time frame of the experiment. The effect of biochar was slightly high for T_3, as it initially had the highest SOC at both the 0–10 cm and 10–20 cm depths (Figure 5A,B). This was expected, as biochar has been shown to increase SOC [33,34]. T_5, however, did not increase SOC, but rather decreased it, as it was lower than the control for most FDs. This (SOC) was significantly lower than T_4 at the 10–20 cm depth on the second FD (72 DAS), indicating that the combination of DM + biochar, over a short period of time, decreases SOC. If the experiment was conducted over a longer time frame, this might be different. DM seems to increase SOC, as it had the highest SOC content for the 0–10 cm and 10–20 cm depth. This is expected, and consistent with the findings of Haynes and Naidu [7] who also demonstrated that adding DM to soils does increase SOC.

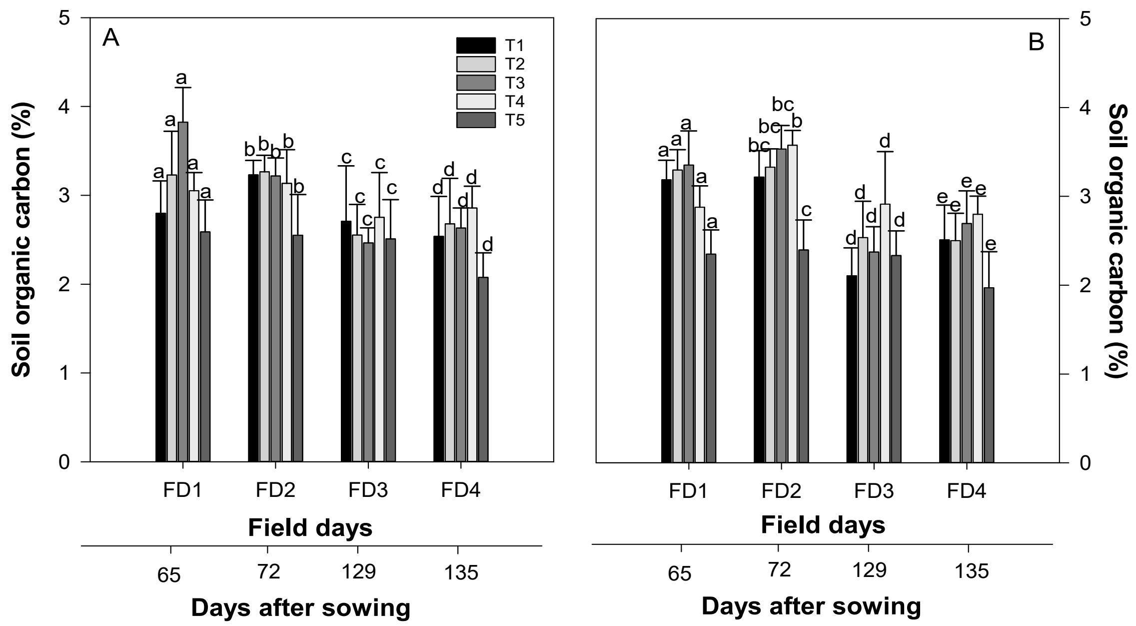

Figure 5. Effect of different soil amendments on temporal variations in soil organic carbon at 0–10 cm (**A**) and 10–20 cm (**B**) sowing depth in podzolic soils under various nutrient management practices. Each vertical bar represents mean whereas bar errors show ± standard error for three replications. Lettering is independent of each other.

