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Effects of Biochar on Soil Fertility and Crop Yields: Experience from the Southern Highlands of Tanzania

Peter M. Rogers[1]*, Pius Z. Yanda[1], Noah M. Pauline[1], Simon Haikola[2], Anders Hansson[3] and Mathias Fridahl[3]

[1]*Institute of Resource Assessment, University of Dar es Salaam, P.O. Box 35091 Dar es Salaam, Tanzania*

[2]*Department of Thematic Studies–Technology and Social Change, Linköping University, 58183 Linköping, Sweden*

[3]*Centre for Climate Science and Policy Research, Department of Thematic Studies–Environmental Change, Linköping University, 58183 Linköping, Sweden*

**Corresponding author. E-mail: rogerspeter120@gmail.com*

Co-authors' e-mails: pyanda@gmail.com, noah.makula@gmail.com, mathias.fridahl@liu.se, anders.n.hansson@liu.se, simon.haikola@liu.se

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Abstract

The world's agricultural production is declining due to severe loss of soil fertility through natural processes or because of human activities. Biochar has been identified as a potential soil amendment to regain its fertility and increase crop productivity. This study aimed to assess the effects of biochar on soil nutrients and crop yields in the southern highlands of Tanzania. Data were collected through key informant and household interviews, and from sampling of soils in coffee farms where biochar of maize cobs origin was incorporated at the rate of 3 t ha^{-1}. Purposive sampling approach was deployed to identify the villages in which farmers have been incorporating biochar in farms. A total of 172 households, 30 key informants, and 12 top and subsoil samples were involved in this study. Quantitative data were analyzed using SPSS version 20, and excel spreadsheet was used for descriptive results and relationships. The findings revealed that biochar significantly increased soil pH, iron (Fe), organic carbon (OC), cation exchange capacity (CEC) and exchangeable bases (potassium-K, magnesium-Mg). T - tests showed significant increase of soil nutrients in biochar treated soils. In addition, biochar increased coffee and maize yields from 1 t ha^{-1} to 3 t ha^{-1}.

Keywords: Biochar, Soil Nutrients, Food Security; Resilience; Adaptation.

Introduction

About 75% of the arable land loses its fertility at the rate of 24 billion tons per year through natural processes and anthropogenic activities, consequently posing threat to global food security (Tan et al. 2005, Watts 2017). The United Nations Convention to Combat Desertification (UNCCD) (2017) indicated that the soils of the world decreased productivity depending on the type of land use or vegetation cover including cropland (20%), forest land (16%), grassland (19%), and rangeland (27%) from 1998 to 2013.

In Africa, cropland showed a decrease in soil fertility with high depletion recorded for nitrogen (N) (22 kg ha^{-1}), phosphorus (P) (2.5 kg ha^{-1}), and potassium (K) (15 kg ha^{-1}) over the past 30 years in 37 countries (Sanchez 2002, Gwenzi et al. 2015). The high rate of nutrient depletion in the soil has been reported to result in declines in yields for wheat, rice, maize, coffee, and barley (Tan et al. 2005, Aslund 2012, Cornelissen et al. 2013, Gwenzi et al. 2015). In Tanzania, the major deficient nutrient elements in soils include N, P, K, calcium (Ca), magnesium (Mg), and sulphur (S) (Bekunda et al. 2002, Amuri et al. 2017). The deficiency of these nutrient elements is exacerbated by soil acidification, salinization, leaching, and erosion that have deteriorated agriculture and food security for 80% people in Tanzania (Bekunda et al. 2002, Leyaro and Morrissey 2013, Amuri et al. 2017). Furthermore, the impacts of climate change are unevenly spreading across the country, with the rainfall models projecting less predictability and more volatility in the intensity and distribution of rains (Chang'a et al. 2010). Vulnerability to climate change has already led to and will likely continue to contribute to a decline in agricultural productivity that threatens food security (Rowhani et al. 2011). The decline in soil fertility and impacts of climate change strike subsistence farmers disproportionately hard, because of insufficient income to amend the soil and low adaptive capacity (Warner and Afifi 2013).

