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Full Length Research Paper

Determination of sufficiency of crop residue for biochar application

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Biochar technology is among possible solutions to the problem of low productivity in farming communities. However, the technology is yet to be adopted by farmers. One of the reasons for this is uncertainty on a sustainable supply of feedstock material. Through the analysis of maize residue, pyrolysis, and biochar application rates, this paper unveils the fact that a region generates enough feedstock for itself without extra activity. The mass of residue generated from a maize field or region was found to be 2.47N (where N is mass of produce). The total mass of maize residue in the selected countries was found to be 40,495,650 tonnes. Out of this amount, 16,198,260 tonnes of biochar could have been produced and applied on a total area of 3,239,652 hectares. This area was about 34% (or one-third) of the total planted area (9,414,000). Thus at an application interval of three seasons, the generated residue would suffice. It was observed that as yield increases the area covered as a percentage of planted area increases. Thus at high yield, there would be extra biochar or residue for other uses. This knowledge would enhance interest in biochar technology as it guarantee sustainable supply of feedstock material.

Keywords: Biochar, crop residue, feedstock, maize, pyrolysis, residue product ratio.

INTRODUCTION

One of the human worries today is the distribution of carbon amongst its key locations: the atmosphere, the biosphere, and lithosphere. It is feared that human activities move carbon from lithosphere and biosphere to the atmosphere quicker than photosynthesis eliminates it from the atmosphere (Brewer, 2012). One of the effects of high rainfalls experienced in tropics is leaching of nutrients from the root zone. Nutrient leaching depletes soil fertility, accelerates soil acidity and subsequently increases fertilizer requirements. It contributes to a reduction in crop yield and adversely affects both surface and ground water quality (Laird *et al*., 2010). While the droughts in semi-arid sub-tropical areas increase the need for expensive irrigation.

Biochar technology is one of the solutions to sequester carbon to the lithosphere (The African Biodiversity Network, 2010). It has the ability to address several other problems such as soil quality, water quality, crop yield (Brewer, 2012) and management of crop residue (Fryda & Visser, 2015). To stimulate farmers to scale up the application of biochar on their farms, these benefits need to be demonstrated explicitly through various farming methods (Nsamba *et al*., 2015) such as tillage and crop residue management.

Biochar is the carbonaceous solid (Brewer, 2012) obtained when biomass (preferably organic wastes) is heated anaerobically (Cornelissen *et al*., 2011). It contains stable carbon and when added to the soil this carbon remains sequestrated for a longer time than it would in the origin biomass (Major, 2010). It improves soil physical properties by increasing aggregate stability, porosity, water infiltration and plant available water while reducing bulk density (Cornelissen *et al*., 2014). Biochar has the ability to retain nutrients against

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leaching, thus improving the efficiency of applied nutrients (Major, 2010) and maintaining land productivity for a longer time (Cornelissen *et al*., 2013).
Despite the abundance of knowledge about benefits of biochar in scientific laboratories and publications, farmers are yet to benefit from it. Among many reasons to this is the uncertainty about sustainable supply of feedstock for biochar production. Policy makers fear that commercial production of biochar would require vast land (which is already scarce) to grow the feedstock material. While farmers still don't see how the crop residues within the farm can suffice the required amount of feedstock. All this is as a result of lack of infornmation in literature about sufficiency of crop residue as feedstock for biochar production. This work unveils the fact that each field, farm or region generates enough feedstock for itself without any extra activity. The analysis was done on a regional level with a view to case study East Africa as a region.

METHODOLOGY

East Africa as a region was used as a study area where six English-speaking countries were selected to represent the region. The literature on biochar's relevance, properties, and effects on soil was reviewed. Secondary data on 2015 maize production and planted area in the selected countries were obtained from IndexMundi.com. Using residue product ratio (RPR) for maize (stalk, husk, and cobs), the total residues for the countries were calculated. A conversion rate of 40% was then used to obtain the mass of biochar that could be produced from calculated residues. Using application rate of 5 $t.Ha.^{-1}$, the area that would have been applied with the obtained quantity of biochar was determined. This area was expressed as a percentage (ratio) of the planted area and then used to determine the number of production seasons required to cover the whole planted area. Then the number of seasons was compared to the recommended application interval to determine if the residue generated were enough to produce biochar for the planted area.

