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Impact Of Biochar And Climate Variability On Soil Available Water Capacity And Millet Yield In Northern Ghana Agriculture Land

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Abstract
The soils of Ghana vary with location due to difference in parent material and climate with low productivity. Biochar is increasingly proposed as an amendment that can improve soil productivity but its effectiveness is texture dependence. Therefore, this study was carried out to find out if biochar application is effective for all soil textures in northern Ghana. To achieve that soil data (texture, organic carbon, soil depth and bulk density) were obtained for 35 locations (cultivated and uncultivated) were collected across the northern regions. A validated crop model of Doorembos and Kassam was used in order to simulate millet yield for each of the 35 locations under both biochar and no-biochar application conditions. Both Crop yield from greenhouse work and derived relationships between biochar and some soil physical properties from laboratory work were used to validate the crop model of Doorembos and Kassam in order to Simulate millet yield for each of the 35 locations under both biochar and no-biochar application conditions. Using these techniques, millet yield maps were derived for the northern regions. In a final analysis millet yields were simulated over a period of 60 years (1971 -2020) for each of the 35 locations. Statistical method of Cumulative Distribution (CDF) was used to obtain the probability plot of the yield. The simulated yields beyond the upper 33% was considered as "good" yields. The results showed that long-term simulations showed that millet yield increased during the last 30 years which was low for both Savannah and Northern regions (Tamale compared to the remaining 3 regions). It is concluded that millet yield increased significantly only for a biochar application of 20 tons/ha. Biochar application even at the latter application rate hardly increases soil Available water content in Ghana's northern region.

Keyword: *Biochar, Available water content, soil, Biochar, millet yield, Ghana.*

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I. Introduction

The soils of Ghana vary with location due to differences in parent material and climate. The productivity of these soils changes once they are converted from their pristine state to agriculture. The northern zones of Ghana which are drylands in the Guinea Savannah belt (Braimoh and Vlek, 2004) are of particular interest because they are major food baskets where cereals such as pearl millet (*Pennisetum* glaucum (L) Br.), sorghum (*Sorghum bicolor (L.) Moench*) and recently maize (Zea mays L.) are extensively cultivated (Dilys Sefakor MacCarthy et al., 2018). The northern zones is of importance because of its agro-ecological productivity by deteriorating rapidly as cultivation intensities (Kugbe and Zakaria, 2015). Studies by Braimoh and Vlek, (2004) indicated that organic matter (OM) of cultivated soils of in Tamale in the Northern Region of Ghana declined from 1. 27 g/kg to 1.0 g/kg within 7 years of cultivation and consequently decline soil nutrient content. Other studies have indicated drastic reductions in soil parameters in the cultivated soils of the northern zone where 80% of the soils has less than 6 % of clay content and 52% have a soil depths less than 50 cm with high stone and iron concretions in the topsoil soils and are generally sandy in nature (Tetteh *et al.*, 2016). The impact of the soil organic matter (SOM) on soil productivity is not limited to the chemical and fertility factors alone, but is a major binding agent that affects soil aggregation and structure, reduces bulk density, as well as enhances infiltration and improves the overall water storage of the soil (Riahi *et al.*, 2009). According to literature, the return of soil residues in the form of biochar can significantly increase SOM and improve soil physical properties. Biochar Increases soil porosity, theorem, would improve infiltration and reduce runoff (Lee et al., 2018). Biochar increases soil water retention/storage (Häring et al., 2017) due to micro- and macro-pore increase: pores created at the interface between biochar and soil particles or small aggregates (Liu et al., 2017). Therefore, drainage and evaporation are reduced (Karhuet al., 2011) theorem, reduced water stress effect on crop growth (Masria et al., 2018). In the particular case of climate change impact, where rainfall intensities have shown increasing trends within this region (Adiku *et al.,* 2010), considerable loss of rainfall as runoff could presumably be offset by biochar application. On the other hand, many studies found no effect or negative effect on WRC for clayey soils, even at application rates of up to 47 t/ha (Kameyama et al., 2016; Hardie *et al.*, 2014). Few studies have investigated the effects of biochar application and the rates of application on the physical properties of soils (e.g. AWC) in northern Ghana, a major bread-basket of Ghana. Given that biochar effectiveness is texture-dependent, will biochar application be effective on all soil types in northern Ghana? To answer this question this study was carried out and intends to add to the limited studies in the field. The success of the biochar technology for soil water availability enhancement should be assessed across the northern regions of Ghana and over time-scales beyond limited field experimentation periods. This study seeks to employ a modified water balance technique that responds to biochar application. Modified water balance refers to the effect of biochar on runoff, drainage and evapotranspiration. The modified water balance has been used as input to the crop models for water limited yield evaluation under varying biochar application rates to assess how limited water affects millet yield under variable biochar application and climate in selected farming zones. Furthermore, the study seeks also to apply Geographical Information Systems (GIS) to extend the impact determined at point locations across the administrative regions of northern Ghana. It is hypothesized that biochar application to the sandy soils of northern Ghana can influence components in the water balance equation and enhance millet yield. Based on this hypothesis, we can establish the following overall objective: evaluate the impact of biochar application on millet yields across northern Ghana under variable soils and climate. Specifically, this involved to: i) apply the validated model to simulate millet yields across the northern zones with and without biochar application, ii), assess the interactive effect of climate change and biochar rates on millet yield by simulating yields for periods up to 60 years for each of the three locations, and iii) apply GIS techniques to assess the spatial variability of the effectiveness of biochar technology across different zones in northern Ghana.

II. Materials And Methods

Site description

The study area is Northern Ghana, the warmest region with one rainy season and a long drying season period. It falls within the Guinea savanna and Sudan savanna ecological zones, with grassland interspersed with trees as the dominant vegetation. The mean annual rainfall of the Guinea savanna is about 900-1100 mm (Ghana Meteorological Service, 2010) which occurs between 4 to 6 months duration with high intensity of rainfall with July to September constituting 60% of the annual rainfall amount, thereby leading to high surface runoff and erosion (Siaw, 2001). The annual rainfall in the Sudan savanna zone is between 500 – 700 mm (Nuhu *et al.,* 2012). The mean monthly temperatures are high throughout the year ranging from 25 ºC to more than 33 ºC. Relative humidity ranges from 75% in the rainy season to 35% in the dry and hot periods.

Soil sampling and laboratory analyses

Three different soil series were sampled (cultivated soil) from the 2 Agro-ecological depths of 20 cm and were air-dried for 24 hours and sieved through 2 mm-mesh and used for laboratory analyses. The 3 soils were from Wa (Upper West), Tamale (Northern) and Navrongo (Upper East) regions. The core sampling method was used for soil bulk density determination and soil texture (percentage of sand, silt and clay) by the hydrometer method. Zones were transported to the University of Ghana for greenhouse and laboratory experiments.