Development in agriculture has identified biochar as a feasible option due to its potential to amend the soil, increase crop yields, and mitigate and adapt to the impacts of climate change (Kimetu et al. 2008, Lehmann et al. 2014, Gwenzi et al. 2015, Cosmidis and Siwingwa 2017, Draper 2018, Nanyuli et al. 2018). In East Africa, biochar improved soil conditions to prevent nitrogen deficiency in plants in Kenya and increased coffee, maize, and beans yields in Embu and Kakamega (Kimetu et al. 2008, Aslund 2012, Nanyuli et al. 2018). In Rwanda, biochar increased coffee yields by 35%, significantly reduced irrigation needs, and fertilizer inputs by 50% (Brown 2017, Draper 2018). Biochar in Tanzania is in infant states mainly in smallholder farmers' projects and initiatives (Brown 2017, Draper 2018, Hansson et al. 2020). Biochar was applied at different rates from 3 t ha^{-1} to 16 t ha^{-1} that increased both increased both soil nutrients and crop yields. Previous research has shown that biochar is produced by using different feedstocks including rice and coffee husks, maize cobs, and chop sticks (Draper 2018, Nanyuli et al. 2018). Based on a survey of 172 rural farming households, the article seeks to answer two research questions. To what extent biochar applications increase soil nutrients in the acidic soils founds in the Southern Highlands of Tanzania? What is the contribution of biochar in increasing crop yields? This article, therefore, provides a unique empirical understanding of the effects of biochar on soil fertility and its influence on crop yields in the Southern Highlands of Tanzania where small scale biochar production and applications have been introduced to smallholder farmers. Few studies have been conducted to investigate the potential of maize cobs biochar in addressing soil fertility and crop production challenges in Tanzania (Cosmidis and Siwingwa 2017, Hansson et al. 2020, Silayo et al. 2020). However, with the existing pilot studies (Hansson et al. 2020), more research work remains to be conducted in areas identified to be potential for biochar technology like the Southern Highlands of Tanzania. Therefore, this study returned to Black Earth Project villages in Mbeya and Songwe Regions (Southern Highlands) in Tanzania where smallholder farmers have adopted biochar technology to investigate the potential of biochar in increasing soil nutrients and crop yields.

Materials and Methods

This study was conducted in Mbeya and Songwe Regions of the Southern Highlands of Tanzania located between latitudes 7° and 9° south, and longitudes 32° and 35° east (Arce and Caballero 2015, URT 2016). The area is covered with thick layers of volcanic and alkali basalt soils and limestone in the lowland areas (Veldkamp 2005, URT 2016). The soils are predominantly dark, greyish and dark brown as well as yellowish-brown with sandy and clay loam on the slopes of Livingstone and Rungwe Mountains (Majule 2010). The soils in the main arable areas are coarse or medium textured ranging from sandy loam and alluvial soil to cracking soil (Veldkamp 2005, Majule 2010). Household interviews were conducted for smallholder farmers in Rungwe, Mbozi, and Mbeya Rural districts. With the support from district and ward extension officers, the villages were purposively selected based on their involvement in biochar production and application initiatives. The sample frame consisted of households with farms, and using agricultural inputs for crop production. The respondents from households were randomly selected using a random number table. The heads of households were targeted in responding to questionnaires as the main decision makers at the family level. A sample size of 172 heads of households was drawn for the study by considering at least 5% of total households as described by Boyd et al. (1981). In addition, the key informants from district and ward extension officers, village executive and ward executive officers were selected for in-depth individual interviews.