3.4. Effect of Soil Amendments on Cation Exchange Capacity

The average CEC value based on a soil report at the beginning of 2016 was 12.5 cmol kg^{-1} [40]. The CEC values obtained in this study ranged from approximately 8.2 to 15.7 cmol kg^{-1} for all treatments tested, with an average CEC of 12.6 cmol kg^{-1}. This value falls within the range of CEC values expected for agricultural soils. No significant differences ($p > 0.05$) were observed among soil nutrient management treatments for CEC at 0–10 cm (Figure 6A) and 10–20 cm soil depths (Figure 6B). However, T_1 treatment had higher CEC values on FD_1 (65 DAS) at 0–10 cm soil depth (Figure 6A), and T_3 expressed similar trends on FD_3 (30 September) and FD_4 (135 DAS). The values for CEC slightly increased (not significant) across field days at 0–10 cm depth, but remained fairly stable at 10–20 cm depth. T_3 and T_5 also increased across the field days, although not statistically significant (Figure 6A,B), indicating that biochar does potentially have an effect on increasing CEC over time within one field season [5,19]. A positive effect of DM on CEC could also be observed for T_4. On the other hand, CEC decreased substantially for T_2 from FD_3 to FD_4. However, since the heterogeneity in the field conditions are very high, the study should be conducted over a longer time frame to test the effect of biochar on CEC values. T_1 appeared to have higher CEC values on FD_1 (65 DAS) at 10–20 cm soil depth (Figure 6B), whereas T_4 expressed similar trends on FD_4 (135 DAS). T_3 and T_4 significantly increased the CEC from the first to the fourth field day at this depth (Figure 4B). T_2, T_3, T_4, and T_5 had no significant effect on increasing CEC during the 3.5 month time period at 0–10 cm depth. However, there was no statistically significant difference between the two depths for all treatments. In general, these results indicate CEC tends to increase over time for the experimental plots treated with biochar (T_3 and T_5), as expected [12,14]. However, it is important to note that the testing period was too short for this study to observe a significant effect on CEC for the biochar treatments, as CEC increases when biochar ages [20]. On the other hand, a general trend of slightly increasing CEC values can be observed for all treatments (except T_2, which decreased on October 6) for the 0–10 cm depth. This could be attributable to the gradual increase in soil pH (Figure 6A,B), as an increase in soil pH has been shown to increase CEC [41]. CEC remained fairly constant for all treatments temporally, as would be expected over a short period of time. The effect of biochar could also be seen in T_3 and T_5, as CEC increased, although not significantly, across the FDs [5,19]. T_5 had the second highest CEC value at the 0–10 cm depth for the last day, while T_3 had the highest at both depths on the last day (Figure 6A,B). As biochar ages, the spontaneous oxidation reactions that occur will cause CEC to increase through addition of functional oxygenated groups, thereby causing its surface charge to be more negative, due to more cations being adsorbed onto its surface [20].