Experiments

Greenhouse experiments

A greenhouse experiment was carried out at the University of Ghana farm. The experimental design comprised 3 soils x 3 biochar application rates x 2 water regimes in a factorial arrangement using a completely randomized design (CRD) with 3 replications, totaling 54 units. The 3 soils were from Wa (Upper West), Tamale (Northern) and Navrongo (Upper East) regions. The biochar application rates were the equivalent of 0, 10 and 20 tons/ha. The water regimes were full irrigation (W1) and low irrigation (W2). The low irrigation treatment was designed to replicate the typical low rainfall regimes of each study location, not only in terms of seasonal amount but also the daily amounts and distribution within the season. The water regimes that were selected for the experiment were obtained by ranking 60 years of seasonal rainfall. The data was used to determine the cumulative distribution function. The years corresponding to upper, median, and lower quartiles were taken as high, average, and low rainfall regimes, respectively. The full irrigation was the same amount for the three zones, been 549.36 mm for low irrigation it was 389.13, 333.90 and 265.23 mm for Navrongo, Wa and Tamale, respectively. Since this study focused only on water-limited growth of millet, fertilizer was applied to all treatments at optimal rates as indicated. The fertilizer used was Ammonium Sulfate, Triple Super Phosphate and Sulphate of Potash, and they were applied at the rate of 90- 40- 40 kg per hectare. Millet (*Pennisetum glaucum*) was grown in PVC columns with an internal diameter of 16 cm and a height of 40 cm. The soils were packed into the columns at the field bulk density, leaving a free board of 5 cm. To mimic field operations, the biochar was applied to only the first 10 cm of the soil. At the level of the soil surface was a runoff hole fitted with rubber tubing to collect runoff during irrigation events. Also, drainage holes were provided at the bottom of the PVC columns. The columns were weighed at the beginning and end of the experiment. The water use (actual evapotranspiration) by the plants was analyzed within the context of the water balance:

$$ETa = I - (R + D) \mp \Delta W \qquad (Eq\ \ 1)$$

where ETa = actual evapotranspiration or water use during the entire growth period (mm), I is the total irrigation water applied (mm), R+D is the total runoff +drainage (mm) and ΔW *is the change in water storage. The* ΔW *was determined as the difference in the weight of the column at the commencement and end of the experiment and converted to mm.*

All plants were harvested at maturity and the grain was separated from the stover to determine grain weight. The data obtained from the greenhouse study was used to validate the Doorenbos and Kassam (1979) model.

Laboratory experiments

A series of irrigation experiments were conducted in the laboratory to assess the effect of biochar application on runoff (R) and drainage (D) components of the water balance. For this, PVC cylinders with an internal diameter of 16 cm and a height of 20 cm were used. Runoff holes were drilled at 3 cm from the top. Also, drainage holes were drilled at the bottom of the columns. The columns were filled with the soils with the biochar application at 0, 10, 20 tons/ha. The soils were irrigated 5 times, using a different intensity (49.76, 37.32, 29.9, 19.9 and 9.95 mm) for each irrigation event. For each irrigation event, data collected included the total irrigation *I*, runoff *R* and drainage *D*. A relationship between (*R+D*) on the one hand, and biochar application rate, *BC*, clay ratio CR, (soil texture) and irrigation amount *I*, on the other hand, was derived using regression methods:

$$(R + D) = f_1(BC, I, CR) \qquad (Eq\ \ 2)$$

where f_1 is the regression a functional relation, *BC* = biochar application rate, *I* = irrigation amount and CR= soil texture parameter or clay ratio, defined as:

$$\frac{\%Sand + \%silt}{\%clay} \qquad (Eq\ 3)$$

Biochar effect on soil physical properties

The effect of biochar application on Field capacity (FC), Permanent Wilting Point (PWP) and the Available Water Capacity AWC and bulk density BD was determined. The experiment was carried out at biochar application rates of 0, 10, 20 and 30 ton/ha using the same 3 soils. The experimental design comprised factorial arrangement of 3 soils x 4 biochar application rates, arranged in completely randomized design with 3 replications, totaling 36 units.

For FC determination, potted soils were wetted to saturation and covered with polythene sheets to prevent evaporation. The wetted pots were allowed to drain for 2 days and thereafter, the soil was sampled to determine the volumetric water content. For the PWP, the sunflower (*Genus helianthus*) response procedure detailed in Taylor and Ashcroft (1972) was followed. For this, sunflower was grown in the potted soils and irrigated until the flowering stage. Thereafter, water application was discontinued until the plant wilted. At this stage, undisturbed soil cores were taken from each treatment, and the water content and the bulk density were determined. The volumetric water content was taken as the PWP.

The available water capacity AWC was calculated as the difference between FC and PWP. The relationships between biochar application rate and the physical properties were also derived as:

$$\mathrm{PWP} = f_2\,(\mathrm{BC}, \mathrm{CR}) \qquad (Eq\ \ 4)$$

$$\mathrm{FC} = f_3\,(\mathrm{BC},\mathrm{CR}) \qquad (Eq\ \ 5)$$
$$\mathrm{AWC} = \mathrm{FC} - \mathrm{PWP} \qquad (Eq\ \ 6)$$

where f_2 and f_3 are functional relationships derived using regression methods.

Validation of Doorenbos and Kassam Equation for Millet Yield Simulation

The simple crop model of Doorenbos and Kassan (1979) was used to simulate millet yield in response to water availability. The model equation is:

$$\left(1 - \frac{ya}{yp}\right) = ky\left(1 - \frac{\mathrm{ETa}}{ETp}\right) \qquad (Eq\ \ 7)$$

where, *ya* = actual yield (kg/ha), *yp* = potential yield (kg/ha), *Ky* = crop response factor, ETa and ETp are the actual and potential seasonal evapotranspiration (mm) , respectively.

The data for model validation were from the greenhouse. The ETp (potential seasonal evapotranspiration, mm) was determined from the evaporation from free water in cylinders placed in the green house. The ETa was determined from *Eq*. 1 as it depended on biochar application like the *R+D* also depended on biochar application (*Eq* 2) The biochar-determined ETa from *Eq*.1 was input into the Doorenbos and Kassam model (*Eq*. 7) to predict the actual yield of millet, *ya*, expressed as kg/ha. The potential or maximum millet yield, *yp*, (kg/ha) was taken as the observed greenhouse yield for each soil under full irrigation treatment (W1). The *ky* for millet (1.3) was taken from literature. The predicted millet yields were compared with the observed yields obtained from greenhouse experiments.

Long-term and multi-location simulation of AWC and millet yield

Thirty-five (35) locations across the northern zone of Ghana were selected for soil physical property and millet yield assessment under varying biochar application rates. At each location, soil data for both pristine (uncultivated) and regularly cultivated farmlands were obtained. For the pristine sites, the data source was the Soil Research Institute of the Council for Scientific and Industrial Research (CSIR), Kumasi. For the corresponding cultivated locations, data were obtained from Tetteh *et al* (2016) and Nketiah (2014). With regard to biochar's impact on the soil's physical property, the main attention was on the Available Water Capacity, AWC. For this, data such as soil texture, bulk density and organic matter content were input into the pedo-transfer equation of Saxton *et al.* (1986) to estimate the AWC at each of the 35 locations. The effect of biochar application on the AWC was derived from Eq. 5 to 7. The long-term simulated millet yields at each of the 35 locations were ranked from the smallest to the largest to obtain the Cumulative Distribution Function (CDF). The averages of the top 33%, middle 33% and bottom 33% were taken as "good", "average" and "bad" yields, respectively. These were used in deriving yield maps for the study area. The flow chart below (Figure 1) illustrates the entire procedure.