Two categories of soil samples were considered (Tan 2005) in a mixed cropping farm (coffee and maize) treated with 3 t ha^{-1} of maize-cobs biochar one year ago and the soils from fields where no biochar was incorporated and these were regarded as the absolute controls. Sampling protocols were used aiming at reducing the sampling error (Clay et al. 2010). The first category was top-soil samples from 0 to 20 cm deep (Dahal et al. 2018). Six (6) soil composite samples were made, two from each district, among them, one sample being from the control plot and the other from the biochar-treated plot. The second category was sub-soil samples that were taken at 20 to 40 cm deep (Dahal et al. 2018) made from the same procedure as the topsoil. Ultimately, there were 12 composite samples, six from treated farms and six from control farms. The samples were subjected to the laboratory analysis in a laboratory at the Sokoine University of Agriculture of Tanzania. Soil pH was measure potentiometrically using a ratio of 2.5 ml water to 1 g soil (McLean 1982), available P using Bray-I method (Bray and Kurtz 1945), soil organic carbon (SOC) using the Walkley and Black (1934) method, total N using the Kjeldahl digestion and distillation procedure (McGill and Figueiredo 1993), and CEC using ammonium acetate method (Chapman 1965).

Data analysis

Data were obtained from 172 administered questionnaires (n = 172), a 100% response rate, and were analysed using SPSS version 20, and excel spreadsheet to find descriptives, level of significances and relationships of biochar's ability to amend the soils and improve crop productions using t-test. Qualitative data were analyzed using content analysis, in which the components of the verbal discussions were broken down into the smallest meaningful units of information, such as the perceptions, values, and attitudes of the respondents. Majority of the respondents were smallholder farmers with about one hectare of farm size. Of the 172 respondents, 68 (40%) of the total sample had prior knowledge about biochar and 44 (26%) of the total sample were using biochar in coffee, maize, and bean farms. Among the issues explored was the contribution of biochar in crop yields as an adaptation strategy to increased climate change resilience.

Results

Effects of biochar on the selected soil properties

The soils with biochar incorporation recorded higher levels of the studied nutrients relative to the non-biochar amended soils. The results showed an avarage increase of soil pH form 4.73 to 5.06. The t-test showed a significant increase of soil pH (t = 2.784, degrees of freedom (df) = 5, p = 0.0387). Figure 1 shows the increase in soil pH concentrations in the biochar-treated soils . Key informants revealed that biochar's specific properties reduce the soil acidity through its alkaline nature and high buffer capacity. The ability of biochar particles to absorb the H^+ ions, as well as decarboxylation processes are the main factors in soil acidity neutralization. The biochar particles in soil are subject to gradual oxidation which leads to the production of functional groups containing oxygen. Biochar application may present an acceptable solution to high soil acidity. The key informants further revealed that, low soil pH values in the control soil samples was a result of the depletion of basic cations in crop harvest and runoff generated from accelerated erosion in the study area. Moreover, high microbial oxidation that produces organic acids, provide hydrogen ions to the soil solution and thereby lowers soil pH.

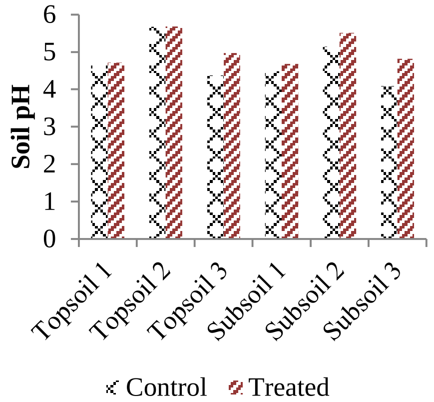

Figure 1: Trends of measured soil pH in control and treated soils.