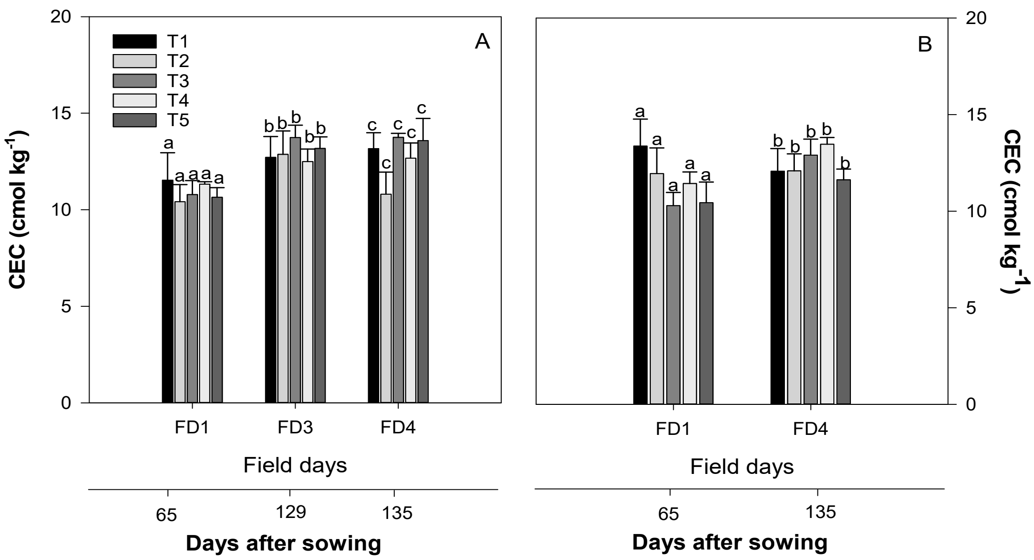

Figure 6. Effect of different soil amendments on temporal variations in cation exchange capacity at 0–10 cm (**A**) and 10–20 cm (**B**) sowing depth in podzolic soils under various nutrient management practices. Each vertical bar represents mean whereas bar errors show ± standard error for three replications. Lettering is independent of each other.

As a result, it is recommended to test CEC over long-term experiments [20]. CEC increased for all other treatments at the 0–10 cm depth (except for T_2, which decreased on October 6). This may be attributed to the soil pH, as an increase in soil pH has been shown to increase CEC [37].

3.5. Effect of Soil Amendments on EC_w and EC_a

There was no significant difference ($p > 0.05$) among soil nutrient management treatments on EC_W at 0–10 cm soil depth (Figure 7A). T_2 had the highest value on the first and second days (65 DAS and 72 DAS), which could be due to an increase in ionic concentration with applications of inorganic fertilizer (Figure 7A). However, significant temporal variations were observed for EC_W at 0–10 cm soil depth and varied in order of $FD_1 > FD_2 > FD_3 > FD_4$ (Figure 7A). DM application (T_4) had relatively high EC_W values for FD_1 and FD_2, potentially due to the higher nutrient concentrations in DM.

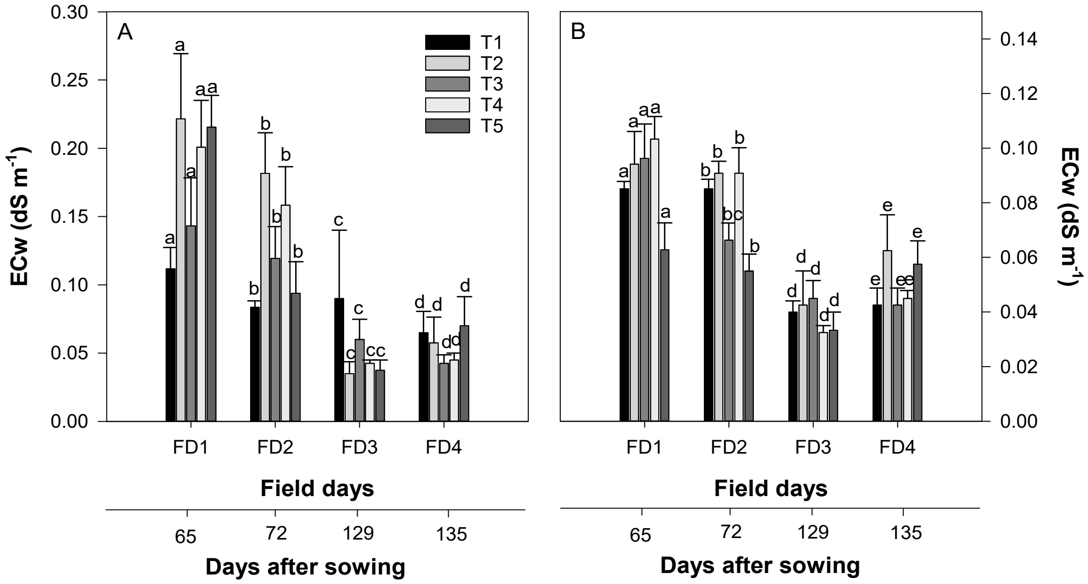

Figure 7. Effect of different soil amendments on temporal variations in electrical conductivity of soil solution at 0–10 cm (**A**) and 10–20 cm (**B**) sowing depth in podzolic soils under various nutrient management practices. Each vertical bar represents mean whereas bar errors show ± standard error for three replications. Lettering is independent of each other.

