Short-term effects of amendments on soil properties and agronomic productivity for a coastal Guyana soil

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There is a multitude of agricultural byproducts worldwide that are not utilized productively. Converting these materials into soil amendments will not only reduce their environmental impact, but also improve soil properties, agronomic productivity, and crop yields. A field study was conducted on a clay (Typic Hydraquent) soil in Guyana to evaluate the impact of various soil amendments on maize (*Zea mays* L.). Three soil amendments used were: rice (*Oryza sativa* L.) hull biochar (RHB), poultry manure biochar (PMB), and sugarcane (*Saccharum officinarum* L.) filter press (FP). These amendments were applied one time at 10 Mg ha^{-1} and were compared to control (C) and chemical fertilizer (CF) treatments. Chemical fertilizer was also added to the RHB, PMB, and FP treatments, while the C received no further additions. Soil physical and chemical properties along with agronomic productivity and yields were measured to assess the impact of soil amendments. Soil parameters were measured at 0-10, 10-20, and 20-40 cm depths. After one growing season, no significant differences were present for several soil physical and hydrological properties (bulk density, porosity, penetration resistance, and water infiltration) measured. However, significant differences were observed for several soil chemical properties after the growing season. Soil pH increased from 4.71-4.92 in the baseline soil to 5.03-5.58 in the 0-10 cm depth, 5.46-5.61 in the 10-20 cm depth, and 5.38-5.54 in the 20-40 cm depth. Overall, electrical conductivity values were low throughout the 0-40 cm soil profile (0.18-0.56 dS m^{-1}) and would not pose a threat of reducing crop yields. The biochar amended plots had the greatest increase in SOC concentration within the 0-10 cm depth, with RHB and PMB having a 49% and 63% increase, respectively, when compared with the control. C:N ratios for all treatment groups were optimal and ranged from 10:1-15:1 after the growing season. Significant decreases in KCl exchangeable acidity for the 0-10 cm depth were noted for PMB and FP amended soil when compared with the C, CF, and RHB treatment groups. Grain and biomass yields in the amended plots (CF, RHB, PMB, FP) were 7.6-8.8 and 2.8-3.2 times greater than the control, respectively. The harvest index for the amended plots was about 2 times greater than that of the control.

Keywords*:* Agriculture, soil amendments, soil properties, biochar, Guyana, South America, tropics

Large quantities of diverse agricultural byproducts are globally available. The feedstock of these byproducts varies across geographical areas of the world. Dominant byproducts come from rice (*Oryza sativa* L.) and sugarcane (*Saccharum officinarum* L.) sectors in Asia; from barley (*Hordeum vulgare* L.), millet (*Panicum milieaceum* L.) and sorghum (*Sorghum bicolor* L.) sectors in Africa; and from sugarcane and maize (*Zea mays* L.) production in Latin America (Tipathi et al. 2019). Large quantities of these byproducts are available globally, and adequate disposal of these materials is a challenge. Farmers in developing countries often burn crop residues along with household burning, field burning, and burning for social reasons (Lal 2017). While burning results in numerous environmental impacts, including the release of greenhouse gases (GHGs) and black carbon (BC) into the atmosphere (Lal 2017), using agricultural byproducts as soil amendments has numerous benefits.

Soil amendments are used to improve soil quality through the input of one or more materials to soil (Diacono et al. 2019). These amendments can either be organic or inorganic. Examples of organic amendments include residues from plant (e.g. straws, leaves, stems, husks, shells) and animal (e.g. manures, slurries, bone/ blood meal) origins (Moonilall et al. 2015). Inorganic amendments

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include sand, vermiculite, perlite, pumice, fertilizers, and soil conditioners (Waddington 1992). Combinations of organic and inorganic materials can make good soil amendments. Among some beneficial agronomic and environmental effects of amendments are: enhancing nutrient cycling, accelerating activity and diversity of soil biota, reducing risks of soil erosion, increasing water storage, moderating soil temperature, and improving soil organic matter (SOM) content (Lal 2016). The use of organic amendments (e.g. crop residues) can increase SOC concentrations (Lal 2017).

Organic amendments can be prepared in an assortment of ways. Biochars (BC) and composts can be produced using various methods and feedstocks (Tan et al. 2017; Velez et al. 2018). BC can be produced from either slow or fast pyrolysis of various feedstocks including crop residues, manures, and woods and be applied as a soil amendment (Velez et al. 2018). At an appropriate rate, the application of BC can improve soil quality, crop yields, and SOC stock (Singh et al. 2010). Beneficial effects of BC on soil physical properties include improvements to bulk density, total porosity, aggregate stability, soil structure, and soil water holding capacity (Tan et al. 2017). Effects of BC on soil chemical properties include those on pH and nutrient availability and retention (Velez et al. 2018). Compost can be produced in various ways (e.g. onsite composting, vermicomposting, and aerated composting) using a multitude of organic residues, agricultural residues, and agro-industrial wastes (Sanchez et al. 2017). Advantageous effects of compost addition to soil include increased water retention, greater air exchange, increased soil organic matter, greater soil fertility, and increased soil microbial diversity and community (Sanchez et al. 2017).

Maize production in Guyana is garnering more interest from stakeholders and producers so that the country can reduce importation and become self-sufficient. Soil amendment application, in the form of agricultural byproducts, can assist with making this a reality. Several studies have been done in Guyana to evaluate the impact of soil amendments on soil properties and crop yields. Ansari and Jaikishun (2011) showed that a combination of sugarcane bagasse and rice straw vermicompost increased production of *Phaseolus vulgaris* L. The vermicompost addition to soil improved soil quality and nutrient retention allowing for better bean quality. Clementson et al. (2016) evaluated the impact of bio-ethanol effluent and vermicompost addition to a fine textured Guyana soil to cultivate pak choy (*Brassica chinensis* L.), lettuce (*Lactuca sativa* L.), and cabbage (*Brassica oleracea* L.). The bio-ethanol effluent increased yields for these three crops by 36, 16, and 21%, respectively. The vermicompost addition improved lettuce and cabbage yields by 20 and 5 %, respectively and decreased pak choy yields by 16%. Persaud et al. (2018) found that rice hull BC addition to a sand, improved soil physical properties (lowered soil bulk density, increased soil water holding capacity) and soil chemical properties (increased soil pH to a favorable range, increased OM content, increased exchangeable cations, increased N and P content). A 25 t ha^{-1} application of biochar increased pak choy yields after one growing season.

Several spent residues and byproducts exist after processing, especially within the three main agricultural sectors in Guyana, and much of these materials are underutilized or not productively utilized at all. Rice hull (rice processing), filter press (sugarcane processing) and manure (poultry production) are some byproduct materials that are readily available for use as soil amendments in Guyana. Globally, it is estimated that about 109 Tg of rice hull is available each year after processing (Bodie et al. 2019). Filter press, called filter cake or press mud, is a solid byproduct of sugarcane milling and is generated through the filtration process (Kumar and Chopra 2016). Large-scale cultivation and processing of sugarcane in South America lead to an ample supply of filter press. Across the world, it is estimated that about 27 Tg of filter press is available after the filtration process of sugarcane juice (Kumar and Chopra 2016). Poultry manure is also found in abundance wherever chickens are reared. Fresh manure production per chicken is estimated at 3.6-5 kg month^{-1}. On a dry weight basis, it is estimated that 0.63 to 1.81 t of manure can result per 1,000 chickens (Sikder and Joardar 2019). Recycling these organic materials back to the soil can assist in building soil health and could translate to improved agricultural production, two national priorities Guyana outlines in their National Strategy for Agriculture Plan (Guyana Ministry of Agriculture 2013). Achieving this will require the use of amendments along with conservation agriculture practices that will enhance soil quality and the use-efficiency of input resources. This study aimed to evaluate the impact of different local amendments on soil properties and agronomic productivity for a maize cropping system along the coastal region of Guyana. Specific objectives for this study were to assess the impact of amendments on 1) soil physical and chemical properties and 2) agronomic productivity parameters and yield.

Materials and methods

Site description

The study was conducted on experimental plots at the National Agriculture Research and Extension Institute (NAREI) Commercial Farm in Mon Repos, East Coast Demerara, Guyana, South America (6° 46’ 21” N, 58° 03’ 51” W). The site has an elevation of 2.74 m above mean sea level and is located 4.5 km south of the coastline of Guyana. Average maximum and minimum temperatures for this region during 2000-2012 were 31.3 °C and 22.8 °C, respectively. Mean maximum and minimum temperatures for 2014 were 29.6 °C and 25.8 °C, respectively. Average annual precipitation during 2000-2012 was 2,239.5 mm, with an average of 186 mm month^{-1}. Mean precipitation for 2014 was 2,250 mm, with an average of 187.5 mm month^{-1}. Soil at the study site was classified as a clay (1.5 % sand, 33.2 % silt, and 65.3 % clay) under USDA textural classification. More specifically, the soil was best classified as a Typic Hydraquent having minor Sulfaquent and Fluvaquent features, as described by USDA soil taxonomy. Baseline soil physicochemical properties, elemental analysis for the field site, critical values for soil physical characteristics and critical values for soil chemical characteristics are presented in Tables 1, 2, 3 and 4, respectively.