The results showed an average increase of Zn from 2.03 mg kg^{-1} to 2.43 mg kg^{-1} and Fe from 2.39 mg kg^{-1} to 4.01 mg kg^{-1}. Figures 2 and 3 show Zn and Fe concentrations in the biochar-treated and control soils. The t-test showed there was no significant increase in Zn in the treated soil (t = 0.6725, df = 5, p = 0.5311), while there was a signficant increase of Fe in the trated soils (t = 3.578, df = 5, p = 0.0159). Moreover, the levels were well below the permissible concentrations for crop production. The key informants asserted that, the increase of Zn and Fe levels were a result of generally higher trace element concentrations in the control soils due to low soil pH and soil erosions in the study area. However, more important observation was biochar may increase Zn concentrations in the top soils; Zn is an essential trace element for plant growth which is required to about 6.0 mg kg^{-1} in the soil solution to avoid harming plant growth. It was further revealed that Fe is an important essential nutrient and its deficiency results in stunted growth and significant reduction in plant productivity. Moreover, the increase of Fe from biochar reduces the bioavailability of heavy metal ions in soil and reduces the translocation of trace elements like copper in heavy-metal-contaminated soil.

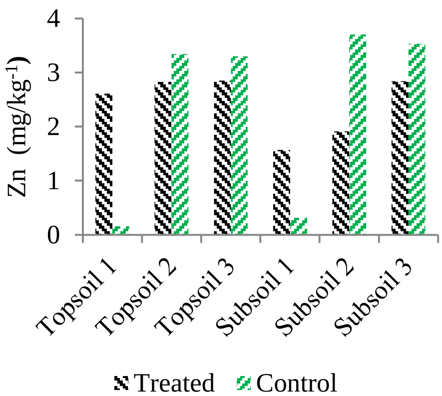

Figure 2: Trends of measured Zn in control and treated soils.

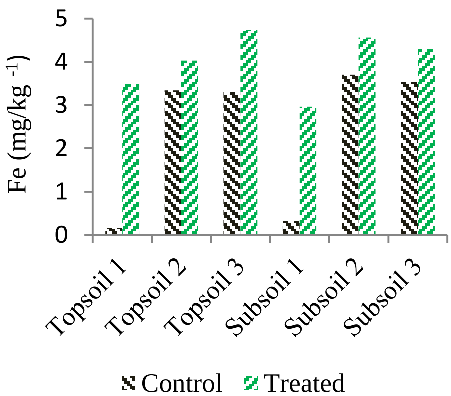

Figure 3: Trends of measured Fe in control and treated soils.

The study showed that, biochar increased total N from 0.1% to 0.19%, OC from 1.39% to 1.52%, TOM from 2.36% to 2.61% in the soils. The increase of total N was slightly low compared to OC and TOM due continuous cultivation and slow decomposition of biochar in the soil. The t- test showed that the increase of OC was significant (t = 7.178, df = 5, p = 0.0008), while the increase of total N was not significant (t = 1.040, df = 5, p = 0.3461) as well as that of TOM (t = 1.840, df = 5, p = 0.1252). Figures 4, 5 and 6 show the levels of total N, OC and TOM in the biochar-treated and control soil samples. The key informants revealed that biochar was able to increase total N, OC and TOM due to its porous nature and large surface area. It was revealed that biochar can reduce nitrogen loss in surface soil by enhancing nitrification of NH_4^+-N into NO_3^--N and eventually increase the soil NO_3^--N contents, thereby, increasing nitrogen availability. It was further revealed that biochar is a carbon material attracting organic matter after decomposition. It was further revealed that, biochar is a carbon material attracting the increase of significant total N, OC and TOM in the soil. However, the slow increase of total N, OC and TOM shown in Figure 4, 5 and 6 was a result of slowly decomposition of biochar and erosion. Moreover, the soil chemical composition of volcanic eruption processes and land-use changes for agriculture may have decreased soil nutrients in the control soils.

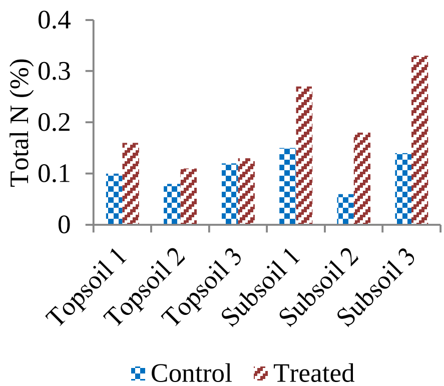

Figure 4: Trends of measured total N in control and treated soils.