A significant reduction in EC_W was observed from T_2 to T_5 on FD_3 (129 DAS) and FD_4 (135 DAS) at 0–10 cm depth, potentially due to absorption of nutrients by plants, or most probably due to gaseous or leaching losses (Figure 7A). EC_W values were quite low at 10–20 cm soil depth, although there was no significant difference between the values across the two soil depths evaluated in this study. A significant difference was recorded among different soil nutrient management treatments on FD_2 (T_1–T_5, $p = 0.028$; T_2–T_5, $p = 0.008$; T_4–T_5, $p = 0.008$) as depicted in Figure 7B; however, no significant differences were observed on other FDs. DM applications (T_4) showed the highest EC_W on FD_1 (65 DAS), while IN (T_2) and IN + biochar (T_3) had the highest values on FD_2 (72 DAS). IN + biochar (T_3) had the highest EC_W values on FD_3, whereas T_2 and T_5 expressed higher EC_W values on FD_4 (135 DAS). EC_W values increased slightly on FD_4 (except T_3) compared to FD_3, more than likely due to slow release properties of the fertilizer, or leaching of the fertilizer into the deeper layers of the soil.

In general, EC_W decreased over the crop growth period in all soil amendments, which might be attributed to uptake of nutrients by growing plants, immobilization, or losses due to leaching and volatilization. An increase in soil EC_W can be expected when ion concentrations are high. In DM and IN, it could be expected that ammonium concentration would be high initially. As ammonium-nitrogen (NH_4^+-N) is water-soluble, EC_W will primarily measure these and other water-soluble ions. This can be seen from the initial high EC_W values for T_2 and T_4 especially [42]. Adding biochar to these plots may increase the concentration of these water-soluble ions more in the long run, decreasing losses of these ions, and causing EC_w to decrease at a slower rate [5,6].

For the EC_a values (only for 0–11 cm depth based on the probe length) obtained using the HD2 probe (IMKO GmbH, Germany), there was no significant difference among treatments ($p > 0.05$) within each field day. When referring to Figure 8, T_4 had the highest value on the first field day (65 DAS). On the third and last FDs (129 DAS and 135 DAS), T_5 had the highest value. EC_a values also decreased significantly from FD_1 to FD_3 (day 2 data are not available for T_2, T_3, T_4, and T_5 and not included in this analysis). The field measured EC_a shows the same trend as the laboratory measured EC_w. This behavior clearly shows the reduction in ionic concentration of soil across the growing season due to nutrient uptake by plants, or losses due to leaching and volatilization [5].

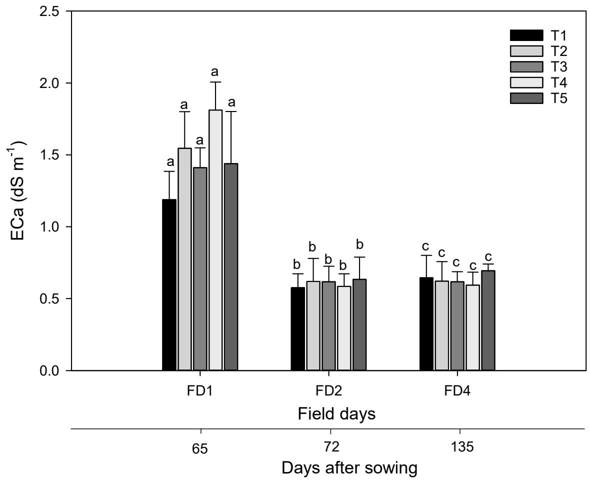

Figure 8. Effect of different soil amendments on temporal variations in apparent electrical conductivity at 0–10 cm sowing depth in podzolic soils under various nutrient management practices. Each vertical bar represents mean whereas bar errors show ±standard error for three replications. Lettering is independent of each other.