Study Area

According to UN development report 2011, East Africa as a region stretches from red sea coast in Eritrea, through Somalia on the horn, coming down along Indian Ocean coast to Mozambique. Going inside it includes Zimbabwe on the south end and Zambia on the southwest and stretches through Uganda following the rift valley. It includes islands in the Indian Ocean as indicated by the map in figure 1.
The majority (75%) of people in East Africa earn their living mainly on agriculture (Alvum-Toll & Karlsson, 2011; Skelton *et al*., 2014). Figure 2 summarises how important agriculture sector is to the people of East Africa.
Due to this high dependence on agriculture and increase in population, agriculture in the region is dominated by the smallholder and subsistence sector (Skelton *et al*., 2014). Smallholder agriculture system of Sub-Sahara Africa is associated with low productivity, intensive growing of high nutrient-demanding crops like maize, poor nutrient management, poor land management practices, high dependence on rain and cultivating in areas prone to floods and droughts (Mulebeke *et al*., 2015; Semalulu & Kaizzi, n.d.; Alvum-Toll & Karlsson, 2011; Skelton *et al*., 2014).
While in areas where large-scale farming exist, they take up fertile land and practice good land management. They also invest in irrigation to free themselves from harsh climate and hence highly productive. However, in most East African countries large scale agriculture is very rare because of topography, high population density and lack of proper land use planning (MAFC, 2013). World Bank (2011) reports a common rate of decrease in per capita land area in most of the East African countries as shown in figure 3. Figure 3 clearly shows that apart from Zambia all the considered countries have the per capita areas of less than the average for Sub-Sahara Africa which is 3.14 Ha. It is also demonstrated in figure 3 that the two countries with the same rate of decrease as that of the world have smaller areas per capita. While those with larger areas per capita than the world average experience a higher rate of decrease than experienced by the world in general. Notably is Kenya which has since crossed into smaller area sizes per capita, but still experiencing a higher decrease rate than that of the world in general.
Due to low profitability of smallholding farming system in Sub-Sahara Africa, some policymakers advocate for the promotion of medium-scale and large-scale farming systems (Shetto, 2007; Baumgartner, 2013). However, World Bank (2011) disputed the argument that large-scale farming system would perform better in land constrained countries of East Africa. Their argument was that countries in Asia (Japan for example) have smaller farm sizes (1 Ha) than Sub-Sahara Africa (2.4 Ha) on average but with much higher productivity (World Bank, 2011). In East Africa, therefore, agriculture systems need to be steered towards increasing the productive capacity and stability of smallholder farming (Branca *et al*., 2011). Among the challenges these smallholder farmers of East Africa face is low soil fertility (Alvum-Toll & Karlsson, 2011). Asea *et al.* (2014) defines soil fertility as the ability of the soil to sustainably produce high yields. In maize production, for instance, a fertile soil would have: Good drainage to evade water logging, good aeration to encourage root development, high water holding capacity, high level of available nutrients and optimum pH of between 6 and 7 (Asea, *et al*., 2014). Also according to McCauley *et al*. (2005), a typical agricultural soil should compose of 50% solid particles and 50% pores. This is ease to achieve if there is a