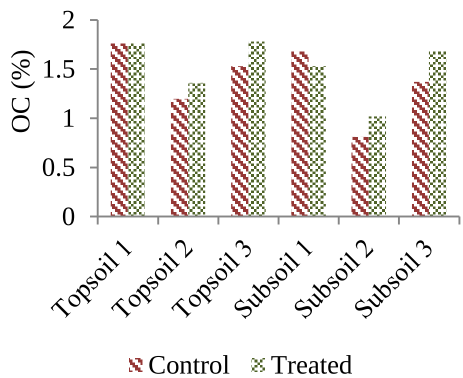

Figure 5: Trends of measured OC in control and treated soils.

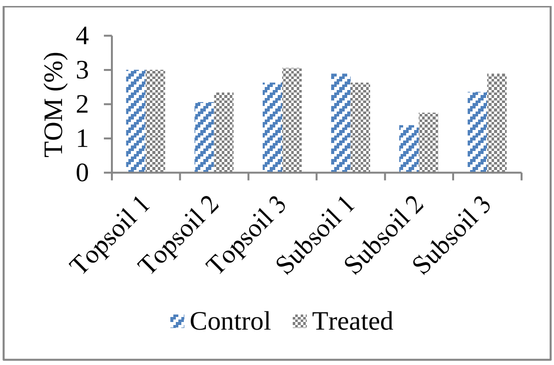

Figure 6: Trends of measured TOM in control and treated soils.

The study showed that CEC increased from 4.26 $cmol_{(+)}\ kg^{-1}$ to 4.91 $cmol_{(+)}\ kg^{-1}$, Mg from 1.09 $cmol_{(+)}\ kg^{-1}$ to 1.74 $cmol_{(+)}\ kg^{-1}$, Ca from 1.32 $cmol_{(+)}\ kg^{-1}$ to 1.36 $cmol_{(+)}\ kg^{-1}$ and K from 0.9 $cmol_{(+)}\ kg^{-1}$ to 0.99 $cmol_{(+)}\ kg^{-1}$. On the other hand, Na remained constatnt at 0.14 $cmol_{(+)}\ kg^{-1}$ both in the control and treated soils. The t- test showed that the increase were significant for CEC (t = 2.961, df = 5, p = 0.0315), Mg (t = 3.979, df = 5, p = 0.0105) and K (t = 3.659, df = 5, p = 0.0146), while insignificant were Ca (t = 0.1530, df = 5, p = 0.8844) and Na (t = 0.3863, df = 5, p = 0.7151). The increase of CEC would help movements and enhance availability of other nutrients in the soil, while Mg and K help plant growth. Figures 7, 8, 9, 10 and 11 show the trends of CEC, Mg, K, Ca and Na levels in the biochar-treated and control soils. The key informants claimed that, the top and subsoils were endowed with CEC, Mg and K since accumulation of organic matter from biochar decomposition both in the top and subsoils. However, the unchanged Ca and decrease in Na in the top soils resulted from continuous cultivation and applications of chemical fertilizers that exhausted the soil. The informants further revealed that, it is likely that leaching contributed to higher nutrients availability in the subsoil. The decrease in Ca and Na could be attributed to the high nutrient uptake by the plants. The low levels of Na in the studied soils do not present deficiencies as it is regarded as a beneficial nutrient that is needed in low quantity to avoid damage in soil structure, permeability, and plant growth.

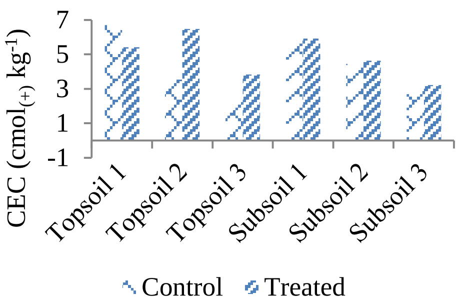

Figure 7: Trends of measured CEC in control and treated soils.