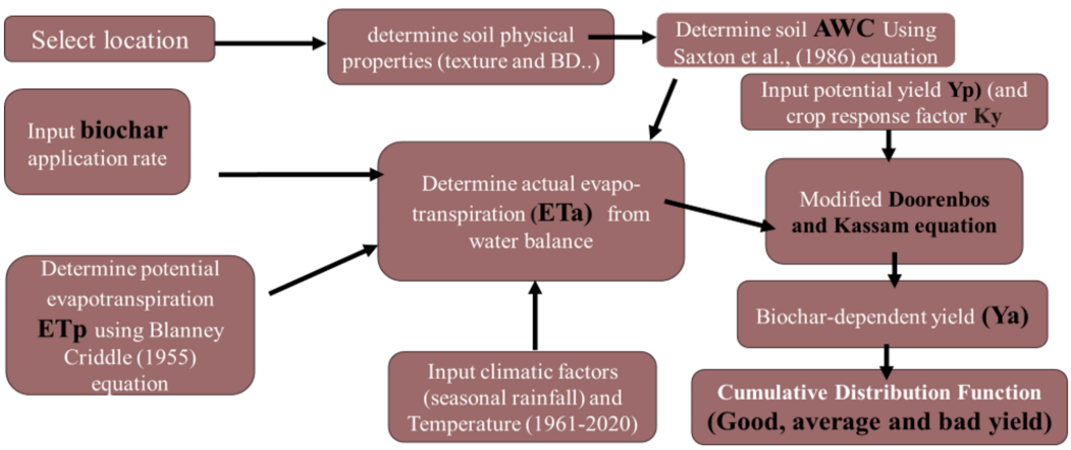

Figure 1 Millet yield simulation procedure

Millet yield and AWC visualization

The map data was at a scale of 1:2000000 covering the selected areas within the northern part of Ghana. The attribute table which contained all the information on the simulated millet yield for both biochar and no biochar amendment was derived and projected to Universally Transverse Mercator (UTM) (Zone 30N) using the WGS84 datum. To visualize the data, the simulated yield data were assigned into class ranges with the number of class categories NC, determined as

$$NC = 1 + \left(\frac{10}{3}\right) logN \qquad Eq\ 9$$

where *NC*= number of classes, *N* = number of observations
The class interval value was calculated as:

$$Interval = \frac{Max\ data - Min\ data}{NC} \qquad Eq\ 10$$

A similar procedure was used for AWC mapping for the various biochar applications. The average 30-year millet yield was used to derive yield maps for the biochar application scenarios. A single layout and legend were used for the three-biochar rates to facilitate comparison for each selected location.

Statistical analysis

Data collected during the experiment was statistically analyzed using ANOVA with GenStat statistical software 12th version. The means were compared using the least significant difference test at $P < 0.05$. The relationships were derived as multiple regressions, using SigmaPlot 4.0 edition. The stochastic dominance method was employed to compare and determine the superiority of biochar application or otherwise. Excel was used for data management. The results visualized were done using ArcGIS. The Wilmott d statistic was used to compare observed and simulated yields for agreement.

III. Results And Discussions

Relationships between biochar, application rate and soil physical properties

A Multiple regression relationships analysis was carried out to establish the relationships among some measured soil physical parameters such as runoff + drainage and biochar and soil clay ratio. The regression equations for the various soil physical properties and biochar rate are summarized in Table 1. The porosity and AWC were positively correlated with biochar application. Therefore, AWC increased with increasing biochar application rate. A negative correlation between biochar and BD and R+D was found, with R2 being more than 0.90. The regression coefficients for all the parameters were found to be significant ($p< 0.001$). This implies that knowledge of the clay ratio (CR) of a given soil and the rate of biochar application would enable the determination of the BD, AWC, and R+D.

Table 1 Multiple regression relationships between biochar and different soil physical parameters

Parameter	Equation (Eq 4.1)	R^2	P <	
Runoff+drainage (R+D)	-41.1+(0.633 * Rain) + (0.0527 * CR) -(1.92*BC) -(1.7*BD)	0.98	0.001	Eq 11. a
Bulk density	1.411 + (0.00771 * CR) - (0.00568 * BC)	0.98	0.001	Eq 11. b
PWP	0.206 - (0.00252 * CR) - (0.000268 * BC) - (0.0688 * BD)	0.95	0.001	Eq 11. c
FC	0.144 - (0.00365 * CR) + (0.00116 *BC) + (0.0705 * BD)	0.94	0.001	Eq 11. d
AWC	0.124 - (0.000524 * CR) + (0.000852 * BC) - (0.0594 * BD)	0.89	0.001	Eq 11. e
ETa	16.385 - (0.361 * BC) + (0.215 * CR) - (7.723 * BD) + (0.562 * Rain)	0.52		11. f

CR = clay ratio, PWP = permanent wilting point, FC = field capacity, AWC =available water capacity

Crop model validation

The validation of the Doorenbos and Kassan (1979) crop model was achieved using the observed greenhouse millet yields. The input requirement for the model includes the maximum or potential evaporation ETp, actual evaporation ETa, and the maximum or potential yield. Using the data collected for Wa soil under high and low irrigation regimes, the model was tested. The measured seasonal ETp in the greenhouse was as the potential evapotranspiration used in the model. Also, the observed millet yield under high irrigation and BC20 was taken to represent the maximum or potential millet yield and the Ky was set to 1.32. Since the actual measured ETa data were available for all other treatments, the millet yield could be simulated. The simulated millet yields for Wa soil for the various water regimes and biochar application rates are shown in Figure 2 in comparison to the observed yields. Wilmott d statistic was use to compare observed and simulated yields for agreement. *d* = was 0.97 which implies a perfect agreement. Hence yield similated for high rainfall were over similated and under estimated for low rainfall. Therefore, the Doorenbos and Kassam model are considered a reliable method to simulate millet yield under varying biochar, soil types and water regimes across the northern zones of Ghana.

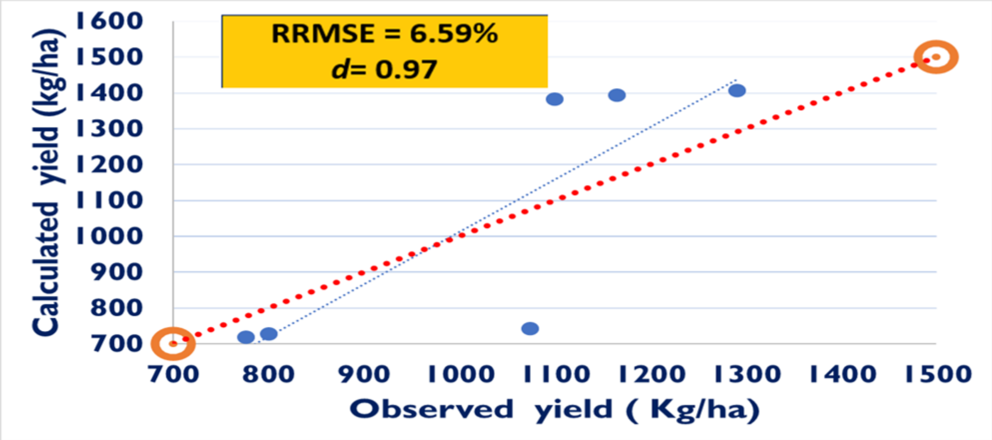

Figure 2. Simulated and observed millet yield for Wa soil under varying rainfall and biochar application rates

Properties of the soils at the selected multi-locations and impact of biochar application on Available Water Capacity