Table 1: Soil physical and chemical properties for the experimental field site before imposing treatments (baseline)

Depth (cm)*	Bulk density (Mg m^{-3})	Volumetric water content (θ)	Particle density (Mg m^{-3})	Total porosity (f_t)	Penetration resistance (MPa)	Soil pH	Electrical conductivity (dS m^{-1})	SOC (%)	TN (%)	C:N Ratio	KCl acidity (cmol$_{(+)}$ kg^{-1})
0-10	1.06 (0.09)*	0.29 (0.04)	2.64 (0.04)	0.60 (0.04)	0.36 (0.04)	4.92 (0.09)	0.65 (0.46)	1.78 (0.14)	0.13 (0.02)	13.7:1 (1.1)	15.3 (4.89)
10-20	1.19 (0.06)	0.41 (0.05)	2.60 (0.01)	0.55 (0.02)	0.71 (0.13)	4.80 (0.11)	1.09 (1.21)	1.80 (0.17)	0.13 (0.02)	13.8:1 (1.1)	18.8 (8.31)
20-40	1.08 (0.06)	0.43 (0.04)	2.62 (0.02)	0.59 (0.02)	1.10 (0.20)	4.71 (0.13)	0.87 (0.50)	1.71 (0.11)	0.12 (0.01)	14.3:1 (1.0)	21.7 (9.78)

*All parameters are n = 15 for each depth increment. Mean values are presented for each parameter with standard deviation in parentheses.

Table 2: Soil elemental analysis for the experimental field site before imposing treatments (baseline)

Depth (cm)*	P	K	Ca	Mg	Na	Fe	Mn	B	Mo	Cu	Zn
					------mg kg^{-1}------						
0-10	16.4 (2.76)	277 (20.6)	1350 (178)	897 (27.1)	818 (85.5)	284 (25.7)	36.4 (5.26)	25.7 (2.96)	0.04 (0.01)	1.22 (0.13)	34.0 (3.57)
10-20	14.9 (2.57)	260 (16.1)	1270 (129)	898 (26.8)	808 (76.8)	269 (19.2)	37.0 (5.85)	25.3 (2.52)	0.04 (0.01)	1.31 (0.14)	32.8 (2.83)
20-40	17.3 (2.16)	299 (37.1)	1420 (96.6)	902 (23.3)	890 (150)	263 (20.1)	42.8 (4.40)	32.6 (5.80)	0.04 (0.01)	1.36 (0.13)	47.0 (12.2)

*All elements are n = 15 for each depth increment. Mean values are presented for each parameter with standard deviation in parentheses.

Table 3: Critical values for soil physical characteristics of the tropics and suitability levels for crop growth

Soil property	Limitation	Suitability	Field site condition
Soil Texture	None	Loam	Clay
	Slight	Silt, silt loam, silty clay loam	
	Moderate	Clay loam, sandy loam	
	Severe	Silty clay, loamy sand	
	Extreme	Clay, sand	
Bulk Density (Mg m^{-3})	None	< 1.20	1.06
	Slight	1.20 – 1.30	
	Moderate	1.30 – 1.60	
	Severe	1.40 – 1.50	
	Extreme	> 1.50	
Penetration Resistance (MPa)	None	< 1.00	0.36
	Slight	1.00 – 1.50	
	Moderate	1.50 – 2.00	
	Severe	2.00 – 2.50	
	Extreme	> 2.50	
Total Porosity (%)	None	> 20	59.5
	Slight	18 - 20	
	Moderate	15 - 18	
	Severe	10 - 15	
	Extreme	< 10	
Water Infiltration Rate (cm min^{-1}) at 30 minutes	None	> 0.08	0.02
	Slight	0.03 – 0.08	
	Moderate	0.02 – 0.03	
	Severe	0.008 – 0.02	
	Extreme	< 0.008	
Saturated Hydraulic Conductivity (cm min^{-1})	None	> 0.03	0.0003
	Slight	0.003 – 0.03	
	Moderate	0.0003 – 0.003	
	Severe	0.00003 – 0.0003	
	Extreme	< 0.00003	

* Suitability and limitations for each soil property provided from Lal, 1994.

Table 4: Critical values for soil chemical characteristics of the tropics and suitability levels for crop growth

Soil property	Limitation	Suitability	Field site condition
Soil pH	None	6.0 – 7.0	4.92
	Slight	5.8 to 6.0 and 7.0 to 7.4	
	Moderate	5.4 to 5.8 and 7.4 to 7.8	
	Severe	5.0 to 5.4 and 7.8 to 8.2	
	Extreme	< 5.0 and < 8.2	
Electrical Conductivity ($dS\ m^{-1}$)	None	< 3	0.65
	Slight	3 - 5	
	Moderate	5 - 7	
	Severe	7 - 10	
	Extreme	> 10	
Soil Organic Carbon (SOC) (%)	None	5 - 10	1.78
	Slight	3 - 5	
	Moderate	1 - 3	
	Severe	0.5 - 1	
	Extreme	< 0.5	

* Suitability and limitations for each soil property provided from Lal, 1994

Experimental design

Treatments for the study were laid out according to a randomized complete block design. Each block contained five treatments: control (C), chemical fertilizer (CF), one-time application of rice hull biochar (RHB) (10 Mg ha^{-1}), one-time application of poultry manure biochar (PMB) (10 Mg ha^{-1}), and one-time application of sugarcane filter press (FP) (10 Mg ha^{-1}). In addition, chemical fertilizer was added to each treatment, except for the control. Each block was replicated three times resulting in a total of 15 plots. Each plot was 5 m long by 5 m wide with 0.5 m buffer between treatments and 1 m buffer between blocks and contained seven rows with 0.76 m spacing between rows.

Amendment preparation

The CF consisted of 12-12-17-2 (12% N, 12% P, 12% K, 2% MgO) fertilizer, muriate of potash (MOP) (0-0-60), and urea fertilizer (46-0-0). The fertilization regime for the maize, in accordance to the recommendations of NAREI, followed the timeline of: 12 days after planting – 200 kg ha^{-1} 12-12-17-2, 36 days after planting – 400 kg ha^{-1} 12-12-17-2, 49 days after planting – 72 kg ha^{-1} MOP and 70 kg ha^{-1} urea.

The RHB and PMB were created using a double barrel kiln. The outer barrel of the kiln measured 1.52 m long with a diameter of 0.97 m. The inner barrel of the kiln measured 1.40 m long with a diameter of 0.71 m. The cover of the barrel was 1.13 m in diameter and had a 0.05 m lip around. The smoke stack was 1.50 m tall with a diameter of 0.11 m. The kiln was constructed with mild steel. Rice hull for the RHB was obtained from a rice mill in Perth Village (Mahaicony, Guyana) while manure for the PMB was obtained from a poultry farm in Novar Village (Mahaicony, Guyana).

The biochar was produced by placing the feedstock material in the inner barrel of the kiln. An 8 cm layer of wood chips, comprising of scrap Greenheart (*Chlorocardium rodiei*) and Mora (*Mora excelsa)* wood, was placed at the bottom of the inner barrel. A 20 cm layer of feedstock was placed in the barrel and this layering process was repeated until the inner barrel was filled. Wood chips were placed as the top layer and a metal mesh was securely placed to cover the opening of the inner barrel. The inner barrel was inverted and centered into the larger barrel. Larger pieces of wood were placed around and on top of the inner barrel when inside the kiln. Tinder material was ignited and allowed to establish thoroughly before the lid of the kiln was closed. The kiln was left for one day to undergo pyrolysis and adequately heat and cool. Sufficient charring occurred throughout the barrel when no fresh feedstock was present. The resulting biochar material was sieved through a mesh to filter out charcoal chips that were previously wood chips. The pyrolysis process was replicated several times until a total of 68 kg of biochar was produced. Per batch, about 32-36 kg of dry rice hull and 50-54.5 kg of dry poultry manure was placed in the inner barrel, respectively. Each biochar batch yielded about 11-14 kg of RHB and 18-20 kg of PMB, respectively.

FP was obtained from an existing amount at NAREI totaling 68 kg. The FP was originally collected from the LBI Sugar Mill in La Bonne Intention Village, E.C.D., Guyana.

The RHB, PMB, and FP treatments were applied by hand to plots on 19 August 2014. These amendments were incorporated into the soil using a machete (cutlass) to a depth of 10 cm. Plots designated as C and CF were also tilled with the machete to this depth to maintain uniformity in application method.

Soil sampling

Intact soil core (5 cm diameter, 5 cm height) and bulk samples were collected from three depths (0-10, 10-20 and 20-40 cm) before treatment imposition and after the growing season (Kladivko et al. 2014). A 40 cm long probe sampler was used to collect bulk soil from 10-12 spots within each research plot. Soil from each respective depth was composited, air dried, gently ground, and sieved through a 2mm sieve. Core and bulk samples were stored in pre-labeled plastic bags pending analysis.

Soil physical analyses

Bulk density was measured by the core method (Grossman and Reinsch 2002). The 5 x 5 cm core samples were trimmed along the edge of the core. Gravimetric water content was determined by drying soil at 105°C for 24 hours. Particle density was measured using the pycnometer method (Flint and Flint 2002), and the particle size analysis by the hydrometer method (Gee and Or 2002). Penetration resistance was measured using a cone penetrometer (Model Hypen1, Pike Agri-Lab Supplies, Inc). The penetrometer was firmly inserted into the soil and the dial gauge was read at different depths (Lowery and Morrison 2002). Water infiltration was measured using a Mini-Disk Infiltrometer (Decagon Device, Inc, Pullman WA). The steady state infiltration (i_c) was observed at 30 minutes, although measurements were taken up to 100 minutes. Infiltration data collected were then fitted to the Philips Model (Philips 1957).