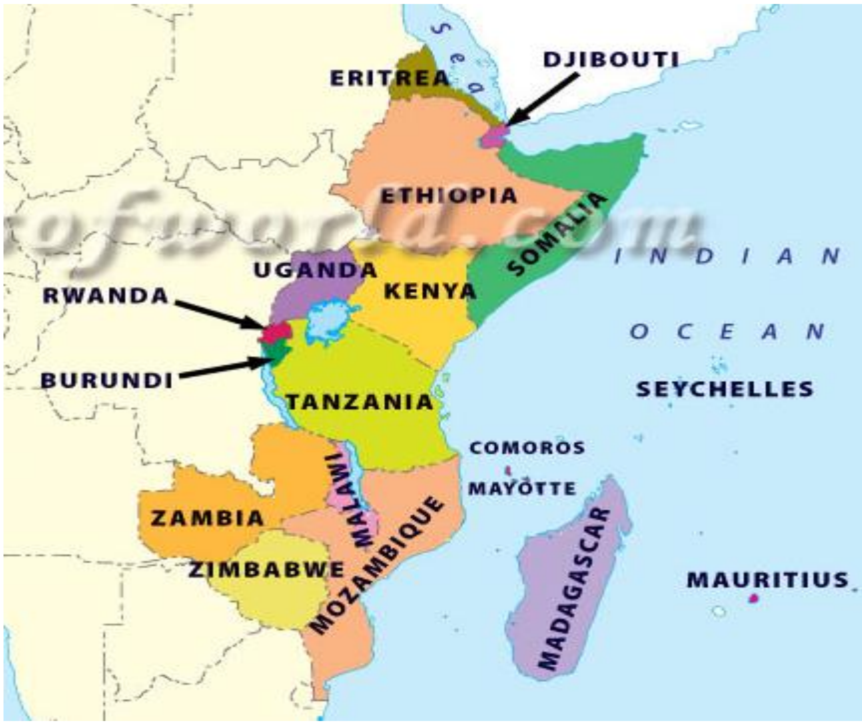

Figure 1. Countries of East Africa Region. Source: UN Development Report, 2011.

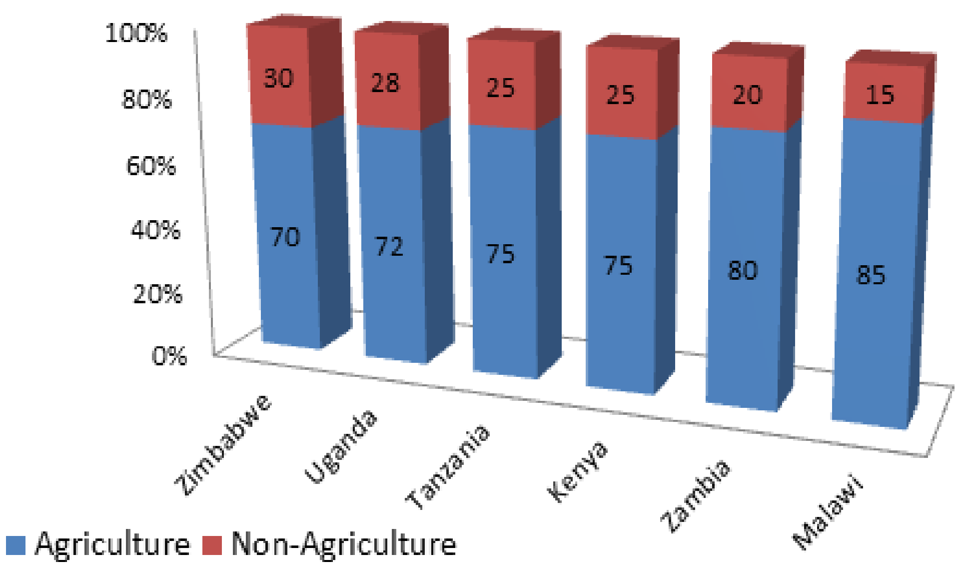

Figure 2. Proportions of Populations depending on Agriculture in East African Countries Sources: UBoS 2014; MAL 2013; MAFC 2013; Anseeuw et al. 2012; Kachule 2011; Alvum-Toll & Karlsson 2011; Feed The Future 2013.

reasonable amount of organic matter in the soil.

However, East Africa soils have an integrally poor fertility because they are old and lack volcanic transformation, inappropriate land use, continuous cultivation, limited addition and maintenance of nutrients and land degradation (Zougmore & Yemefack, n.d.; Alvum-Toll & Karlsson, 2011; Semalulu & Kaizzi, n.d.). One sure way to increase and maintain soil fertility is the use of biochar (Alvum-Toll & Karlsson, 2011). Numerous pot and field biochar trials have been conducted in the region and results have shown both instant and sustainable improvement on soil fertility