Selected soils of the study area

The soil properties at multiple locations in northern Ghana is required to assess millet yield simulation across the regions. A total of 35 locations were selected in five regions of northern Ghana (Upper West, Upper East, Northern East, Northern and Savannah), as shown in Table 2. These soils at these locations were either pristine (i.e., had not been previously cultivated) or long-term cultivated croplands. As previously indicated, the data for the pristine locations were sourced from the Soil Research Institute, Kumasi, whereas data for the cultivated farmlands were from Tetteh *et al.* (2016) and other unpublished sources. The cultivated locations are those that were closest to the pristine locations. All the data are summarized in Table 2. All the soil has high bulk density between 1.23 to 1.7(g/cm^3) with high sand content which is more than 40% except for Lima2, Pani1, Siare and Volta soils where the sand percentage ranged from 9 to 15.5% under pristine conditions. Generally, the percentage of sand for each soil was found to have increased under cultivation, probably due to the erosion of fine soil materials. This erosion can lead to considerable soil depth reduction as shown in Table 2. For the pristine soils, depth ranges from 50 to 195 cm whereas for the cultivated sites the depth ranges from 30 to 74 cm. Hence, there was a reduction of more than 50% of their original depth and this consequently reduced soil organic carbon percentage (Table 2). A similar result was shown by Senayah *et al.*, (2009), who reported severe removal of topsoil on several northern Ghana agriculture lands. Over a period of 30 years Tenchera, Tafali and Varempere soil series lost 73%, 37% and 36% of their initial depths, respectively. The reduction of soil depth at these locations can be attributed to the land management systems. In northern Ghana, agricultural lands are more exposed to both wind and water erosion because the topsoils of the land remain bare soil after harvest (at least 6 months annually) and since crop residues are used as animal feed, housing material and domestic fuel and not as soil cover. In general, soils in the Northern and Savannah regions are less deep than those in Northern East, Upper West and Upper East at pristine sites. Similarly, clay content in Upper West, Upper East and Northern East soils is higher than those in the Northern and Savannah soils.

Table 2. Some characteristics at the selected sites

Location	**Soil**	**% OC**	**Sand**	**Silt**	**Clay**	**CR**	**BD**	**Z (cm)**	**Location**	**% OC**	**Sand**	**Silt**	**Clay**	**CR**	**BD**	**Z (cm)**
			Pristine						**Cultivated**							
Upper East	Bongo	0.05	49.1	15.8	35.1	1.85	1.7	160	Samboligo	0.04	82.6	11	6.4	14.6	1.55	40
	kupela3	0.98	60.36	33.42	6.22	15.08	1.26	90	Tekuru	0.57	81.7	10.3	6	15.3	1.55	30
	Mimi1	0.37	82.96	12.74	4.3	22.26	1.36	165	Biraba	0.3	80.7	15.1	4.2	22.8	1.55	40
	Siare	2.02	9	46	45	1.22	1.4	160	Samboligo	0.41	82.6	11	6.4	14.6	1.55	40
	Tafali	0.25	83.5	13.5	3	32.33	1.58	140	Biraba	0.3	80.7	15.1	4.2	22.8	1.55	40
	Volta	3.49	15.5	49.5	35	1.86	1.49	140	Famisa	0.38	50	40	10	9	1.68	74
Upper West	Pani1	1.47	13	58	29	2.45	1.41	140	Goli	0.32	85.2	8.8	6	15.7	1.55	40
	Pani2	3.9	46.	31.	22.	3.5	1.	150	Pase	0.6	53.	35	11	8.	1.	30

		2	1	8	1	2	41				8	.2		1	55	
	Varempera1	0.35	80.8	12.9	6.3	14.87	1.7	102	Naaha	0.06	82.6	13.2	4.22	22.7	1.55	40
	Varempera4	0.38	80.59	10.99	8.42	10.88	1.5	107	Zonko	0.38	68.5	23.5	8	11.5	1.55	30
Savannah	Kolungu	0.75	75.81	17.77	6.42	14.58	1.23	140	Joanokponto	0.42	81	17	2	49	1.55	40
	Kupela1	0.8	67.7	25.9	6.4	14.63	1.6	122	Nahari	0.21	81	12	7	13.3	1.5	52
	Kupela2	0.72	61.18	34.76	4.06	23.63	1.3	107	Bole	0.44	68	26	6	15.7	1.5	60
	Lima1	0.69	71.12	22.68	6.2	15.13	1.73	125	Joanokponto	0.42	81	17	2	49	1.55	40
	Lima2	1.01	12	52	36	1.78	1.36	152	Joanokponto	0.42	81	17	2	49	1.55	40
	Mimi2	0.33	90.9	4	5.1	18.61	1.51	80	Nanniiki	0.37	83	13	4	24	1.36	60
	Mimi3	1.11	75.52	18.2	6.28	14.92	1.42	120	Joanokponto	0.42	81	17	2	49	1.55	40
	Murugu	1.16	70.18	26.12	3.7	26.03	1.63	150	Damongo	0.25	92	3	5	19	1.7	70
	Sambu	0.40	60.50	37.10	2.50	39.00	1.30	60	Zang	0.8	50.7	47.2	2.1	46.6	1.4	40
	Vampere2	1.07	68	22	10	9	1.49	90	Nahari	0.21	81	12	7	13.3	1.5	52
	Vampere3	0.28	71.7	25.5	2.8	34.71	1.31	152	Nahari	0.21	81	12	7	13.3	1.5	52

Source: Ghana soil research institute, Tetteh et al., (2016) CR = Clay ratio, z = soil depth

Table 2. Continued

Location	**Soil**	**%OC**	**Sand**	**Silt**	**Clay**	**CR**	**BD**	**Z (cm)**	**Sites**	**%OC**	**Sand**	**Silt**	**Clay**	**CR**	**BD**	**Z (cm)**
			Uncultivated						**Cultivated**							
Northern East	Lumo	0.83	69.30	22.00	8.70	10.49	1.52	195	Famiso	0.4	50.0	40.0	10.0	9.0	1.68	74
	Kpelesawgu2	1.02	36.75	35.75	27.50	3.00	1.34	80	Mangali	0.8	35.9	58.0	6.1	15.0	1.46	40
Northern	Kpelesawgu3	0.3	61.7	33.3	5	19	1.36	55	Zang	0.8	50.7	47.2	2.1	46.6	1.4	40
	Kpelesawgu6	0.2	75.1	19.9	5	19	1.38	95	Yarigu	0.2	44.8	51.1	4.1	23.4	1.4	40
	Lima-volta	0.4	60.2	34.8	5	19	1.34	120	Yarigu	0.3	71	27.4	1.6	61.5	1.4	40
	Nyankpala	1.5	24.2	53.4	22.5	3.4	1.14	130	Zakoli	0.2	44.8	51.1	4.1	23.4	1.4	40
	Kpelesawgu	1.5	50.3	39.7	10	9	1.51	115	Famisa	0.4	50	40	10	9	1.68	74
	Kpelesawgu5	2.6	48.5	39	12.5	7	1.16	50	zang	0.8	50.7	47.2	2.1	46.6	1.4	40
	Lima-volta1	0.9	63.7	28.9	7.5	12.3	1.42	50	Zakoli	0.2	44.8	51.1	4.1	23.4	1.4	40
	pasga	1.3	18.8	43.7	37.5	1.7	1.21	100	Mangali	0.8	35.9	58	6.1	15.4	1.5	40
	Kpelesawgu4	1.1	70.1	22.4	7.5	12.3	1.37	100	Zakoli	0.2	44.8	51.1	4.1	23.4	1.4	40
	changnalili	1.1	62.9	29.6	7.5	12.3	1.32	110	Zakoli	0.2	44.8	51.1	4.1	23.4	1.4	40
	Techinan	0.8	73.4	24.6	2	49	1.54	120	Boting	0.1	76.2	13.8	10	9	1.55	40

									li							
	Kasele	1.3	73.1	19.4	7.5	12.3	1.36	120	Zakoli	0.2	44.8	51.1	4.1	23.4	1.4	40