Soil chemical analyses

Soil pH and electrical conductivity (EC) were determined by using a 2.5:1 soil to water suspension (Thomas 1996; Rhoades 1996). A Thermo-Scientific Orion Star Series pH/ Conductivity Meter was used to measure both parameters. Total carbon (TC) and total nitrogen (TN) concentrations were measured using the dry combustion method at 900˚ C. A 15 µg soil sample, passed through a 250 µm sieve, was placed in small aluminum tins and analyzed in a Flash 2000 Thermo Scientific Organic Elemental Analyzer. TC is presented as soil organic carbon (SOC) because soil pH was < 7.0 (Olson et al. 2014). Exchangeable acidity was measured using the potassium chloride (KCl) method (Thomas 1982). Plant available nutrients were determined using a modified version of the Mehlich III extraction (Mehlich 1984). A 1 g sample of soil was mixed with 10 mL of Mehlich III solution for 5 minutes. The solution was syringe filtered and the extract was analyzed through an inductively coupled plasma mass spectrometry (ICP) for B, Ca, Cu, Fe, K, Mg, Mn, Mo, Na, P and Zn.

Agronomic productivity

Maize seeds were planted in all experimental plots on 20 August 2014. One seed was planted per hole. Holes for seeds were spaced apart 15 cm within the row. This planting rate resulted in 12-13 seeds planted m^{-2} or about 234 plants $plot^{-1}$. Seeds were provided from the Inter-American Institute for Cooperation on Agriculture (IICA) – Guyana. The cultivar used was an open field pollinated yellow corn variety (Pioneer, Belize).

Germination percentage was measured on 08 September 2014 by calculating the total number of seeds that germinated as a proportion of the total number of seeds planted within a 1 m^2 area. Crop stand was measured on 15 September 2014 by recording the number of plants present within a 1 m^2 area of the plot. Each of these parameters was measured in triplicate. Crop height (cm) was measured periodically throughout the growing season from five randomly selected plants within a plot. Crop height was measured from the base of the plant to the most visible leaf from the whorl and to the top of the tassel, once it had formed. Measurements began one week after germination and were recorded on a bi-monthly basis. Height (cm) of the flag and ear leaves were measured before harvesting from the same plants selected for plant height. The heights were measured from the plant's base. The ear count was measured from 10 randomly selected plants within each plot before harvesting. Canopy cover was estimated using digital photography (Nielsen et al. 2012). A Sony DSC-W320 digital camera was used to capture photographs in three different locations within each plot. Photographs were taken when the camera was level with the horizon and out at arm's length. They were then analyzed using SamplePoint (Version 1.56) (Booth et al. 2006). A total of 100 randomly assigned points were selected within the photograph and classified either as soil or crop. The canopy cover (%) was calculated using the ratio of points that contacted crop canopy to the total number of points.

Harvest and yield

Harvesting occurred when plants were at physiological maturity (R6 stage). Plots were harvested on 16 December 2014 (122 days after germination). The aboveground biomass and grain yields were measured within a 1 m^2 area of the two center rows for each plot. Plants were harvested by clipping the base of the plant near the soil surface. Fresh biomass (stover and grain) and cob masses were recorded. Two maize stalks and cobs, respectively, were each placed in paper bags and allowed to air dry. Dry grains were separated from the cob by hand. A grain moisture meter (Dickey-John Mini-Gac) was used to determine the moisture content of the grain. Dry masses for biomass and grains were adjusted to 15.5 % moisture content.

Statistical analysis

Statistical analysis was performed using SAS, version 9.2 (SAS 2007). The general linear model (GLM) was used to perform statistical analysis to assess the impact of amendments on soil physicochemical and agronomic productivity parameters measured while accounting for variation due to blocks. Data collected were categorized into five treatment groups – control (C), chemical fertilizer (CF), rice hull biochar (RHB), poultry manure biochar (PMB) and sugarcane filter press (FP). When an indication of a statistically significant difference at $p<0.05$ was present, a post-hoc comparison using the Tukey-Honest Significant Differences (HSD) test was carried out.

Results and discussion

Soil physical properties

A summary of soil physical properties at the end of the growing season is presented in Table 5. No statistically significant differences among treatments were observed at any of the soil depths for the soil physical parameters measured at the end of the growing season. These results were expected because of the short-term duration of the study.

Bulk density ranged from 1.04 to 1.42 Mg

m^{-3} for the surface 0-10 cm depth, 1.35 to 1.51 Mg m^{-3} for the 10-20 cm intermediate layer, and 1.10 to 1.30 Mg m^{-3} for the 20-40 cm sub-soil layer. Total porosity was from 0.46 to 0.60, 0.42 to 0.48 and 0.50 to 0.58 for the surface, intermediate and sub-soil layers, respectively. After the growing season, a reduction in ρ_b and increase in f_t was seen for the two biochar amended plot (RHB and PMB), when compared against the C. All ρ_b values after the growing season for each depth increment were higher when compared to the initial baseline values before treatment imposition. This may have been due to continued soil settling throughout the growing season. The intermediate soil depth (10-20 cm) had higher ρ_b values observed for the baseline values and at the end of the growing season. This increase could be attributed to a compacted plow pan that may have developed within this depth. Tillage operation prior to this study involved moldboard plowing before field preparation and planting. The plow depth coupled with the use of heavy machinery could have created a compacted plow pan. In instances when this occurs, the compacted layer has a much higher ρ_b than the subsequent uncompacted layer below. Application of soil amendments can have varying effects on ρ_b (Mukherjee and Lal, 2013). Busscher et al. (2011) reported decreases in ρ_b with an addition of 2.1% (g g^{-1}) rate of biochar from pecan (*Carya illinoinensis*) shell to a coastal loamy sand. Similarly, Novak et al. (2012) reported decreases in ρ_b with respective 2 % (g g^{-1}) additions of biochars from peanut (*Arachis hypogaea* L.), pecan shell, and poultry litter on a loamy sand. Mankasingh et al. (2011) reported ρ_b reduction with a 6.6 Mg ha^{-1} addition of biochar from cassia (*Cassia sp.*) stem to a soil in India. Karhu et al. (2011) observed an increase in f_t with the addition of biochar from birch (*Betula pendula*) on a silt loam soil. Rossetto et al. (2008) and Diaz et al. (2010) observed favorable changes in soil structure with the addition of FP.

Penetration resistance (PR) ranged from 0.86 to 1.00 MPa for the 0-10 cm depth, 0.96 to 1.01 MPa for the 10-20 cm depth, and 0.97 to 1.12 MPa for the 20-40 cm depth. PR values for all three depths are well below 2 MPa where root growth restriction might become a problem (Gugino et al., 2009). Busscher et al. (2010) and Busscher et al. (2011) noted decreases in PR with increasing rates (0.5-2.1% (g g^{-1})) of biochar from pecan shell feedstock when added to a loamy sand.

Table 5: Soil physical parameters for field site at the conclusion of the growing season

Depth (cm)*	Treatment	Bulk density (Mg m^{-3})***	Volumetric water content (θ)	Total porosity (f_t) **	Air porosity (f_a)	Penetration resistance (MPa)
0-10	C	1.21 (0.11)	0.19 (0.05)	0.54 (0.04)	0.35 (0.06)	0.90 (0.10)
	CF	1.28 (0.06)	0.26 (0.07)	0.51 (0.02)	0.25 (0.08)	0.89 (0.11)
	RHB	1.20 (0.18)	0.16 (0.17)	0.54 (0.10)	0.38 (0.14)	0.86 (0.14)
	PMB	1.04 (0.12)	0.16 (0.04)	0.60 (0.08)	0.44 (0.10)	1.00 (0.23)
	FP	1.42 (0.28)	0.21 (0.09)	0.46 (0.09)	0.25 (0.06)	1.00 (0.26)
10-20	C	1.35 (0.09)	0.37 (0.02)	0.48 (0.04)	0.11 (0.02)	0.96 (0.12)
	CF	1.48 (0.33)	0.32 (0.08)	0.43 (0.13)	0.11 (0.19)	0.96 (0.15)
	RHB	1.44 (0.14)	0.23 (0.11)	0.45 (0.05)	0.22 (0.07)	0.97 (0.19)
	PMB	1.37 (0.16)	0.25 (0.09)	0.48 (0.06)	0.23 (0.15)	1.01 (0.17)
	FP	1.51 (0.24)	0.37 (0.05)	0.42 (0.09)	0.05 (0.13)	0.96 (0.22)
20-40	C	1.30 (0.16)	0.37 (0.08)	0.50 (0.06)	0.13 (0.11)	0.97 (0.24)
	CF	1.27 (0.07)	0.31 (0.09)	0.52 (0.03)	0.21 (0.09)	1.00 (0.20)
	RHB	1.22 (0.18)	0.37 (0.08)	0.53 (0.03)	0.16 (0.08)	1.00 (0.17)
	PMB	1.12 (0.05)	0.29 (0.15)	0.57 (0.08)	0.28 (0.22)	1.04 (0.17)
	FP	1.10 (0.35)	0.25 (0.11)	0.58 (0.13)	0.33 (0.25)	1.12 (0.22)

*All parameters are n = 15 for each depth increment. Mean values are presented for each parameter with standard deviation in parentheses. ** Particle density was calculated to be 2.62 Mg m^{-3} for the soil at the field site. *** NS = not significantly different at p<0.05.