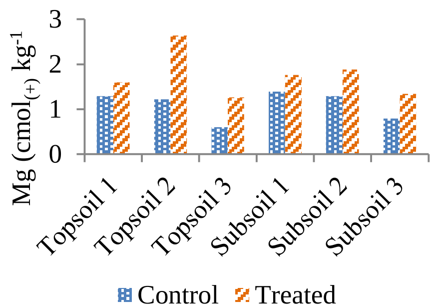

Figure 8: Trends of measured Mg in control and treated soils.

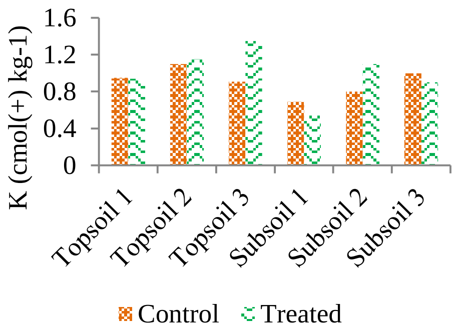

Figure 9: Trends of measured K in control and treated soils.

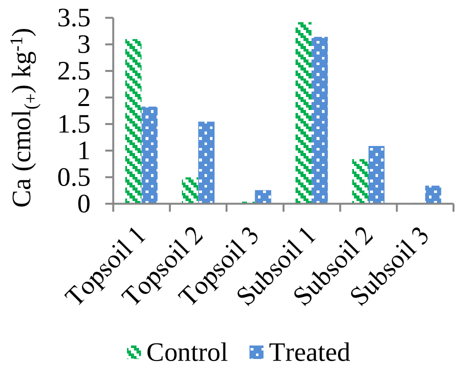

Figure 10: Trends of measured Ca in control and treated soils.

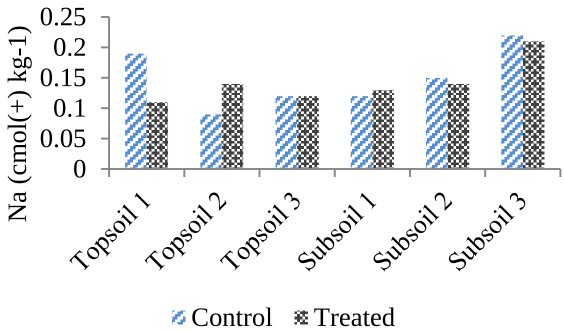

Figure 11: Trends of measured Na in control and treated soils.

Biochar application increased P from an average of 2.63 mg kg^{-1} to 3.83 mg kg^{-1}. Variations in available P contents resulted from inherently low P containing minerals in acidic soils. The variation was influenced by the intensity of soil weathering, erosion, and low ability of P-fixation with Fe and Ca. Moreover, the variation was influenced by competition among plants in coffee farms as phosphorus is essentially needed for their growth. Figure 12 shows the increase of P in biochar-treated and control soils. The t-test showed that the increase in P was not significant (t = 1.793, df = 5, p = 0.1330). The key informants revealed that, poor farm management systems that kept weeds and wild plants in the farms increased P demands in the acidic soils. This means, more abundant biomass absorbs a larger amount of available P, causing P depletion in the soil. Moreover, low pH conditions in soils influence the chemical structure of P to change making it less available in crops, especially in control soils.

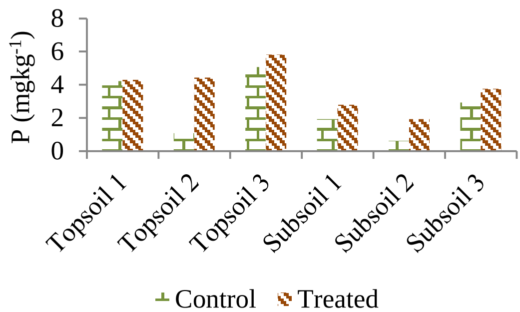

Figure 12: Trends of measured P in control and treated soils.