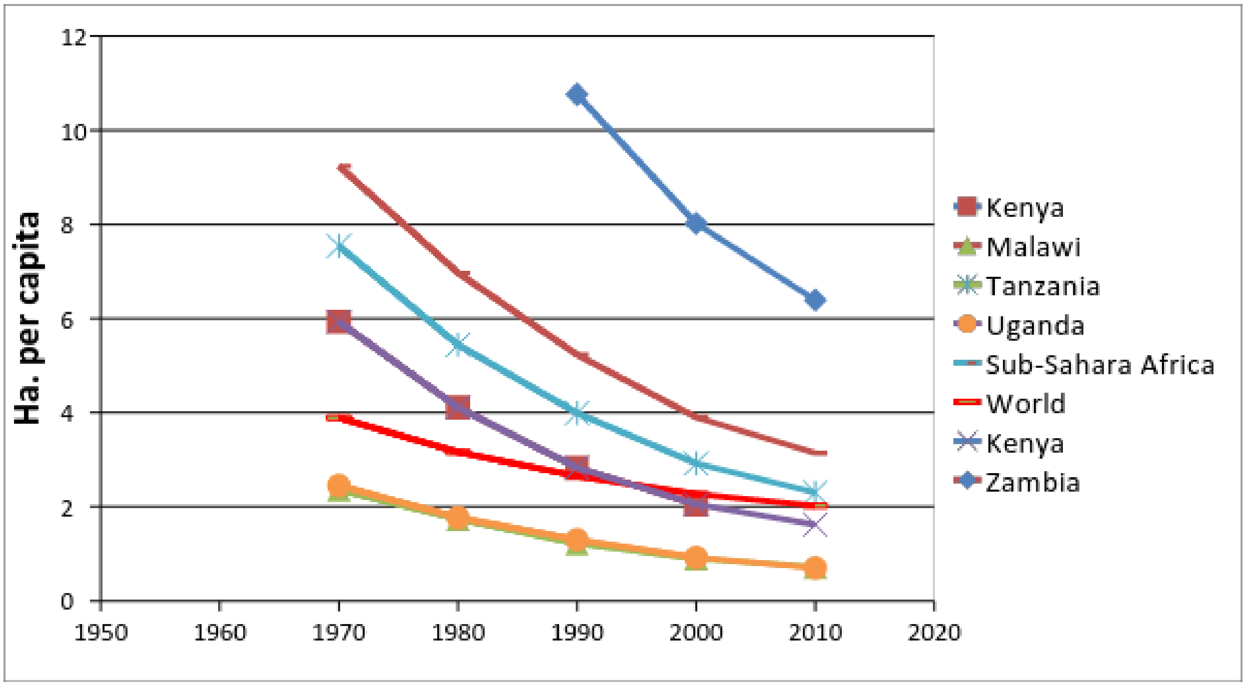

Figure 3. Trends of per capita areas in the East African Countries in the past 40 years. Source: Own analysis using World Bank 2011 data.

(Nair *et al*., 2013; Verheijen *et al*., 2010; Deal *et al*., 2012; Cornelissen *et al*., 2014). Moreover, there are documented empirical evidence that biochar is able to address several other problems such as soil quality, water quality, crop yield, carbon sequestration, energy production and green gas emission. It is logical, therefore, to suggest that East African smallholder farmers need biochar technology as part of the solution to the challenges they are facing.

Properties

Biochar has been defined here as the carbonaceous solid obtained when biomass is heated anaerobically. Thus biochar is an organic material by nature (Verheijen *et al*., 2010). To explain how biochar affects the soil, to which it is added, its physical and chemical properties are to be understood. Biochar properties are highly heterogeneous within individual biochar particles, among different originating feedstock and at different pyrolysis conditions (Brendova *et al*., 2012; Verheijen *et al*., 2010; Jindo *et al*., 2014). This heterogeneity provides a possibility to engineer biochar with properties suitable to a particular soil (Verheijen *et al*., 2010). Table 1 shows the general description of biochar composition of major plant nutrients and pH.

However, various permutations of feedstock materials and pyrolysis conditions produce different compositions (Brendova *et al*., 2012). One such permutation done by Alvum-Toll & Karlsson (2011) in Kenya involved heating at 450°C for 1 hour gave the compositions in table 2.

Fryda & Visser (2015) reports that the elemental composition of biochar is directly related to that of the feedstock material. They characterised the oakwood before pyrolysis at 400°C and 600°C and the produced biochar was as well characterised. This helped to compare the elemental composition of the biochar and that of the originating material. The results showed a reduction in nitrogen content from 1.6% in raw oakwood to 0.3 and 0.1% nitrogen in biochar pyrolysed at 400 and 600°C respectively. While carbon content increased from 52% in raw oakwood to 72 and 79% carbon in biochar pyrolysed at 400 and 600°C respectively

Yargicoglu *et al*. (2015) observes surface area of 40.63 $m^2.g^{-1}$ and volatile matter content of 28% in biochar derived from pinewood pyrolysed at 450° C. While when Jindo *et al*. (2014) pyrolysed rice husks at 400°C, they obtained biochar with surface area of 194 m^2g^{-1} and volatile matter content of 22%.