Source: Ghana Soil Research Institute, Tetteh et al., (2016) CR = Clay ratio, z = soil depth

Impact of biochar on Available Water Capacity (AWC)

The soil AWC for the different selected soils varied (Figure 3), but generally followed the clay content and soil depth. For uncultivated (pristine) condition, Bongo series (Upper East) which had the highest clay content also had the highest simulated AWC (276.4 mm) followed by Lumo soil series (Northern East) of 268. 9 mm, and also had the highest depth (195 cm). Kpelesawgu5 soil series (Northern region) had the lowest AWC of 63.3 mm and shallow soil depth (50 cm). Kupela3 series at Upper East region recorded the lowest AWC at the Savannah region though it was 25.23% deeper than Kupela1 series. The higher AWC of Kupela1 could be attributed to a slightly higher clay content. A similar trend was observed for the uncultivated soil, although the Techiman series (Northern region) and Volta series (Upper East region) had the same percentage of clay content (10%), the latter series had a higher AWC of 57% because its depth was 46 % deeper than that of Techiman. In the same way Vampere1 (Upper West) and Tafali series (Upper East) had the same depth (40 cm), but Vampere1 with a difference of 0.2 % in clay content recorded higher AWC, which was 15% greater than Tafali soil AWC. This implies that not only soil depth affects AWC, but clay content is also very important. In general, the AWC for the uncultivated (pristine) soils ranged from 63.3 to 268 mm when no biochar was applied. The corresponding range for the cultivated soil was 52 -108 mm. The main difference between the pristine and cultivated soils can be attributed to depth, texture and organic matter content. The cultivate soils are sandy with low organic carbon (SOM). According to Ray and Nyle (2017), when the soil is rich in organic matter the Field Capacity (FC) is much higher than that of an equal volume of mineral matter.

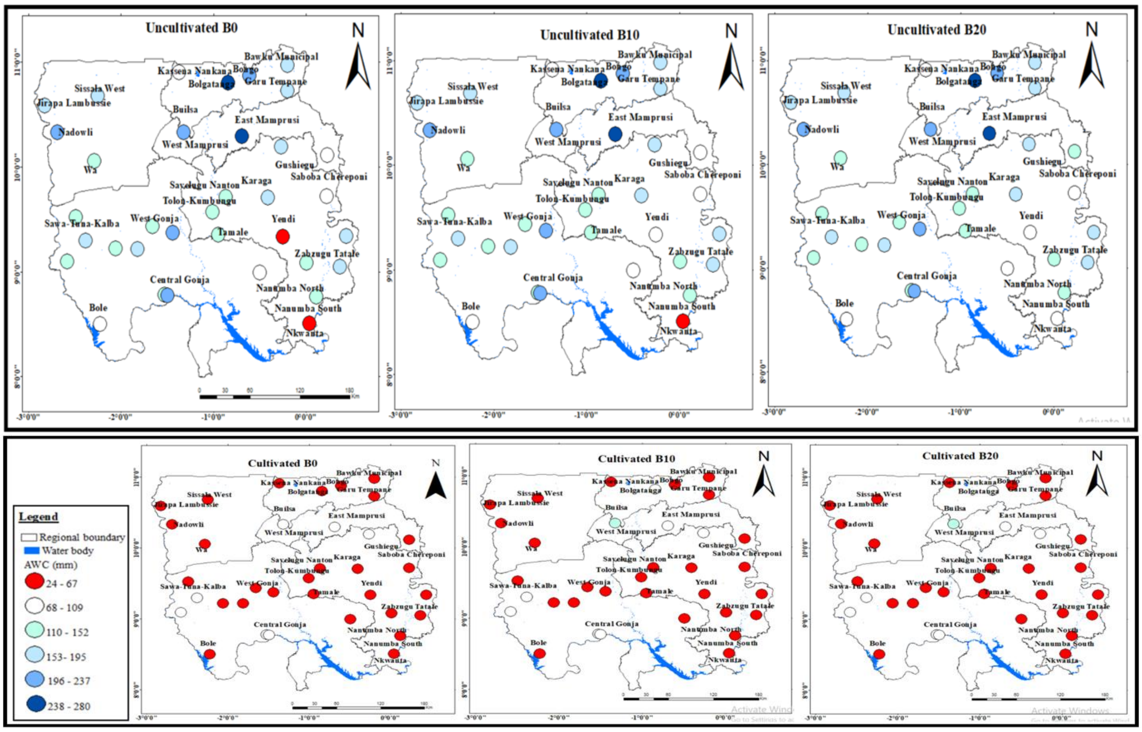

Figure 3. Spatial distribution of the AWC under different biochar application rates; top figure: pristine (uncultivated); bottom figure: cultivated soils.

Soils with lower FC can be improved by the incorporation of higher levels of organic matter (Adamu and Aliyu, 2012). The question whether biochar application can impact the AWC was addressed by applying *Eq* 11e (Table 1), which determines the AWC as a function of CR, BC and BD. The estimated AWC are converted to the equivalent ponded depth units (mm) by multiplying with soil depth (z). Simulated AWC was found to increase as the rate of biochar application rate increased. The spatial distribution of the simulated AWC for the selected soils under different biochar management system is represent in Figure 3. The AWC values are classified into 6 categories with an interval of 43 mm. Among the two-soil management system, AWC showed large variability. The first two lower AWC classes which ranged from 23.8 to 109 mm were for cultivated soils except the case of Kpelesawgu series at the border between West Mamprusi and also at Builsa District, which fell in the third class under BC10 and BC20. The remaining three AWC classes were found in pristine soils which ranged from 195 to 280.1 mm, but a few soil series under this land management were also found in the first two classes (67 -109) especially at Bole, Central Gonja, Sabola Cherreponi, Nanumba, Nkwanta and Yendi districts (Savannah, Northern and Northern East region). Though the AWC ranges of BC0 and BC10 on uncultivated soils were similar, the main distinction was that a higher proportion of AWC under BC10 were above 200 mm and these can be found in the Upper East and Northern regions. When the biochar rate was increased to 20 ton/ha (BC20), three (3) out of the 35 soils series that had AWC than less 110 mm, had a gradual improvement in the AWC with biochar application rate. These soil series are located at Yendi, Nkwanta and Soboba Chereponi District (Northern and Northern East region). The simulated AWC for the cultivated soils was generally low (Figure 3). Without biochar application (BC0), only 4 out of 35 sites had AWC greater than 80 mm which was found in the District of Central Gonja, Builsa,Gushiegu and West Mamprusi (Savannah, Northern and Northern East region). The increase in biochar application rate to 10 and 20 ton/ha (BC10, BC20) did not change the AWC of the study area but one soil between the border of Builsa and West Mamprusi increased from 108 to 112 mm. All the other sites soil series had no significant improvement in the AWC upon biochar application. The general deduction was that for highly sand-textured soils of the northern regions of Ghana, biochar application, limited to the top 10 cm of the soil could hardly increase the AWC significantly.