Mean values for soil hydrological properties are presented in Table 6. There were no significant differences among treatments for soil hydrological parameters measured. Steady state infiltration (i_c) (cm min^{-1}) ranged from 5.67 x 10^{-4} to 1.80 x 10^{-3}. The CF, RHB, PMB, and FP groups had higher infiltration rates than that of the soil under C (Figure 1). Transmissivity (A) (cm min^{-1}) was between 0.033 and 0.057 while sorptivity (S) (cm $min^{-1/2}$) was between 0.441 and 0.589. The CF and PMB amended soils had sorptivity values similar to the unamended soil (0.441 and 0.449 vs 0.448 cm $min^{-1/2}$) The RHB and FP soils have slightly higher sorptivity values (0.542 and 0.589 cm $min^{-1/2}$). These values indicate that the soil at the field site was good at absorbing water. Transmissivity followed a similar pattern to sorptivity were the CF and PMB closely resembled the unamended soil and the FP and RHB had slightly higher transmissivity values. However, among all treatment groups, transmissivity values were rather low signaling that water movement within soil was very low. This can be seen in the i_c values obtained in this study because they fall within the slow rate class for a clayey soil (USDA-NRCS). Soil hydrological properties can be altered through amendment application. Bayabil et al. (2015) reported improvements to hydraulic conductivity and water infiltration rate on a clayey soil in Ethiopia with addition of biochar produced from the feedstock of *Eucalyptus camaldulensis*, *Acacia abyssinica*, and *Croton macrostachyus*. Barnes et al. (2014) reported decreases in i_c for a sandy soil and an organic soil with application of 133 Mg ha^{-1} of biochar from mesquite (*Prosopis sp.)* but saw increases in i_c with a clayey soil at the same application rate. Kumar et al. (1985) reported increases in available water and water retention with FP application on a sandy soil in Australia.

Table 6: Soil hydrological properties for field site at the conclusion of the growing season

Treatment*	Steady state infiltration (i_c) (cm min^{-1}) **	Transmissivity (A) (cm min^{-1})	Sorptivity (S) (cm $min^{-1/2}$)
C	1.80 x 10^{-3}	0.037	0.448
CF	1.49 x 10^{-3}	0.056	0.441
RHB	1.30 x 10^{-3}	0.033	0.589
PMB	8.67 x 10^{-4}	0.057	0.449
FP	5.67 x 10^{-4}	0.036	0.542

*All treatments are *n* = 3 for each parameter measured. ** NS = not significantly different at $p<0.05$.

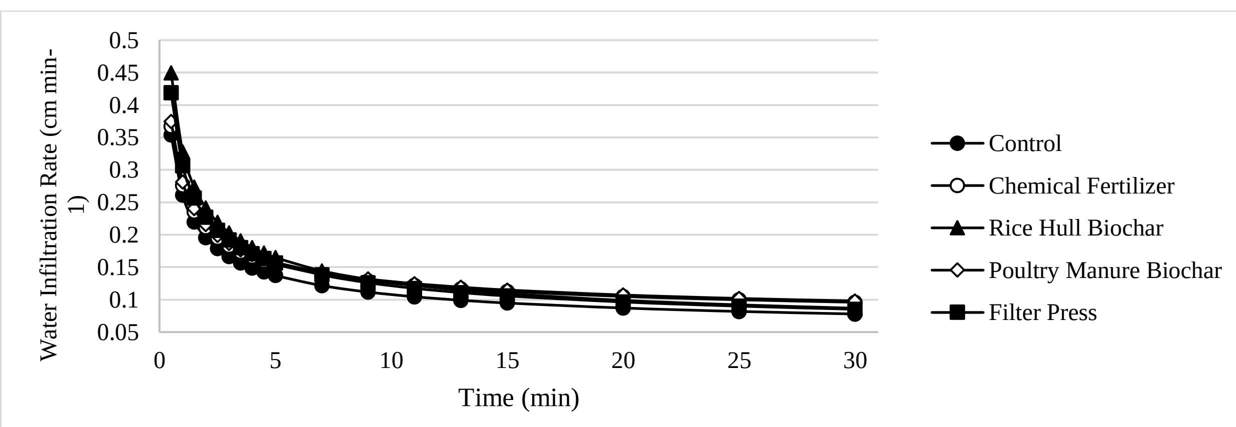

Figure 1: Water Infiltration rates for soils after amendment application. Mean values are displayed. NS = not significantly different.

Soil chemical properties

A summary of chemical properties for the soil sampled after the conclusion of the growing season is presented in Table 7. Soil pH differed significantly among treatments at 0-10 cm depth ($F_{(4,10)} = 7.60$, $p < 0.01$) and observed the trend of: C (5.58) ≥ RHB (5.24) = CF (5.13) = PMB (5.04) = FP (5.03). Soil pH ranged from 5.46 to 5.61 and 5.38 to 5.54, respectively, for the 10-20 cm and 20-40 cm depths and did not differ significantly. Soil pH increased in all treatments after the growing season ended as compared to the baseline pH values (4.92 – 0-10 cm, 4.80 – 10-20 cm, 4.71 – 20-40 cm) for the field site. This increase can mainly be attributed to the liming effect of the amendments (amendment pH higher than that of the soil) coupled with the buffering capacity of the soil at the field site. Influence of soil pH is dependent on the feedstock used, and in the case of the biochar treatment, the temperature at which pyrolysis occurred. Application of RHB has been shown to increase soil pH by 0.1-0.2 units in a red soil of China (Liu et al. 2017) as well as a sandy soil (Tabela sand) in Guyana by 2.1-2.9 units when applied at a rate of 5-50 t ha^{-1} (Persaud et al. 2018). Application of 1-4 t ha^{-1} of PMB, via slow pyrolysis, was shown to increase soil pH by 0.2-0.18 units in a Bangladesh soil (Sikder and Joardar 2019). Application of FP at rates of 60 t ac^{-1} and 120 t ac^{-1} increased soil pH 0.02 and 0.05 units, respectively, for a Fluvent soil in Ethiopia (Fantaye et al. 2016). The increase in soil pH at the field site will allow for greater nutrient availability and chemical mediated processes.

Electrical conductivity (EC) (dS m^{-1}) differed significantly among treatments in the surface layer ($F_{(4,10)} = 3.98$, $p < 0.05$) and observed the trend of: PMB (0.56) ≥ RHB (0.45) = CF (0.42) = FP (0.41) ≥ C (0.19). EC (dS m^{-1}) ranged between 0.18 to 0.28 for the intermediate layer and 0.20 to 0.40 for the sub-soil layer and showed no significant differences present. Soil EC increased in all amended soils when compared against the control, but was lower overall when compared against the baseline values obtained before initiating the study. For all depths measured, EC values were below 1 dS m^{-1} and are within the optimum range for maize growth. RHB application to a sandy soil in Guyana resulted in mean soil EC of 0.15 dS m^{-1} at application rates of 5, 25, and 50 t ha^{-1} (Persaud et al. 2018). PMB application (4 t ha^{-1}) to a Bangladesh soil was shown to increase soil EC by 3% (Sikder and Joardar 2019). FP addition at a rate of 60 t ac^{-1} and 120 t ac^{-1} to a Fluvent and Aquert in Ethiopia increased soil EC by 0.04-0.08 dS m^{-1} and 0.05-0.17 dS m^{-1}, respectively (Fantaye et al. 2016). Amended soils in this study yielded EC values that did not exceed the critical threshold for maize yield declines.

Soil organic carbon (SOC) (%) differed significantly among treatments at 0-10 cm depth ($F_{(4,10)} = 21.66$, $p < 0.001$) and observed the trend of: RHB (3.02) = PMB (2.75) > FP (1.95) = CF (1.87) = C (1.84). SOC concentrations were between 1.71 to 1.83 % at 10-20 cm depth and between 1.57 to 1.71% at 20-40 cm depth and lacked significant differences among treatments. Concentration of SOC was the highest in the surface soil depth for the two BC treatments. This was expected, as BC is a black carbon source. When compared with the control, addition of RHB increased SOC concentrations by 64% while PMB addition increased it by 49%. Mekuria et al. (2014) reported a 54-184% increase in SOC concentration when 10 Mg ha^{-1} of RHB was added to two clayey soils in Laos. Persaud et al. (2018) noted a 1.12 to 3.62 % increase in soil organic matter concentration in an acidic, sandy soil in Guyana when RHB was added at rates of 5, 25, and 50 t ha^{-1}. SOC concentration in a Bangladesh soil doubled with 4 t ha^{-1} of PMB addition (Sikder and Joardar 2019). In an Alfisol in Australia, PMB addition at rates of 10, 25, and 50 t ha^{-1} increased SOC concentration by 80 %, when compared against an unamended soil (Chan et al. 2008). FP application at rates of 60 t ac^{-1} and 120 t ac^{-1} to an Aquert in Ethiopia increased SOC concentration from 1.68 % to 2.31% and 3.04%, respectively. Similarly, in a Fluvent in Ethiopia, SOC concentration increased from 1.07 % to 1.25 % and 1.39 %, respectively (Fantaye et al. 2016). SOC is a key soil parameter that strongly influences many physical and chemical properties and is related to the amount of C that is added to the soil via amendment application (Blanchet et al. 2016).