For EC_w and EC_a measurements, values decreased temporally. EC_w values were mostly lower in the 10–20 cm depth than the 0–10 cm depth as a result of ion presence being higher on the top layers of the soil initially, where the fertilizer and biochar were applied. The effect of biochar on EC could be seen for T_5 [13], as the values again increased on the last field day for EC_a and both depths for ECw (135 DAS). The effect could not be seen for T_3. However, values for T_3 would more than likely also increase over a longer time frame. T_2 and T_4 had high EC_w and EC_a values initially, which was also expected, as EC has been shown to increase when there are high ion concentrations in the soil [9]. Hence, the temporal decrease for most treatments can be attributed to the decrease in ion concentrations due to leaching or uptake by plants.

Another potential cause for different variability could be due to the sampling locations and number of samples collected from the plots. Each plot has an area of 1 m x 6 m, and stratified samples were collected only from three locations within each plot. Due to high soil variability and manual mixing of biochar, this might have affected on the high variability observed in biochar treated plots. On the other hand, DM was applied as a liquid, and so it is possible for it to be mixed better within the entire treatment plot compared to that of biochar.

3.6. Relationship among Soil EC and Soil Organic Carbon

A significant ($p = 0.000$) positive Pearson's correlation (r = 0.578) was recorded between soil EC_a and SOC (Figure 9A). A similar trend was observed between soil EC_a and SOC at 0–10 cm ($p = 0.000$ and r = 0.5276) (Figure 9B) and 10–20 cm soil depths ($p = 0.000$, r = 0.51974) irrespective of FDs. However, SOC has a stronger correlation (r = 0.57814) with EC_a than EC_w (r = 0.5276 or r = 0.51974), which may indicate that EC_a is more closely correlated with SOC. When referring to Figure 9A–C, it can be seen that significant correlations were obtained for SOC with EC_a [43] and EC_w at both depths (EC_a, EC_w 0–10 cm, & EC_w 10–20 cm, $p = 0.000$). It would be assumed that SOC is more closely correlated with EC_a than EC_w, as EC_a measures the bulk properties of the soil, such as SOC.

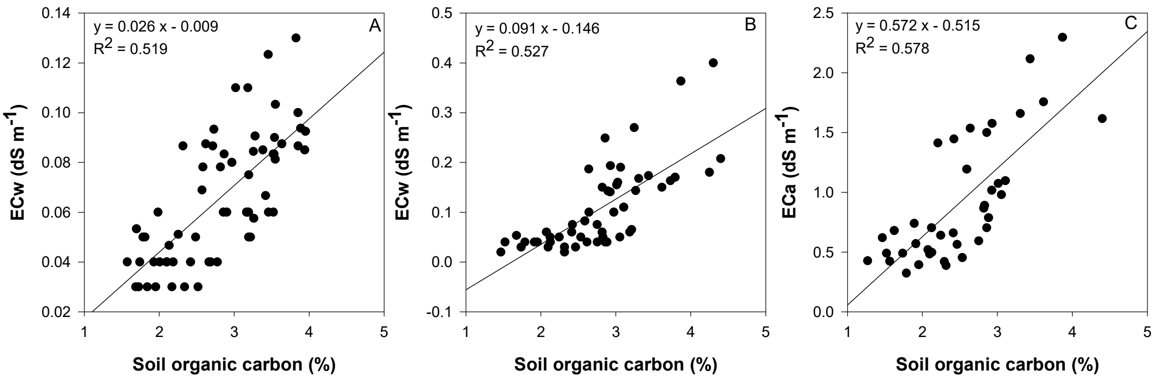

Figure 9. Relationship between soil organic carbon and bulk electrical conductivity, EC_a (**A**) at 0–10 cm depth, electrical conductivity of soil solution, EC_w at 0–10 cm (**B**) and 10–20 cm (**C**) soil depths in podzolic soils under various nutrient management practices.