How Biochar Affects Soil Properties

The application of biochar to improve the soil is an old technology. Brendova *et al*. (2012) reported that in 1929 John Morley in The National Greenkeeper noted the improvement to soil porosity when charcoal was added to the soil. Because of its high porosity, when biochar is added to the soil it increases general soil porosity and enhances distribution of micropores in the soil (Verheijen *et al*., 2010). Through this effect on the porosity of the soil, biochar is able to improve both sandy and silty soils' water retention and infiltration (Shackley *et al*., 2010). However, the presence of hydrocarbons functional groups on the surface of the biochar particles makes it highly hydrophobic to avail water to the roots even in very low water content (Fryda

Table 1. General ranges of composition of major elements in biochar Source: Verheijen et al. 2010.

	pH	C (g/ kg)	N (g/ kg)	C:N	P (g/ kg)	Ca (g/ kg)	K (g/ kg)
Min.	6.2	172	1.7	7	0.2	0.015	1.0
Max.	9.6	905	78.2	500	73.0	11.600	58.0
Mean	8.1	543	22.3	61	23.7	-	24.3

Table 2. Concentrations of Macronutrients in Biochar from Different Materials Source: Alvum-Toll & Karlsson 2011.

Plant Material	C (%)	N (%)	P (%)	K (%)	Ca (%)	Mg (%)
Banana Leaves (Fresh)	51.2	1.05	0.16	8.68	1.83	0.76
Maize Stovers	52.2	0.58	0.10	1.03	0.64	0.50
Banana Leaves (Wilted)	54.0	1.37	0.12	0.55	4.13	0.72
Coffee Leaves	54.1	2.63	0.27	4.80	3.33	1.01
Coconut Leaves	61.0	0.47	0.10	3.00	1.29	0.55
Cassava Leaves	60.8	1.73	0.31	4.01	3.22	0.99

and Visser, 2015). Due to its large surface area, biochar increases Cation Exchange Capacity (CEC) thereby preventing nutrient leaching and enhance plant uptake of nutrients (Alvum-Toll & Karlsson, 2011). Biochar's low bulk density (associated with soil organic matter) lead to enhanced nutrients release and retention while lowering compactability of the soil to which it is added (Verheijen *et al*., 2010). Owing to its alkalinity, biochar also has a liming effect on the soil. Apart from making nutrients more available to plants, biochar can also add some nutrients (Alvum-Toll & Karlsson, 2011) as it contains both major and minor nutrients element.

Determination of Sufficiency of Residue

Although it may take till 2020 for pyrolysis technologies to reach a large scale, they have potential to impact sustainable soil management on a regional level (Madari *et al*., 2012). Pyrolysis is such a simple process that achieving user friendliness, energy efficiency, easy of adoption and limiting the emission of greenhouse gases is easy (Nsamba *et al.,* 2015). However, the challenge is seen in the availability of feedstock, such that it is thought that large area in Africa will be channelled to the production of the feedstock (The African Biodiversity Network, 2010). The determination of the sufficiency of feedstock given here is aimed at changing this perception about biochar. Though the feedstock can be any biomass (Verheijen *et al.,* 2010), the residue of a grown crop are recommended. Considering that maize is a high nutrient demanding crop and it is widely grown as staple food in East Africa countries (Asea *et al*., 2014), it is considered as a crop to be grown here. Hence the sufficiency of its residue for biochar application is determined. Table 3 shows 2015 maize production and planted area in the East African countries as reported in the indexmundi. The third column has yields calculated from the given data.

Estimating the quantity of maize residue production is quite challenging as no one tracks the production of residues as they do with crops (Berazneva, 2013). One of the reliable estimating methods can be the use of RPR. According to Hewlett (n.d.), maize residue comprises of husk 12%, leaf 27%, stem 49% and cob 12% of total residue mass. Meanwhile, Koopmans & Koppejan (1997) reported the RPRs for maize residue as Stalk at 2, Cob at 0.273 and Husk at 0.2.