Simulation of millet yields across the multiple locations

<u>*Temporal variability of yields*</u>

The 60-year long term simulation of millet yield at each location were regrouped into 2 classes: from 1961 to 1990 and 1991 to 2020. With these two groups each of 30 years were realized. By using the Cumulative Frequency distribution, the yields in each year group were summarized into “good” (i.e., Upper 33%), “average” (middle 33%) and “poor” (lower 33%). Millet yield were simulated at each location, assuming that biochar application was limited to the top 10 cm of the soil only the results are summarized in Table 3. As for simulated AWC biochar application was to the top 10 cm. In general, millet yield responded to biochar application rate for both cultivated and uncultivated soil with the rank order: BC20>BC10>BC0. For the uncultivated soil the ranking of the 30 years simulated yield (1961-1990) showed that the highest 33% yield ranged from 1557 to 2500 kg/ha (Table 3). The middle or average yields were 1480 -2488 kg/ha and the lowest 33% yield (poor yield) were 1025 -1887 kg/ha. The simulated yield ranges for 1991-2020 were similar to the first 30 years (Table 4). In effect, it is expected that at least 1.5 ton/ha of millet yield can be obtained if soil conditions remained as the initial pristine soil, during the first 30 years (1961-1990) of cultivation. For soils that are already cultivated, simulated high yield levels were 815-2406 kg/ha, the middle level being 618-2249 kg/ha and the low-level yields were 421-1556 kg/ha during the first 30 years. Hence, millet yields can be as low as 0.5 ton/ha.

Table 3 Simulated Millet yield for selected sites from 1961 to 1990

Location	**Soil**	**Uncultivated soil millet yield (kg/ha)**									**Cultivated soil millet yield (kg/ha)**								
		CDF Low t 33%			**CDF Middle 33%**			**CDF High 33%**			**CDF Low 33%**			**CDF Middle 33%**			**CDF High 33%**		
		B0	**B10**	**B20**	**B0**	**B10**	**B20**	**B0**	**B10**	**B20**	**B0**	**B10**	**B20**	**B0**	**B10**	**B20**	**B0**	**B10**	**B20**
Upper East	Bongo	1820	1853	1887	2469	2480	2488	2500	2500	2500	848	950	1053	1388	1491	1593	1464	1566	1667
	kupela3	1529	1580	1632	2179	2230	2281	2491	2499	2500	424	557	690	618	753	888	815	951	1088
	Mimi1	1789	1822	1854	2457	2470	2481	2500	2500	2500	719	822	926	1032	1135	1239	1375	1479	1583
	Siare	1797	1830	1864	2459	2473	2483	2500	2500	2500	848	950	1053	1388	1491	1593	1464	1566	1667
	Tafali	1744	1781	1818	2427	2445	2462	2500	2500	2500	805	911	1018	1319	1428	1536	1447	1551	1655
	Volta	1758	1795	1832	2434	2452	2468	2500	2500	2500	1446	1506	1566	2165	2207	2249	2335	2372	2406
Upper West	Pani1	1704	1741	1779	2401	2424	2443	2500	2500	2500	827	932	1037	1323	1429	1534	1534	1639	1745
	Pani2	1726	1762	1798	2421	2439	2455	2500	2500	2500	424	561	697	737	874	1011	818	954	1091
	Varempera1	1587	1635	1683	2272	2318	2354	2500	2500	2500	820	926	1031	1210	1315	1420	1634	1740	1846
	Varempera4	1597	1642	1688	2290	2331	2364	2500	2500	2500	421	557	694	649	785	922	899	1036	1173
Savan	Kolung	15	15	16	21	21	22	24	24	24	71	82	92	10	11	12	13	14	15

nah	u	38	75	12	28	65	02	61	76	90	9	2	6	32	35	39	75	79	83
	Kupela 1	1519	1560	1601	2093	2134	2175	2444	2460	2477	1009	1091	1173	1412	1494	1576	1853	1936	2018
	Kupela 2	1436	1481	1526	1992	2037	2082	2396	2418	2436	1124	1197	1269	1566	1639	1712	2052	2122	2182
	Lima1	1539	1579	1619	2115	2156	2196	2453	2469	2485	719	822	926	1032	1135	1239	1375	1479	1583
	Lima2	1583	1618	1653	2182	2217	2252	2484	2495	2499	719	822	926	1032	1135	1239	1375	1479	1583
	Mimi2	1376	1428	1480	1905	1957	2009	2342	2371	2397	1106	1179	1251	1548	1621	1693	2033	2105	2168
	Mimi3	1499	1540	1582	2070	2112	2153	2434	2451	2467	719	822	926	1032	1135	1239	1375	1479	1583
	Murugu	1584	1619	1654	2181	2216	2252	2484	2495	2499	1247	1310	1374	1726	1790	1853	2211	2254	2293
	Sambu	1173	1245	1318	1688	1761	1833	1776	1849	1914	770	874	978	1134	1238	1342	1196	1299	1402
	Vampere2	1382	1434	1486	1910	1962	2014	2345	2374	2400	1009	1091	1173	1412	1494	1576	1853	1936	2018
	Vampere3	1556	1591	1626	2155	2190	2225	2474	2487	2496	1009	1091	1173	1412	1494	1576	1853	1936	2018

Table 3. continued

Location	Soil	Uncultivated soil millet yield (kg/ha)									Cultivated soil millet yield (kg/ha)								
		Low 33%			Middle 33%			High 33%			Low 33%			Middle 33%			High 33%		
		B0	B10	B20	B0	B10	B20	B0	B10	B20	B0	B10	B20	B0	B10	B20	B0	B10	B20
Northern East	Lumo	1656	1685	1715	2277	2304	2327	2500	2500	2500	1288	1349	1410	1779	1840	1901	2252	2289	2326
	Kpelesawgu2	1407	1464	1521	1974	2026	2077	2030	2069	2109	792	896	1000	1156	1260	1364	1218	1321	1424
Northern	Kpelesawgu3	1120	1198	1277	1608	1686	1765	1691	1769	1847	770	874	978	1134	1238	1342	1196	1299	1402
	Kpelesawgu6	1442	1496	1551	2016	2065	2114	2061	2099	2134	792	896	1000	1156	1260	1364	1218	1321	1424
	Lima-volta	1597	1638	1638	2200	2233	2233	2184	2209	2209	756	860	965	1121	1225	1329	1183	1286	1389
	Nyankpala	1644	1683	1722	2245	2276	2307	2216	2240	2263	792	896	1000	1156	1260	1364	1218	1321	1424
	Kpelesawgu	1494	1536	1579	2060	2102	2145	2429	2446	2463	1288	1349	1410	1779	1840	1901	2252	2289	2326
	Kpelesawgu5	1025	1110	1195	1480	1565	1650	1557	1642	1727	770	874	978	1134	1238	1342	1196	1299	1402
	Lima-volta1	1042	1128	1213	1497	1582	1668	1575	1659	1744	792	896	1000	1156	1260	1364	1218	1321	1424
	pasga	1518	1566	1614	2109	2152	2194	2127	2155	2184	792	896	1000	1156	1260	1364	1218	1321	1424
	Kpelesawgu4	1530	1578	1625	2120	2163	2203	2134	2162	2190	792	896	1000	1156	1260	1364	1218	1321	1424
	changnalili	1563	1608	1652	2163	2199	2235	2160	2186	2212	792	896	1000	1156	1260	1364	1218	1321	1424
	Techiman	1484	1525	1567	2056	2097	2139	2429	2445	2462	754	858	961	1067	1171	1274	1411	1514	1618
	Kasele	1603	1645	1687	2205	2238	2271	2188	2213	2238	792	896	1000	1156	1260	1364	1218	1321	1424