Total N (TN) (%) differed significantly among treatments at the surface depth ($F_{(4,10)}$ = 24.70, $p < 0.001$) and observed the trend of: PMB (0.25) > RHB (0.20) ≥ FP (0.19) = CF (0.19) ≥ C (0.16). Concentration of TN ranged between 0.16-0.17 % in the intermediate depth and 0.15-0.16 % in the soil-soil depth and showed no significant differences, respectively. Concentration of TN increased in the surface soil depth with amendment application for all treatments except the C. The two BC treatments showed the greatest increase. RHB and PMB addition increased the TN concentration by 25% and 56% at the 0-10 cm depth. Manure based BC is usually higher in TN due to the manure feedstock being already rich in N. A feedstock that is high in N is likely to produce BC that is also high in N (Novak et al. 2014). Application of other BCs to soil have could have varying effects on TN, due their feedstock source, properties, and elemental composition (Novak et al. 2014). This is very apparent in BC made from manure feedstock (e.g., poultry manure) versus BC made from a lignocellulosic-based feedstock (e.g., rice hull). The C:N ratios for all three depths in this study were similar among all treatments and ranged from 10:1 to 15:1, well within the optimal range for crop growth. C:N ratios of > 24:1 can begin to immobilize nutrients and adversely affect crop growth (Velez et al. 2018).

KCl exchangeable acidity ($cmol_{(+)}$ kg^{-1}) differed significantly among treatments at 0-10 cm depth ($F_{(4,10)}$ = 4.88, $p < 0.05$) and followed the trend of: CF (23.6) ≥ RHB (18.3) = C (16.9) ≥ PMB (14.3) = FP (14.3). No significant differences among treatments were observed in the 10-20 cm and 20-40 cm depths. Exchangeable acidity ($cmol_{(+)}$ kg^{-1}) ranged between 14.3-19.6 at 10-20 cm depth and between 14.3-18.3 at 20-40 cm depth. Exchangeable acidity was high in the CF treatment of the surface soil layer. With the baseline soil samples being strongly acidic (pH <5.0), it was likely that the exchangeable acidity would be high due to the presence of Al^{3+} and H^+ ions on the CEC. Amendment application of PMB and FP decreased exchangeable acidity in the surface soil depth. The amendments likely acted as a liming agent, thus increasing the soil pH and reducing the exchangeable acidity (Novak et al. 2009).

Table 7: Soil chemical parameters for field site at the conclusion of the growing season

Depth (cm)*	Treatment	Soil pH **	Electrical conductivity (dS m^{-1})	SOC (%)	TN (%)	C:N Ratio	KCl acidity ($cmol_{(+)}$ kg^{-1})
0-10	C	5.58 (0.15) a	0.19 (0.02) b	1.84 (0.16) b	0.16 (0.01) c	11.5:1 (0.58) b	16.9 (2.31) ab
	CF	5.03 (0.02) b	0.42 (0.05) ab	1.87 (0.06) b	0.19 (0.01) bc	9.8:1 (0) b	23.6 (4.00) a
	RHB	5.24 (0.18) ab	0.45 (0.26) ab	3.02 (0.08) a	0.20 (0.01) b	15.1:1 (0.58) a	18.3 (4.62) ab
	PMB	5.13 (0.15) b	0.56 (0.04) a	2.75 (0.39) a	0.25 (0.02) a	11.0:1 (1.0) b	14.3 (2.31) b
	FP	5.04 (0.07) b	0.41 (0.41) ab	1.95 (0.12) b	0.19 (0.01) bc	10.3:1 (0.58) b	14.3 (2.31) b
10-20	C	5.61(0.09)	0.18 (0.03)	1.71 (0.08)	0.16 (0.01)	10.7:1 (0.58)	16.9 (2.31)
	CF	5.60 (0.13)	0.25 (0.05)	1.73 (0.12)	0.16 (0.01)	10.8:1 (0)	18.3 (2.31)
	RHB	5.46 (0.11)	0.28 (0.04)	1.80 (0.14)	0.16 (0.01)	11.3:1 (0.58)	16.9 (2.31)
	PMB	5.56 (0.02)	0.26 (0.05)	1.83 (0.05)	0.17 (0)	10.8:1 (0)	14.3 (6.93)
	FP	5.56 (0.20)	0.25 (0.05)	1.71 (0.11)	0.16 (0.01)	10.7:1 (1.0)	19.6 (2.31)
20-40	C	5.50 (0.14)	0.20 (0.03)	1.65 (0.11)	0.15 (0.01)	11.0:1 (0.58)	18.3 (2.31)
	CF	5.43 (0.19)	0.34 (0.15)	1.71 (0.15)	0.16 (0.02)	10.7:1 (0)	18.3 (2.31)
	RHB	5.38 (0.04)	0.32 (0.04)	1.66 (0.03)	0.16 (0.01)	10.4:1 (0.58)	16.9 (2.31)
	PMB	5.51(0.06)	0.40 (0.15)	1.69 (0.03)	0.16 (0)	10.6:1 (0.58)	14.3 (2.31)
	FP	5.54 (0.08)	0.32 (0.06)	1.57 (0.11)	0.15 (0.02)	10.5:1 (0.58)	16.9 (2.31)

*All parameters are n = 15 for each depth increment. Mean values are presented for each parameter with standard deviation in parentheses. ** Mean values in columns within a depth followed by a different letter are significantly different at p<0.05. NS = not significantly different.

Elemental analysis for macro- and micronutrients for the soil sampled at the end of the growing season is presented in Table 8. Concentrations of P, K, Ca, and Mg (mg kg^{-1}) differed significantly among treatments at the 0-10 cm depth. Concentration of P (mg kg^{-1}) was higher in the FP (170) and PMB (171) amended soils than that of the C (17.3) and CF (67.8), and RHB (113). Concentration of K (mg kg^{-1}) was significantly lower in the unamended soil (300) than that in the other treatments (565-757). Concentration of Ca (mg kg^{-1}) for the FP treatment (1660) was higher than that of C, CF, and RHB treatments (1360-1400). Concentration of Mg (mg kg^{-1}) was the highest in the C (887) versus that for the other treatments (807-832). Concentration of P differed significantly among treatments at the 10-20 cm depth and followed the trend of PMB (28.6) $\geq$ FP (23.1) = PMB (20.1) = CF (19.0) > C (15.1). Concentration of macronutrients did not differ significantly among treatments at the 20-40 cm depth.

Concentration of Fe, Mn, and Cu (mg kg^{-1}) differed significantly among treatments at the surface depth. Concentration of Fe and Mn were the highest in the FP amended soil (268, 34.2) and the lowest in unamended soil (230, 21.8). Concentration of Cu was greater in the unamended soil (1.09) and the lowest in the CF (0.94) and biochar amended soils (0.87-0.89). Concentration of micronutrients did not differ significantly among treatments at the 10-20 cm depth. At the sub-soil depth, concentration of Fe was the highest in the unamended soil (295) while that of Mo was the highest in the RHB amended soil (0.05).

The P content in the amended soils was at minimum, 4 times higher than in the unamended control. The FP amendment and RHB and PMB amendments, after pyrolysis, are inherently nutrient rich materials. The ~10x increase in the P concentration for the FP and PMB soils and ~6.5x increase for the RHB amended soils can be explained by this. Similarly, the ~2.2-2.5x increase in K concentration in the RHB, PMB< and FP amended soils can also be explained by the addition of a nutrient rich amendment. Novak et al. (2014) showed that addition of PMB and BCs made from other agricultural byproducts can have multifold increases (1-26x increase for P; 3-14x increase for K) that can increase the fertility status of a sandy soil. Novak et al. (2009) reported increased concentrations of macronutrients (P, K, Ca) and variable effects on micronutrients (Mn, S, Zn) with addition of 0.5-2% (g g^{-1}) biochar from pecan shells to a sandy soil. FP is a material rich in organic carbon and macro- and micronutrients that can be readily accessible to plants (Kumar and Chopra 2016). Fantaye et al. (2016) showed that FP addition to a Fluvent soil increased available P concentration 10x with addition of 120 t ha^{-1}. Similarly, in an Aquerts soil, there was a threefold increase with FP addition at this rate. Addition of organic amendments to acidic soils, similar to ones utilized in this study, has been shown to produce a liming effect that increases soil pH, subsequently increasing the uptake of plant available nutrients.

Table 8: Soil elemental analysis of the field site at the conclusion of the growing season