Thus using these factors the quantity of maize residue generated can be obtained from crop production values as follows:

Assuming the recorded mass of the produce is **N kg** then:-

- About 2.0***N*** kg of the stalk is expected which represents 76% (27+49) of residue.
- About 0.273***N*** kg of cobs is expected which represent 12% of residue.
- About 0.2***N*** kg of husk is expected which represent 12% of residue

Table 3. Maize Production and Planted Areas in East African Countries. Source: www.indexmundi.com/agriculture, accessed on 14th April 2016.

Country	Production x1000 (t.)	Planted Area x1000 (Ha.)	Yield ($t.Ha^{-1}$)
Tanzania	5500	4000	1.4
Malawi	2877	1750	1.6
Kenya	2800	1700	1.6
Zambia	2618	964	2.7
Uganda	2600	1000	2.6
Zimbabwe	700	1530	0.5
TOTAL	**16395***	**9414***	

*Totals do not include Zimbabwe figures.

Thus summing the parts of residue a total mass of **2.47N** kg of residue is expected.
According to table 4, a total of **16,395,000** tonnes of maize was produced from an area of **9,414,000** Ha. Meaning that 16395000 x 2.47 = **40,495,650** tonnes of residues were generated and that would have been available for pyrolysis.
Now to determine how much biochar could have been obtained from this quantity of residue the temperature of pyrolysis and residence time is considered. Djurić *et al*., (2014) reports that as temperature increase from 300ºC to 650ºC biochar yield reduces from 40% to 28%. This means that if the maize residue is heated at 300ºC at a low heating rate, it is possible to get 40% of it as biochar. Thus the conversion rate of 0.4 can be used to calculate the mass of biochar.
Then out of the 40,495,650 tonnes residue 40495650 x 0.4 = **16,198,260** tonnes of biochar is expected. But then what can this quantity of biochar do against a total area of **9,414,000** Ha? There are two ways of applying a given rate of biochar. One is by applying at the given rate at once; the other is applying a less rate repeatedly until the accumulative amount reaches the given rate. Taking the first method and assuming the rate of 5 $t.Ha^{-1}$ (Major, 2010), the amount would have been able to cover a total of:

$$\frac{16,198,260}{5} = 3,239,652.Ha.$$

It should be noted here that 3,239,652 Ha. is approximately one-third of the total area of **9,414,000** Ha. This then implies that one-third of each maize field can be applied with biochar at the rate of 5 $t.Ha^{-1}$ every after three seasons. Biochar is highly recalcitrant to decomposition in the soil. A single application provides beneficial effects over several growing seasons (Major, 2010).

Economic Benefits

Biochar technology has been identified as one of the solutions to low productivity of the weathered acidic tropical soils. It has been used to double maize yield in Indonesia (Cornelissen *et al.,* 2011). However, in most East African countries the soils might not be so poor that application of biochar is able to double the yield. Nevertheless, the use of maize residue as soil amendment through biochar technology can substantially reduce the cost of fertilization. According to Berazneva *et al.* (2014), the value of maize residue when used for soil amendment is $0.06 per kilogram. While every kilogram of maize residue used as soil amendment reduces the cost of fertilising the field by $0.04 (Berazneva, 2013). Although this value applies even without pyrolysis, biochar technology ensures the maximum amount of residue usage for soil amendment.
Thus taking an average yield of 2 $t.Ha^{-1}$ for the region (Table 3), every hectare of maize would yield: 2000 x 2.47 = **4940** Kg of residue. If this entire residue is pyrolysed and applied on the field as biochar there will be a total of 4940 Kg x $0.04 Kg^{-1} x 0.4 = $**79.04** saving on fertilizer cost. At an average price of $35 per 50 Kg bag of Urea (or any other NPK compound fertiliser), this translate to about two bags of fertilizer. Thus instead of applying a total of eight bags of fertilizer per hectare as per recommendation, a farmer will save two bags and apply only six for the same expected yield.