Table 4. Simulated millet yield for selected soil from 1991 to 2020

Location	Soil	Uncultivated soil millet yield (kg/ha)									Cultivated soil millet yield (kg/ha)								
		CDF Low 33%			CDF Middle 33%			CDF High 33%			CDF Low 33%			CDF Middle 33%			CDF High 33%		
		B0	B10	B20	B0	B10	B20	B0	B10	B20	B0	B10	B20	B0	B10	B20	B0	B10	B20
Upper East	Bongo	2113	2145	2178	2493	2496	2500	2500	2500	2500	995	1096	1197	1516	1618	1720	1549	1650	1751
	kupela 3	1785	1835	1886	2375	2398	2418	2500	2500	2500	462	595	729	773	906	1038	828	962	1097
	Mimi1	2084	2116	2148	2491	2494	2497	2500	2500	2500	988	1089	1190	1509	1611	1713	1542	1643	1744
	Siare	20	21	21	24	24	24	25	25	25	99	10	11	15	15	16	15	17	18

		90	23	55	91	94	97	00	00	00	5	96	97	16	42	43	49	26	27
	Tafali	2031	2067	2103	2482	2488	2491	2500	2500	2500	971	1073	1176	1469	1574	1680	1493	1601	1708
	Volta	2044	2080	2116	2485	2489	2493	2500	2500	2500	1682	1741	1800	2352	2376	2398	2420	2448	2468
Upper West	Pani1	1967	2003	2037	2500	2500	2500	2500	2500	2500	1025	1138	1250	1517	1631	1745	1582	1696	1809
	Pani2	1989	2023	2052	2500	2500	2500	2500	2500	2500	555	701	847	833	981	1129	895	1043	1190
	Varempera1	1836	1887	1938	2475	2487	2497	2500	2500	2500	975	1088	1200	1501	1615	1729	1627	1741	1854
	Varempera4	1847	1896	1946	2480	2490	2498	2500	2500	2500	526	672	818	837	985	1133	910	1057	1205
Savannah	Kolungu	1424	1461	1497	2240	2277	2313	2491	2498	2500	656	759	862	1089	1192	1294	1428	1531	1634
	Kupela1	1408	1449	1489	2202	2242	2283	2482	2490	2498	930	1011	1093	1486	1568	1649	1922	2004	2085
	Kupela2	1328	1373	1418	2097	2142	2187	2449	2462	2476	1038	1109	1181	1649	1721	1793	2128	2193	2254
	Lima1	1427	1467	1506	2224	2264	2304	2487	2495	2500	656	759	862	1089	1192	1294	1428	1531	1634
	Lima2	1467	1502	1537	2296	2327	2356	2500	2500	2500	656	759	862	1089	1192	1294	1428	1531	1634
	Mimi2	1274	1325	1376	2005	2056	2107	2408	2429	2449	1020	1091	1163	1631	1703	1775	2109	2176	2239
	Mimi3	1388	1429	1470	2179	2220	2261	2475	2486	2494	656	759	862	1089	1192	1294	1428	1531	1634
	Murugu	1468	1503	1538	2295	2327	2356	2500	2500	2500	1153	1216	1279	1816	1879	1942	2291	2333	2365
	Sambu	1716	1785	1850	1734	1806	1877	1260	1332	1403	1153	1256	1359	1166	1269	1372	830	932	1034
	Techinan	1373	1415	1456	2164	2205	2246	2471	2483	2491	691	794	897	1124	1227	1329	1463	1566	1669
	Vampere2	1279	1330	1382	2010	2061	2113	2411	2431	2450	930	1011	1093	1486	1568	1649	1922	2004	2085
	Vampere3	1441	1475	1510	2269	2303	2335	2497	2500	2500	930	1011	1093	1486	1568	1649	1922	2004	2085

Table 4. Continued

Location	Soil	Uncultivated soil millet yield (kg/ha)									Cultivated soil millet yield (kg/ha)								
		CDF Low 33%			CDF Middle 33%			CDF High 33%			CDF Low 33%			CDF Middle 33%			CDF High 33%		
		B 0	B 10	B 20	B 0	B 10	B 20	B 0	B 10	B 20	B 0	B 10	B 20	B 0	B 10	B 20	B 0	B 10	B 20
Northern East	Lumo	1536	1565	1594	2373	2388	2402	2500	2500	2500	1192	1252	1312	1952	2006	2060	2252	2289	2325
	Kpelesawgu2	1970	2016	2061	2006	2046	2085	1507	1563	1618	1174	1277	1380	1187	1291	1394	851	953	1055
Northern	Kpelesawgu3	1634	1712	1789	1651	1729	1807	1202	1279	1356	1153	1256	1359	1166	1269	1372	830	932	1034
	Kpelesawgu6	2006	2050	2093	2037	2075	2112	1545	1596	1645	1175	1278	1381	1188	1291	1394	851	953	1056
	Lima-volta	2157	2186	2215	2175	2202	2227	1689	1726	1763	1140	1243	1346	1152	1256	1359	816	918	1021
	Nyankpala	2195	2222	2246	2210	2233	2256	1731	1766	1801	1175	1278	1381	1188	1291	1394	851	953	1056
	Kpelesawgu	1504	1588	1673	1520	1604	1689	1101	1185	1268	1154	1257	1360	1167	1271	1374	831	933	1035
	Kpelesawgu5	1384	1426	1469	2167	2209	2252	2471	2483	2492	1192	1252	1312	1871	1932	1992	2333	2363	2393
	Lima-volta1	1521	1606	1690	1537	1622	1706	1118	1202	1286	1175	1278	1381	1188	1291	1394	851	953	1056
	pasga	2087	2122	2155	2105	2139	2172	1618	1660	1702	1175	1278	1381	1188	1291	1394	851	953	1056
	Kpelesawgu4	2091	2125	2158	2109	2142	2175	1622	1665	1707	1175	1278	1381	1188	1291	1394	851	953	1056
	changnalili	2127	2158	2189	2145	2176	2206	1659	1698	1737	1175	1278	1381	1188	1291	1394	851	953	1056
	Techinan	1373	1415	1456	2164	2205	2246	2471	2483	2491	691	794	897	1124	1227	1329	1463	1566	1669

	Kasele	2161	2190	2219	2179	2206	2231	1695	1731	1768	1175	1278	1381	1188	1291	1394	851	953	1056