Depth (cm)*	Treatment	P **	K	Ca	Mg	Na	Fe	Mn	B	Mo	Cu	Zn
						------mg kg^{-1}------						
0-10	C	17.3 (1.96) c	300 (21.8) b	1400 (61.8) bc	887 (17.5) a	778 (139)	230 (18.5) b	21.8 (1.87) b	29.2 (5.59)	0.04 (0.01)	1.09 (0.04) a	41.2 (12.0)
	CF	67.8 (15.2) bc	565 (36.4) a	1360 (47.7) c	826 (48.9) b	697 (132)	259 (17.4) ab	30.7 (1.59) ab	28.6 (4.77)	0.04 (0.01)	0.94 (0.03) b	41.5 (10.5)
	RHB	113 (4.57) ab	661 (29.6) a	1390 (26.3) bc	832 (26.8) ab	649 (24.3)	253 (19.0) ab	28.6 (4.47) ab	27.4 (3.86)	0.04 (0.01)	0.89 (0.06) b	35.2 (3.56)
	PMB	171 (40.0) a	757 (204) a	1550 (68.8) ab	825 (44.8) b	703 (87.4)	256 (3.95) ab	31.0 (5.24) ab	31.5 (8.22)	0.04 (0.01)	0.87 (0.03) b	44.3 (13.7)
	FP	170 (50.5) a	654 (47.8) a	1660 (84.1) a	807 (6.45) b	759 (149)	268 (23.4) a	34.2 (3.22) a	36.6 (10.4)	0.04 (0.01)	1.01 (0.06) ab	55.5 (13.0)
10-20	C	15.1 (1.55) b	296 (26.8)	1390 (62.6)	882 (26.7)	849 (86.0)	267 (9.66)	25.1 (2.38)	33.8 (1.42)	0.04 (0.01)	1.34 (0.09)	47.2 (6.45)
	CF	19.0 (1.72) ab	337 (98.1)	1570 (104)	861 (12.1)	920 (262)	280 (26.0)	23.9 (2.17)	35.1 (8.16)	0.04 (0.01)	1.28 (0.11)	55.3 (27.4)
	RHB	20.1 (2.52) ab	321 (61.4)	1430 (96.3)	857 (37.6)	868 (163)	292 (27.4)	28.4 (3.87)	33.3 (6.49)	0.04 (0.01)	1.29 (0.10)	47.3 (13.8)
	PMB	28.6 (8.30) a	362 (60.5)	1600 (68.2)	864 (32.7)	869 (151)	267 (15.4)	22.7 (0.27)	33.0 (2.43)	0.03 (0.01)	1.27 (0.03)	50.5 (12.3)
	FP	23.1 (2.89) ab	317 (45.5)	1510 (96.4)	845 (30.8)	861 (97.4)	269 (43.8)	22.6 (1.08)	36.4 (9.86)	0.04 (0.01)	1.32 (0.302)	53.2 (10.6)
20-40	C	15.3 (1.71)	339 (26.2)	1320 (151)	874 (27.3)	988 (43.0)	295 (16.6) a	30.0 (5.93)	34.6 (2.77)	0.04 (0.01) ab	1.36 (0.01)	56.4 (3.61)
	CF	16.2 (2.17)	312 (40.5)	1390 (46.3)	871 (13.3)	942 (140)	275 (26.6) ab	27.8 (2.43)	32.8 (5.39)	0.03 (0.01) bc	1.28 (0.11)	49.9 (10.8)
	RHB	17.3 (1.51)	314 (48.4)	1300 (82.0)	874 (44.4)	983 (172)	292 (6.89) ab	32.5 (5.49)	31.2 (4.13)	0.05 (0.01) a	1.30 (0.09)	49.2 (10.6)
	PMB	17.9 (1.81)	313 (50.0)	1450 (130)	872 (30.4)	938 (130)	287 (17.4) ab	29.2 (1.63)	30.8 (4.83)	0.04 (0.01) ab	1.32 (0.01)	46.9 (11.4)
	FP	19.0 (1.61)	295 (61.0)	1450 (102)	866 (29.6)	896 (179)	254 (24.9) b	26.5 (0.70)	31.7 (7.85)	0.03 (0.01) c	1.34 (0.04)	44.5 (14.0)

*All parameters are $n = 15$ for each depth increment. Mean values are presented for each parameter with standard deviation in parentheses. ** Mean values in columns within a depth followed by a different letter are significantly different at $p<0.05$. NS = not significantly different.

Soil suitability for crop growth

Baseline values for several soil physical (Table 1) and chemical (Table 2) properties were compared against critical values for crop growth in tropical soils for those properties at 0-10 cm depth (Table 3 and Table 4). Soil textural classification for the field site was a clay and was classified with an extreme limitation. Bulk density (1.06 Mg m^{-3}), PR (0.36 MPa), and f_t (59.5%) had values below a critical threshold that would limit maize growth and yields. Water infiltration rate (0.02 cm min^{-1}) and K_s (0.0003 cm min^{-1}) had moderate to severe limitations. Soil pH (4.92) exhibited extreme limitation while EC (0.65 dS m^{-1}) showed no limitations. SOC concentration (1.78 %) displayed slight limitation. Soil parameters that are at suboptimal levels have the greatest potential to be improved in order to result in improved soil quality and crop yields.

Several amended soils showed changes in their limitations at the end of the growing season when compared with the baseline values. Bulk density for the PMB and RHB treatments registered no limitations while the CF and FP had slight and severe limitations, respectively. In all amended soils, bulk density increased throughout the growing season. This could have been caused primarily by soil settling throughout the growing season. PR continued to have no limitations with values ranging from 0.86 to 1.00 MPa at the end of the season. Similarly, f_t did not possess any limitations as all values were greater than 20%. Water infiltration rate decreased overall for all of the treatment groups (<0.02 cm min^{-1}). The CF and RHB treatments possessed values that were classified as severe while the PMB and FP had values classified as extreme. With soil pH values increasing for all amended soils, the limitation was reclassified from extreme to severe. Soil EC values remained low across all treatment groups and did not possess any limitations. All amended soils showed improvements to SOC content. However, the improvements seen for SOC concentration in the CF, FP, and PMB treatments did not improve the suitability classification for crop growth, thus keeping with a moderate ranking. The RHB amended soil was the only one to be reclassified to a better crop suitability ranking (slight limitation). After one growing season, there were some dynamic soil properties, such as soil pH and SOC content that showed slight rating improvements. Changes may be more apparent for several of the chemical properties, however, many physical properties may show little to no change in the short-term and take a longer time for changes and improvements to be seen.

Agronomic productivity

Agronomic productivity, in the context of this study, evaluates the physiological development of maize throughout the growing season and grain and biomass yields at harvest. Germination percentage for maize seeds was 98.3 % for the C and CF treatment groups and 100 % for the RHB, PMB, and FP treatment groups (Table 9). Crop stand was 6.19, 6.11, 6.07, 6.15, and 6.30 m^{-1} for the C, CF, RHB, PMB, and FP treatment groups, respectively. Free et al. (2010) reported that biochar application to two sandy loam soils resulted in > 96 % germination and had no significant effect on maize germination.

Total height and height at the flag and ear leaves exhibited significant differences among treatments. The final total height (cm) ($F_{(4,10)} = 46.78$, $p < 0.001$) followed a trend of: FP (226.2) = CF (225.4) = PMB (222.9) = RHB (219.9) > C (131.6) (Figure 2). A similar trend was observed for all other sampling dates prior to the final measurement. Flag leaf height (cm) ($F_{(4,10)} = 70.11$, $p < 0.001$) followed the order of: PMB (179.5) = FP (179.2) = CF (177.5) = RHB (173.1) > C (103.3). Ear leaf height (cm) ($F_{(4,10)} = 35.95$, $p < 0.001$) observed the trend of: FP (90.1) = PMB (88.8) = CF (87.3) = RHB (82.8) > C (44.0). Glaser et al. (2002) reported that the aboveground productivity (germination, growth, and yield) increased significantly for various crops with biochar amendment. On an Alfisol in Nigeria, M'bagwu and Piccolo (1997) observed that maize height, aboveground biomass, and root/shoot biomass increased by factors of 1.48, 1.86, 1.98, and 1.73, respectively, relative to the control, with the addition of humic acid biochar. Syuhada et al. (2016) observed that maize height increased with increasing rates (10, 20, 30 Mg ha^{-1}) of biochar from oil palm (*Elaeis guineensis*) byproducts in a sandy soil in Malaysia. Maize height and aboveground biomass increased when amended with 5-10 Mg ha^{-1} of PMB in a loam soil (Brantley et al. 2016).

Table 9: Agronomic productivity parameters throughout the growing season

Treatment*	Germination percentage (%)	Crop stand (# of plants m^{-1})	Flag leaf height (cm)	Ear leaf height (cm)	Ear count (# of ears $plant^{-1}$)
C	98.3 (2.9)	6.19 (0.56)	103.3 (17.1) b**	44.0 (8.14) b	0.77 (0.43) b
CF	98.3 (2.9)	6.11 (0.51)	177.5 (6.03) a	87.3 (4.08) a	1.03 (0.18) a
RHB	100 (0)	6.07 (0.62)	173.1 (5.06) a	82.8 (7.3) a	1.00 (0) a
PMB	100 (0)	6.15 (0.46)	179.5 (13.8) a	88.8 (11.8) a	1.03 (0.18) a
FP	100 (0)	6.30 (0.54)	179.2 (11.5) a	90.1 (10.3) a	1.03 (0.18) a

*Mean values are presented for each parameter with standard deviation in parentheses.
**Mean values for treatment followed by a different letter are significantly different at p<0.05.
NS = not significantly different.

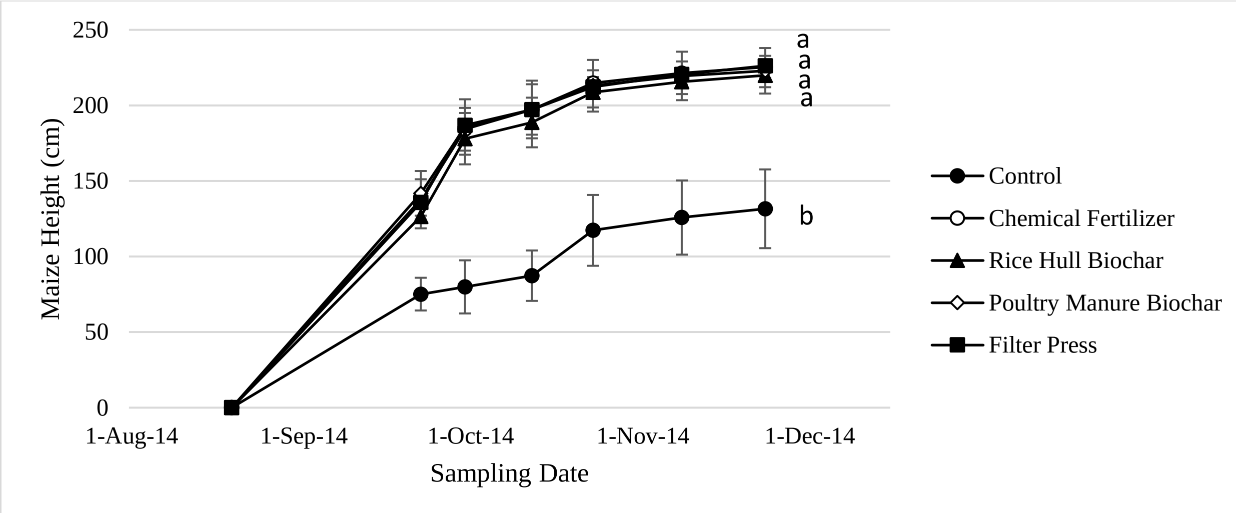

Figure 2: Maize crop height measurements for the first growing season. Mean values are displayed with error bars representing standard deviation. Means compared within a sampling date showing a different letter are significantly different at p<0.05.