Effects of biochar on crop yields

The results shows that majority of respondents were applying biochar in farms (n = 44) and contributed to increased crop yields. They further showed that the respondents acknowledge biochar to have increased coffee (93.20%), maize (90.90%) and bean (70.50%) yields from 1 t ha^{-1} to 3 t ha^{-1}. A linear regression test showed a significant relationship between biochar and crop yields, i.e. coffee yield p = 0.002115 maize yield p = 0.00565 and Beans p = 0.00342. Figure 13 shows the perceptions of smallholder farmers about biochar's ability to increase crop yields. The key informants revealed that, the increase in coffee yields was observed in cherries size, quantity of cherries per coffee plant as well as the size of coffee trees. In maize and beans, the increase was in grain sizes, big stems, and nourished spread leaves. This indicated that biochar applications increased coffee, maize and bean yields.

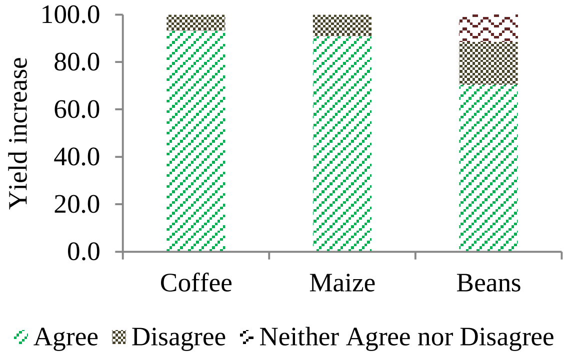

Figure 13: Perceptions of respondents on the effects of biochar on crop yields.

The information from key informants revealed that biochar applications increased coffee, maize, and bean yields, which in turn improved livelihoods by increasing food security and generation of income. This motivates more farmers to engage in biochar applications in farms despite land fragmentation due to population increase in the study area. Moreover, the use of biochar reduced erosion since well grown roots and leafs of coffee plants prevented movements of soils both during rainy and windy seasons in the study area.

Discussion

Soil fertility and crop yields of coffee, maize and beans have been increased as a result of biochar applications in the farms. The significant increase in soil pH resulted from maize cob biochar enabled water retainment in the soil especially in the topsoils. The increase triggers a regulation of plant nutrients availability by controlling chemical forms of different nutrients and also influences their chemical reactions. This finding corresponds to Oguntunde et al. (2004) that biochar reduced soil acidity by 31.9 % in the degraded soils, it increased soil pH in acidic soils by 0.5–1 (Horneck et al. 2011, Lehmann et al. 2014). This finding also corresponds to Zhang et al. (2015) and Rawat et al. (2019) that amending with biochar increased soil productivity due to its C, H, K and Mg composition that improve soil pH and CEC. Adoption of biochar made from well researched feedstocks, i.e., maize cobs is essential to elevate soil pH that makes other nutrients available for plant uptake to increase in crop yields (Bohn et al. 2001). Biochar increased micronutrients of Fe and Zn, the increase was a result of abundant basalt parent materials from which the soils were formed. The increase was insignificant and optimal for plant growth of less than 100 mg kg^{-1} (Foth and Ellis 1997). This indicates biochar application in volcanic soils may consider types of feedstocks and quantity of biochar to apply to avoid overdosing of the treatment. This finding corresponds to Horneck et al. (2011) report that, biochar increased Fe and Zn in medium levels adequate for plants to grow. It also corresponds to Aslund (2012) and Nanyuli et al. (2018) that biochar increased Fe in acid soil in Kenya. On the other hand, Zn and Fe play important roles in the formation of auxin, enzyme systems, and component for dehydrogenases, proteinases, and peptidases.