Biochar effect was minimal for the pristine or uncultivated soils, which already had good structure, high AWC and high productivity. The challenge is whether tropical soils can be restored in their initial state when cultivated. For the cultivated soil, biochar application did increased yield somewhat but the effectiveness varied with location. In the Upper East Region, the highest simulated yield for Volta series was 2406 kg/ha under BC20. For Upper West, the highest simulated yield was 1846 kg/ha for Varemper1 under BC20. For Savannah Region, the highest simulated yield was 2293 kg/ha for Murugu under BC20. For Northern East Region, the highest simulated yield was 2326 kg/ha for Lumo under BC20. In the Northern Region, the highest simulated yield of 2326 kg/ha was for Kpelesawgu. In general, high application of biochar (>20 ton/ha) may be beneficed to millet yields, with yield levels doubling, compared with B0, where yield levels for cultivated soil hardly exceed 1.0 ton/ha. As shown in Figures 4 and 5 only two locations which are at the border between the Northern Region and Upper East Region, had simulated yield of 1900 kg/ha under BC0. But there were 6 locations mainly in the Savannah Region (3 soils), one at the border between the Northern region and Northern East, one at East Mamprusi District and another at Gushiegu District (Northern region) that can be improved upon biochar application at 10 ton/ha. At the highest application rate of 20 ton/ha (BC20) all the soil at Savannah and Northern regions showed a significant improvement in the millet yield except for one soil at Bole, Central Gonja District in the Savannah Regions. Only four (4) soil out of the 35 selected soil had no significant improvement in the millet yield even under BC20 mainly at Upper East and Savannah region. Based on the principles of stochastic dominance, namely "more is preferred to less" it could be suggested that at least 20 ton/ha of biochar application is required to attain any significant millet yield increase in northern Ghana. The major difference between the first (1961-1990) and second (1991-2020) 30-year time slices was the slight increase in rainfall and temperature during the last 30 years. At Tamale (Northern Region,) rainfall increased by 12 mm whereas temperature increased by 0.4 ^{o}C. At Navrongo (Upper East) rainfall increased by 57 mm and temperature by 0.5 ^{o}C, which may affect evapotranspiration rates and crop yields.

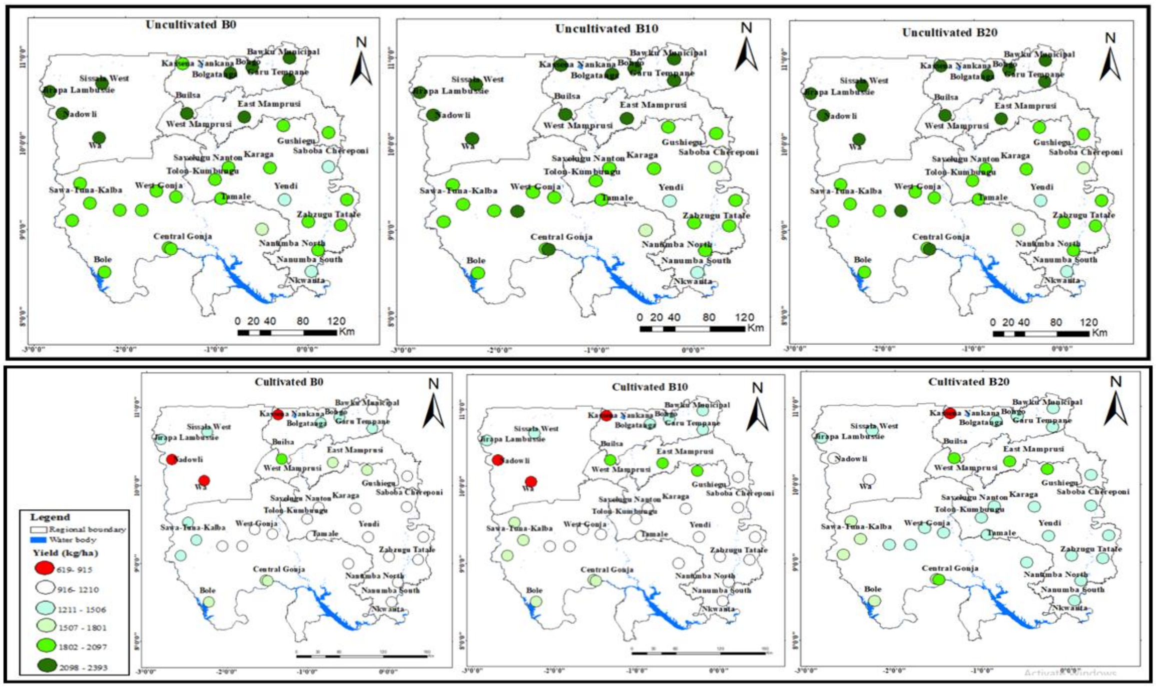

Figure 4. spatial distribution of millet yield under different soil management system for the first 30 years (1961-1990)

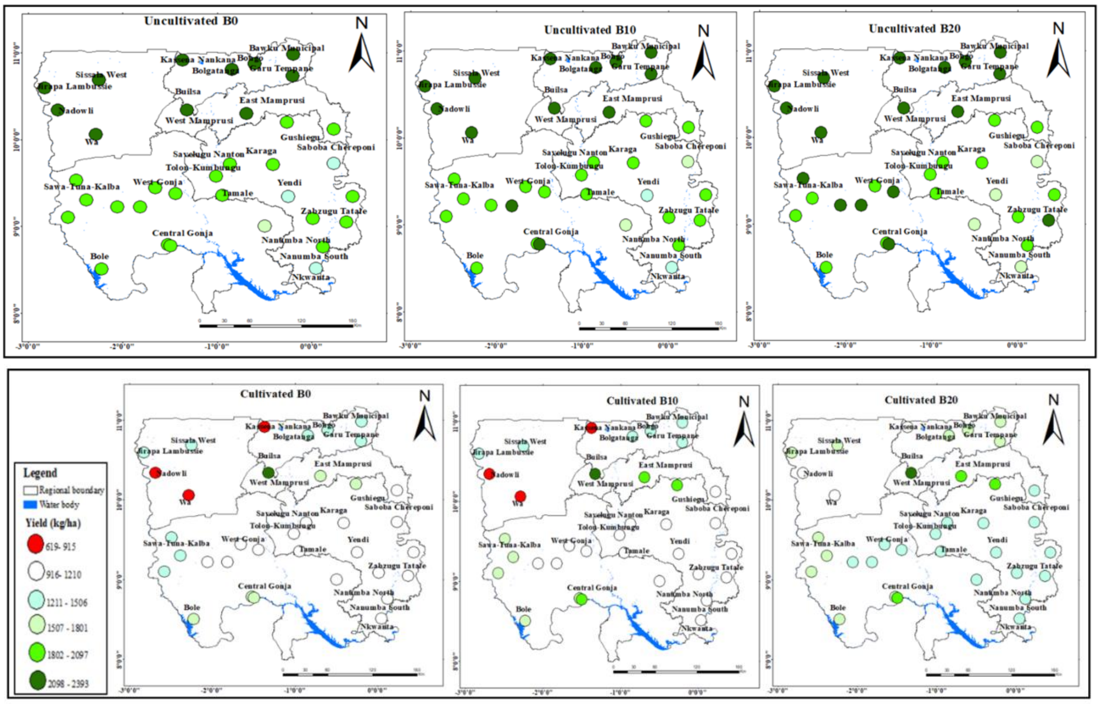

Figure 5. Spatial distribution of millet yield under different soil management system for the second 30 years (1991-2020)

IV. Conclusion

Biochar-dependent Millet Performance and AWC in northern Ghana at 35 locations showed that biochar application across multiple sites across northern Ghana could only be effective in enhancing the AWC if application rates were at least 20 ton/ha, in which case the AWC would increase only 7% of the sites. The improvement of millet yield in uncultivated soil was marginal (3.56%) when biochar was applied at 20 ton/ha, especially in the savannah and Northern Regions. Biochar effect was minimal for the uncultivated or pristine soils, which already had good structure, high AWC and high productivity. Under this rate of 20 ton/ha, 83% of the selected soils showed millet yield to significantly increase under current cultivation conditions. Based on these findings it was concluded that biochar technology is the promise amendment to improve Northern Ghana sandy soil in order to increase millet yield under varying climate condition.

Compliance with ethical standards Acknowledgments

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Disclosure of conflict of interest

The authors declared that there is no conflict of interest.

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