Canopy cover was measured at three different periods of the growing season (Figure 3). At the three dates when measurements were taken, canopy cover was significantly lower ($p<0.0001$) in the unamended plots compared with that of the amended. No differences in canopy cover were observed among the CF, RHB, PMB, and FP treatments. Canopy cover in the amended plots was about 80% greater than that of the control plots 34 days after planting and about 52% greater than the control plots 69 days after planting. Kondrlová et al. (2016) showed that 10 t ha^{-1} and 20 t ha^{-1} biochar application to an Orthic Luvisol increased maize canopy cover by 31% and 21 %, respectively, compared to the control, throughout the sampling period (66 days after planting).

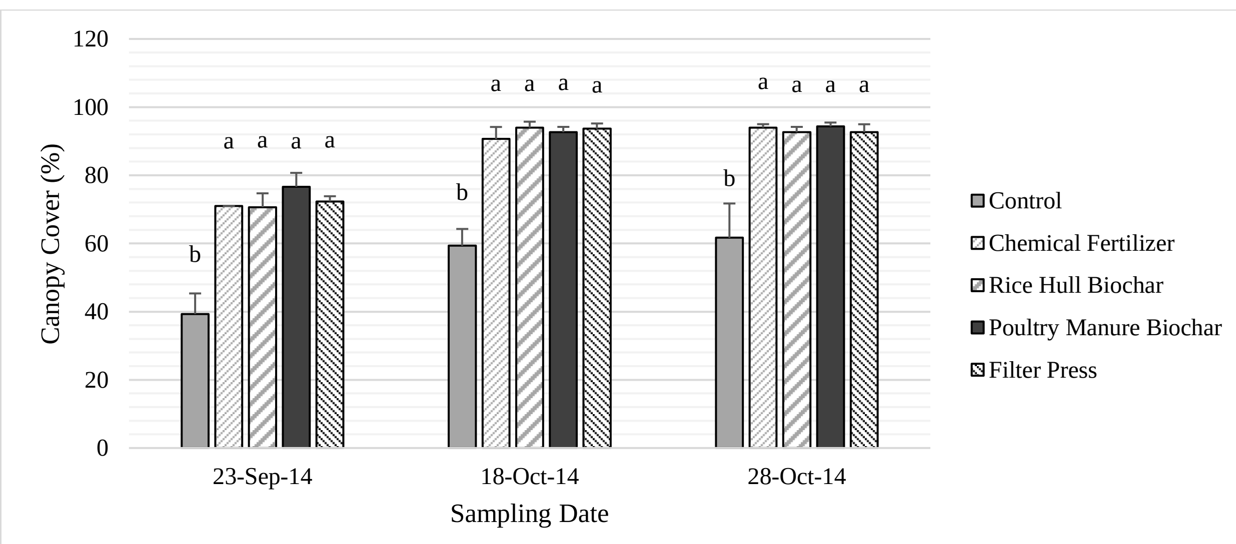

Figure 3: Maize canopy cover change at different periods throughout the first growing season. Mean values are displayed with error bars representing standard deviation. Bars with a different letter for a sampling date are significantly different at p<0.05.

Grain and biomass yields varied among treatments ($F_{(4,10)} = 32.66$, $p < 0.001$ and $F_{(4,10)} = 23.43$, $p < 0.001$) and observed a trend of: CF = PMB = RHB = FP > C (Figure 4, Figure 5). Ear count was significantly different among treatments ($F_{(4,10)} = 7.18$, $p < 0.01$) and followed a trend where: FP (1.03) = PMB (1.03) = CF (1.03) = RHB (1.00) > C (0.77) (Table 9). Yield measurements for each treatment followed a trend similar to that of the other productivity parameters. A pictorial comparison for grain yield between treatment groups is presented in Figure 6. Addition of amendments can have varying effects on crop yield. Major et al. (2010) reported yield increases in maize after four years of a single application of 8 and 20 Mg ha^{-1} of BC, respectively, on an Oxisol in Colombia. Kimetu et al. (2008) reported continuous maize yield increases when amended with BC and inorganic fertilizer. Varying BC addition to an Aquic Paleudult in the U.S. reduced grain and biomass yields by 30% and 15%, respectively, over a three year period (Novak et al. 2019). Using different BCs and amendments as a soil amendment has also resulted in scenarios where reported yields showed minimal increases and even some declines (Novak et al. 2019). Few studies have assessed the use of FP as a soil amendment outside of a sugarcane agroecosystem.

The harvest indices (HI) (%) also differed significantly among treatments ($F_{(4,10)} = 36.46$, $p < 0.001$) and followed a trend of RHB (41) = CF (40) = PMB (40) = FP (40) > C (19) (Figure 7). An average HI for maize is between 47-56 %, depending on the variety (Ertl, 2013). Grain filling of the cob, observed after the harvest, was sparse towards the top portion of the ears (Figure 6), which may be attributed to the lack of rainfall during the silking stage of the crop and high maximum temperatures during the daytime. Bolanos and Edmeades (1996) reported a 40% reduction in maize yields due to drought in tropical lowland areas. With a lack of water during the silking stage, grain filling can be reduced, leading to declines in yields (Chang et al. 2014) and ultimately decline in the HI. Amendment application has been shown to improve HI in maize systems. Major et al. (2010) reported a maize HI of 47% two years after biochar application.

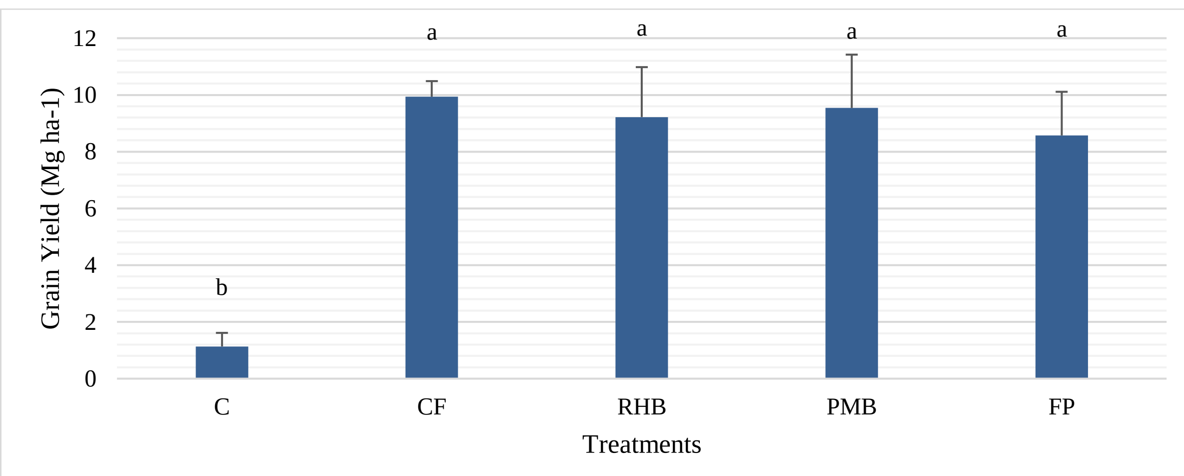

Figure 4: Maize grain yield at the conclusion of the first growing season. control – C, chemical fertilizer – CF, rice hull biochar – RHB, poultry manure biochar – PMB, filter press – FP. Mean values are displayed with error bars representing standard deviation. Bars with a different letter are significantly different at p<0.05.

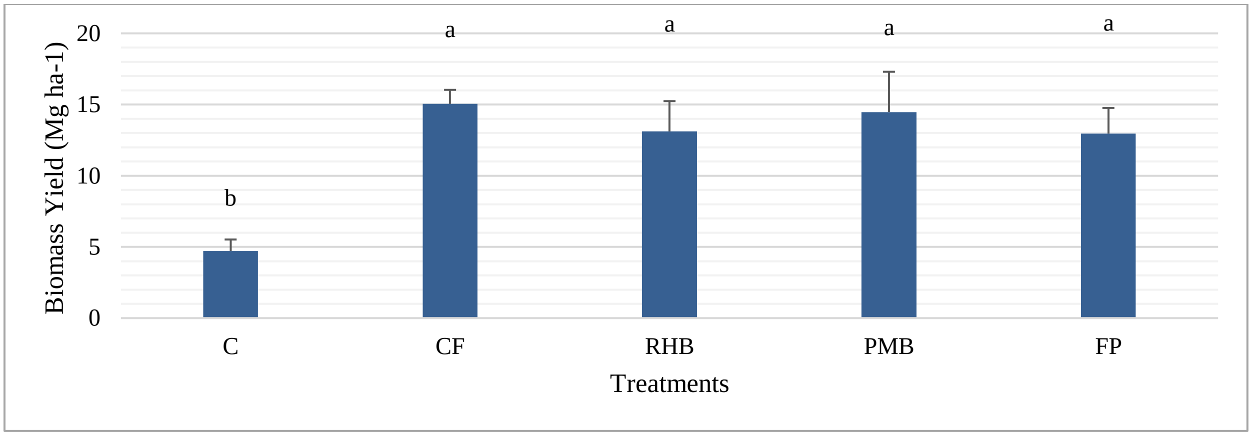

Figure 5: Maize biomass yield at the conclusion of the first growing season. control – C, chemical fertilizer – CF, rice hull biochar – RHB, poultry manure biochar – PMB, filter press – FP. Mean values are displayed with error bars representing standard deviation. Bars with a different letter are significantly different at $p<0.05$.