Adoptability

To check if this is adoptable one can look at the current practices on maize residue in the region. According to (Berazneva 2013) the common practices in the region includes:

- Burning on situ or after gathering – This is done for two purposes, to clear for the next planting or to destroy phytomass which may carry diseases/pest to the next crop
- Using it as soil amendment to improve fertility – This is done in two ways, as mulch when fallowing or in reduced tillage and composting.

Biochar technology as part of the Integrated Soil Fertility Management (ISFM) and residue management can achieve all of the above purposes. However, some

Table 4. Area that can be Applied with Biochar as Percentage of the Planted Area at National Level.

Country	Production x1000 (t)	Planted Area x1000 (Ha.)	Residue x1000(t)	Biochar x1000 (t)	Area Applied x1000(Ha.)	Covered Area as %ge of Planted Area
Tanzania	5500	4000	13,585.00	5,434.00	1,086.80	**27.17**
Malawi	2877	1750	7,106.19	2,842.48	568.50	**32.49**
Kenya	2800	1700	6,916.00	2,766.40	553.28	**32.55**
Zambia	2618	964	6,466.46	2,586.58	517.32	**53.66**
Uganda	2600	1000	6,422.00	2,568.80	513.76	**51.38**
Zimbabwe	700	1530	1,729.00	691.60	138.32	**9.04**
TOTAL	**16395***	**9414***	**40,495.65***	**16,198.26***	**3,239.65***	**34.41**

*Totals are exclusive of Zimbabwe values.

farmers use the residues as cooking fuel and feeding the livestock (Berazneva 2013).

Meanwhile, Alvum-Toll & Karlsson (2011) reported that farmers were interested in using biochar as a soil amendment if it was proven that it is beneficial and economically viable. In some cases, the livestock feeding on the residue left on the field may not belong to the owner of the field. Thus to effectively implement the collection of residue the following harvesting method is recommended: The maize stalks (while with their ears) are cut and gathered in standing heaps (”*mukukwes*”) immediately it attains maturity. Normally the maize is ready to be gathered in “*mukukwes*” at the moisture content of 34%. Then the stalks stand on the “*mukukwe*” for two months or until the grains dry to less than 14% moisture content.

With portable sheller the maize is shelled right at “*mukukwe*” site so that both husks and cobs are left together with the stalks for pyrolysis. In most cases, however, cobs are used as fuel during pyrolysis. In this case, the available residue for pyrolysis is less by 12%.

DISCUSSION

Having a model at hand the quantity of residue available for pyrolysis at national, district or farm levels can be determined. For instance table 4 shows the derived possible amount of biochar for each country and amount of area which can be applied with biochar at 5 $t.Ha^{-1}$ in each country. The last column shows the area that could be applied with biochar as a percentage of the total area planted. It is clear from here that as yield increases the percentage of planted area that can be applied with obtainable biochar increases. This means that as the yield improve, as a result of biochar application, a yield which will give enough biochar to apply the whole planted area may be reached. Notably is the over 50% coverage of planted areas in Zambia and Uganda. This implies that at these yields (2.7 and 2.6) the residue is more than enough to produce biochar for half of the field. Thus the farmer has a free opportunity to increase the yield by increasing biochar application rate. There are so many ways this free opportunity provided by biochar technology can be utilised by the farmers. Others would save $79.04 from fertilizer reduction and maintain the yield.

In some cases, farmers may want to use the cobs as fuel for pyrolysis. In this case, the quantity of residue available for pyrolysis will be less by 12%. So far there is no recommendation on the suitable interval to apply biochar. However, due to its recalcitrance to decomposition in the soil, biochar does not need to be applied every season (Major, 2010). The three season interval obtained here should not be taken as standard but it has been found to be the minimum possible at the given yield.

CONCLUSION

The challenges farmers of East Africa face require concerted efforts. Biochar technology is one feasible way of working around the challenge of limited farming land while solving the problem of soil fertility. It has been shown here that biochar technology can be achieved by the resources found on the farm. Maize fields in East Africa generate sufficient residue to successfully implement biochar application. The worry most of the farmers have had about the lack of feedstock has partly been cleared. This will also serve to clear the concerns among policy makers that biochar will cause deforestation as it will require cutting down trees to use for feedstock. The saving of two 50 Kg bags of fertilizer per hectare demonstrates direct benefits to farmers as well as governments in case of subsidy. A free opportunity to increase yield provided by biochar technology has also been unveiled.

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