Biochar increased total N, OC and TOM due to availability of soil organic matter obtained after biochar applications. However, the increase on OC was significant. The obtained soil organic matter spearheaded decomposition in topsoils where high concentrations of biochar remains were observed. The increase of OC and TOM may be a result of the ability of biochar to retain about 63% of carbon after pyrolysis. This suggests that the increase of biochar quantity in the soil and the use of mixed biochar with other organic substrates may complement the increasing total N, OC and TOM. This concurs to Horneck et al. (2011) and Cosmidis and Siwingwa (2017) that, high total N and OC depend on high total organic matter and the rate of decomposition of organic material in the soil. Aslund (2012) revealed that biochar improved OC and TOM availability to plants in Kenya. However, soil erosion, leaching, low carbon input may significantly contribute to low total N, and TOM especially to control soil (Horneck et al. 2011). This finding corresponds to a study that green waste biochar improved soil organic carbon in coffee yields, quality of cherries, and carbon sequestration benefits (Dahal et al. 2018).

The increase of CEC, Mg and K was uptimum for plant growth.The increase was also a result of volcanic nature of the soil that increased carboxylate groups on the surfaces of biochar, which was exposed to organic acids sorbed of which it contributed to the negative surface charges to biochar particles (Liang et al. 2006, Mikkelsen 2010). This finding corresponds to Novak et al. (2009) that biochar increased CEC, Mg and K in agricultural farms. Biochar has also been found to increase CEC of highly weathered and nutrient-poor soils (Kookona et al. 2011, Lehmann et al. 2014, Zhang et al. 2015). Moreover, potassium increased as influenced by the minerals present in the soil, ability of weathering, farm management practices, climatic conditions, the ability of soil development, and the parent material from which the soil is formed (Majule 2010). Kloss et al. (2012) reported that biochar from maize cobs releases high K content when applied into soils. However, the lower exchangeable K contents in the control soil may be due to continuous K losses during harvest. However, the increase of Ca was insignificant and Na decreased. This could be due to low soil pH under continuous cultivation that allowed excessive leaching (Bohn et al. 2001, Horneck et al. 2011, Zheng et al. 2013). This indicates biochar regulates the availability of Ca and Na to low levels to allow permeability and plant growth (Horneck et al. 2011).

The increase in available P was affected by the intensity of soil weathering, erosion, and low susceptibility to fixation by Fe and Ca. To increase of available P in the soil, biochar may be mixed with manures or diammonium phosphate (DAP) fertilizer by farmers to have short-term better organic matter mineralization. This result corresponds to Zheng et al. (2013) that biochar hardly increased available P in the soil. On the other hand, available P in control soils can be explained by the inherently low P-containing minerals in acid soils, and competition among plants. This may be a result of the low pH in soils that influenced the chemical changes in structure of P making it deficient in the soils of the study area (Bekunda et al. 2002, Majule 2010).

The findings of the present study revealed that biochar increased crop yields of coffee, maize and beans from the traditional harvest of one ton to three tons per hectare. It also corresponds to that increase in maize yields involved leaves and grains with biochar applications obtained by other researchers (Kimetu et al. 2008, Cornelissen et al. 2013, Gwenzi et al. 2015). Oguntunde et al. (2004) observed the yield increase of grain and biomass of maize by 91% and 44%, respectively. This corresponds to Cosmidis and Siwingwa (2017) that biochar increased coffee yields in during Black Earth project in Mbeya and Songwe in Tanzania as well as in Rwanda in 2014. Biochar has been reported to increase coffee yields with good quality of cherries and carbon sequestration (Brown 2017, Dahal et al. 2018, Nanyuli et al. 2018). Moreover, linear regressions indicated a significant relationship between the amount of biochar applied in the farms and the increase of coffee, maize and beans. Moreover, this study recommends biochar adoption by increasing the amount of maize cobs biochar in Tanzania.

Conclusion

Biochar amends the soils by enhancing nutrients availability and/or solubility. The increased adoption of biochar technology in the study area is related to the increased productivity potentials in various food and cash crops including coffee, maize, and beans. The study recommends that despite the realized success with biochar applications, more investigation is needed on different types of crops, feedstock, and amount of biochar to be applied as this will continue to build more confidence on the importance of biochar technology in Tanzania.

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