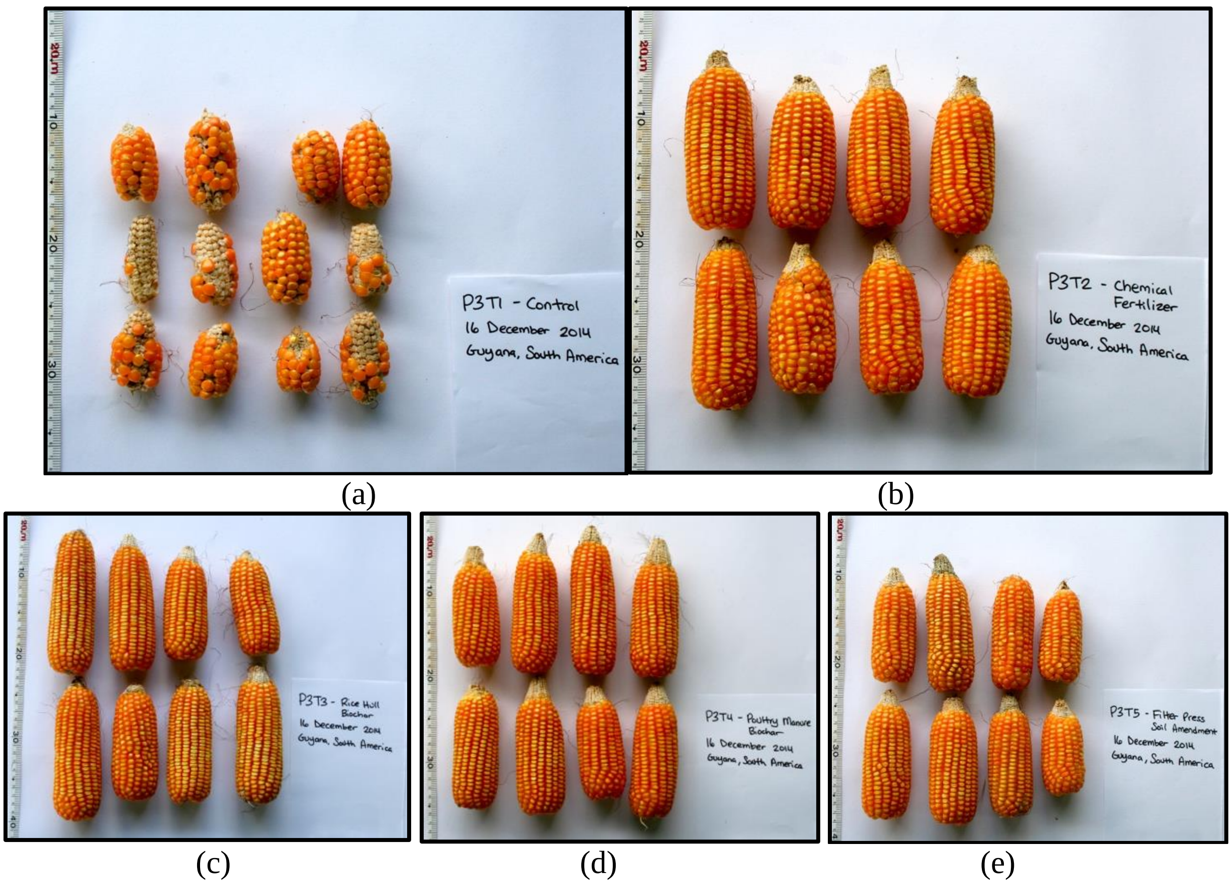

Figure 6: Grain yield sample after the first growing season. (a): control (C), (b): chemical fertilizer (CF), (c): rice hull biochar (RHB), (d): poultry manure biochar (PMB), (e): filter press (FP).

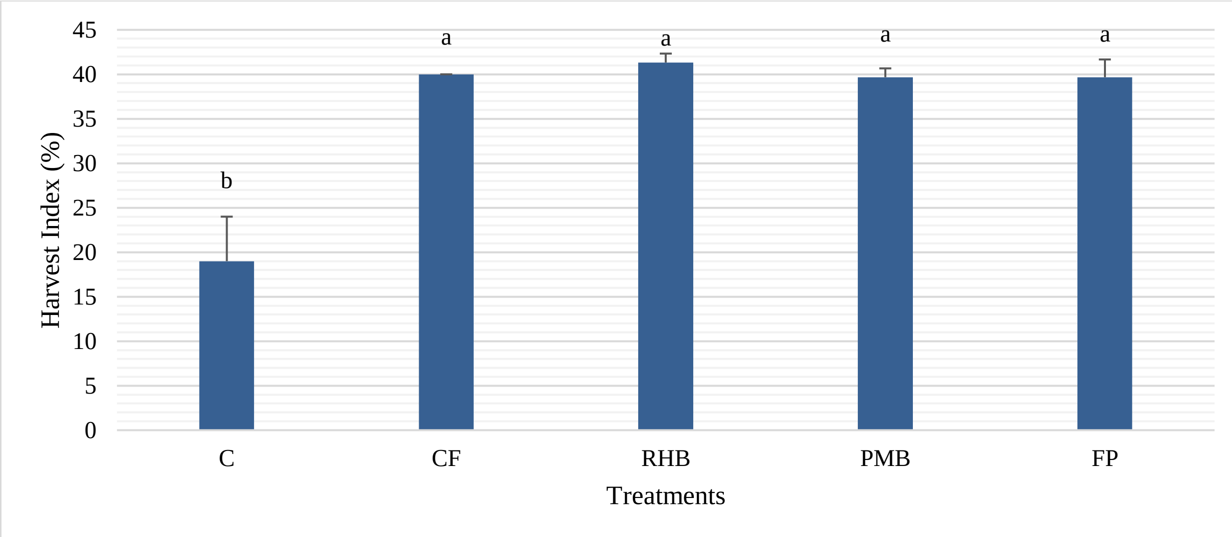

Figure 7: Harvest index for the first growing season. control – C, chemical fertilizer – CF, rice hull biochar – RHB, poultry manure biochar – PMB, filter press – FP. Mean values are displayed with error bars representing standard deviation. Bars with a different letter are significantly different at $p<0.05$.

Conclusion

This study evaluated the short-term impact of several amendments on varying soil physical and chemical properties and agronomic productivity on a coastal Guyana soil. After one growing season, no significant differences were present for several soil physical and hydrological properties (bulk density, porosity, penetration resistance, and water infiltration) measured. However, significant differences were observed for several soil chemical properties after the growing season. Soil pH increased from 4.71-4.92 in the baseline soil to 5.03-5.58 in the 0-10 cm depth, 5.46-5.61 in the 10-20 cm depth, and 5.38-5.54 in the 20-40 cm depth. Overall, electrical conductivity values were low throughout the 0-40 cm soil profile (0.18-0.56 dS m^{-1}) and would not pose a threat of reducing crop yields. The biochar amended plots had the greatest increase in SOC concentration within the 0-10 cm depth, with RHB and PMB having a 49% and 63% increase, respectively, when compared against the control. C:N ratios for all treatment groups were optimal and ranged from 10:1-15:1 at the conclusion of the growing season. Significant decreases in KCl exchangeable acidity for the 0-10 cm depth were noted for PMB and FP amended soil when compared against the control, CF, and RHB treatment groups. Grain and biomass yields in the amended plots were 7.6-8.8 and 2.8-3.2 times greater than the control, respectively. The harvest index for the amended plots was about two times greater than that of the control.

Results from this study provide supporting evidence for the use of locally available agricultural byproducts as soil amendments from some of Guyana's largest agricultural sectors (rice, sugarcane, and poultry production). The improvements observed in the measured soil properties helped to alleviate some soil related constraints (mainly chemical/fertility indicators) in the short-term. Little improvement was noted for several soil physical properties during this time. The decreases observed in bulk density and penetration resistance and the increase observed in water infiltration are some beneficial improvements that can positively impact clay soils along the coastal region of Guyana. A better indication of the effects these amendments have on these crucial soil properties will become more apparent as time goes on. The utilization of the amendments evaluated in this study has the potential to both improve soil quality and boost agricultural yields for clay soils in Guyana. Best management practices need to be coupled with organic amendment application to improve overall soil quality within agroecosystems and reduce the amount of non-renewable inputs cycling within the system. Increasing the use of agricultural byproducts, in the form of organic amendments, can allow Guyana to achieve its long-term agricultural goals for food and nutritional security along with strengthening of the country's green industry.

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