3.7. Relationship among Soil EC_a, EC_w and CEC

Significant negative correlations ($p = 0.000$) were observed between CEC, EC_w (Figure 10A) and EC_a (Figure 10B) at 0–10 cm depth when comparing CEC with EC_a and EC_w across all FDs irrespective of treatments. This can be accounted for by the increase in CEC, while EC_a and EC_w decreased temporally, as discussed earlier.

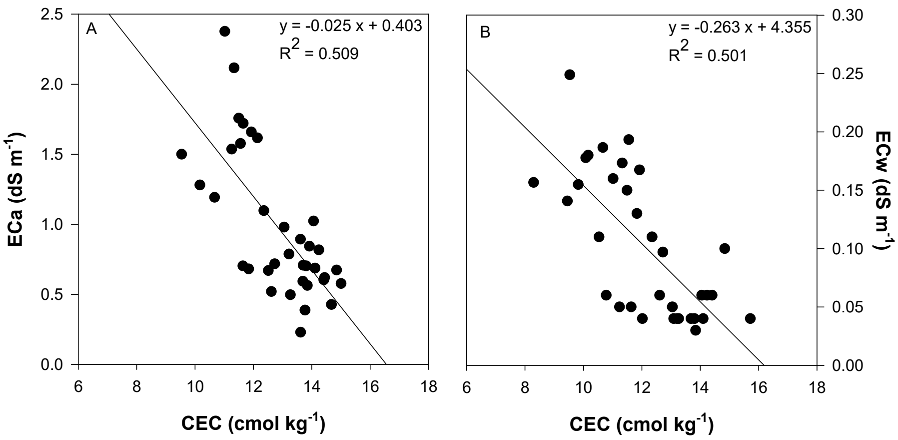

Figure 10. Relationship between cation exchange capacity and electrical conductivity of soil solution, EC_w (**A**) and bulk electrical conductivity, EC_a (**B**) at 0–10 cm soil depths in podzolic soils under various nutrient management practices.

We observed that EC_w and EC_a can be correlated significantly with SOC (Figure 9) and CEC (Figure 10) with reasonably acceptable R^2 values regardless of FDs and treatments. Considering significant associations were obtained, EC_a measurements alone can be made and related back to the SOC and CEC measurements without these having to be measured directly, saving money, time, and labor.

4. Conclusions

Biochar was shown to have positive effects on the measured physicochemical properties of the soils obtained in the silage corn field at PBRS over the 3.5 month time frame of this experiment.

pH decreased on FD_2, and then increased significantly at FD_3 and FD_4 within days, irrespective of treatments. SOC was highest initially for T_3, while T_5 had fairly low SOC for all field days. T_3 and T_5 did increase CEC the most out of all treatments in the 0–10 cm depth. For EC_w and EC_a, T_5 increased on the last day, indicating that the combination of DM + biochar is effective in increasing EC_w. If these tests were to be done over a longer time frame, it is assumed that the positive effects of BC will be amplified, showing significant increases of these physicochemical properties. Enhancing these soil properties may potentially enhance soil health, and as a result, soil fertility and crop productivity. Significant correlations were found for EC_w and EC_a with SOC and CEC data. However, further investigation between EC_a data and soil properties should be carried out to address uncertainties associated in predicting these properties before using EC_a as soil proxy to map soil's physicochemical properties over large areas. If EMI can be used, continuous, large, and non-point scale measurements can be made without having to disturb the soil, saving a lot of labor, time, and money. This will be used to map the spatio-temporal variability of important soil properties of Newfoundland. From this study, it can be concluded that DM has great potential to be used as a soil amendment in podzolic soils to provide nutrients for growing crops, whereas biochar could increase the cation exchange capacity and pH of podzolic boreal soils, reducing the liming requirement and benefiting the environment. Further studies are required to evaluate the effects of different rates of biochar, its sources, and particle size along with nutrient management strategies on physicochemical properties of podzol soils in boreal ecosystems.

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