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RESEARCH ARTICLE

Participatory trials of on-farm biochar production and use in Tamale, Ghana

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Abstract

Urban agriculture is characterized by fast rotation of cropping cycles and high inputs and outputs on relatively small areas of land. Depletion of soil organic carbon and low nutrient use efficiency are severe agricultural constraints in the sandy soils of West Africa. We hypothesized that such an intensive system would provide ideal preconditions for the use of biochar, that biochar would enhance yields in urban horticulture, and that farmers would be able to produce biochar for on-farm use in Tamale, Ghana. Therefore, we studied the opportunities and challenges of biochar using a semi-participatory research approach. Working with 12 participant farmers, we defined research questions which were relevant to their livelihoods and collected qualitative and observational data, which determined the selection of variables to measure quantitatively. Different quality parameters such as leaf color and stiffness of lettuce were important to farmers and marketers when assessing the agronomic benefits of biochar. By adding biochar to their normal agricultural practice farmers were able to increase lettuce yields by 93%. This remarkable increase might be partially caused by farmers' improved management of biochar plots: they concentrated their resources where they expected to yield the largest returns. Using a simple top-lit updraft gasifier, a special chimney for rice husk carbonization, it was relatively simple for farmers to produce biochar in the field, with an efficiency of 15–33%. These stoves' payback times were between 1 and 2 months. Yet, rather than the efficiency of the carbonization technology, often emphasized in biochar research, the availability of feedstock and labor considerations determine the technology selected by farmers for biochar production. This is a novel approach to considering the economic realities of farmers in a semi-participatory appraisal where farmers both produce and apply biochar. This is crucial in order to understand and identify meaningful and economically viable uses of biochar.

Keywords Biochar · Lettuce · Organic carbon · Rice husk · Soil fertility · Urban agriculture · West Africa

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1 Introduction

In West Africa urban horticulture is an intensive cropping system where the intensive production of cash crops justifies the high level of inputs, such as mineral fertilizers and pesticides. The use of organic fertilizers is common, but the input of organic carbon rarely matches the loss by mineralization. Depletion of soil organic carbon (Predotova et al. 2010) is one of the main causes of soil degradation (Bationo et al. 2007; Lal 2009). Due to irrigation during the dry season, continuous soil cultivation and high temperatures, carbon turnover is fast. Soil organic carbon declined by 24% within 2 years after conversion to intensive horticulture compared with the initial carbon stocks under rain-fed maize cultivation (Häring et al. 2017). Therefore, high organic input rates are required to increase and maintain soil organic carbon (de Ridder and van Keulen 1990). The mineralization and subsequent loss of soil organic carbon as CO_2 liberates plant nutrients. Replenishing nutrient stocks with mineral fertilizers provides nutrients readily available for the crops, but has two major disadvantages; they are often prone to leaching or volatilization losses and frequently cause a depletion and subsequent deficiency of nutrients not supplied with the compound-fertilizer (de Ridder and van Keulen 1990). High inputs of nitrogen (N), phosphorus (P) and potassium (K) have been measured in urban agricultural systems in Niamey, for example, as well as other urban centers within the sub-region (Diogo et al. 2010).

In the study region, urban horticulture is characterized by multiple, overlapping cropping cycles. Tamale is a rapidly growing city in a traditionally agricultural area, where markets for exotic vegetables are expanding (Gyasi et al. 2014). In a separate study, farmers in Tamale annually fertilized six vegetable crops with untreated waste water and mineral fertilizers, applying relatively high rates of 710 kg N, 260 P and 280 kg K ha^{-1} (Akoto-Danso et al. submitted). In a similar study in Ouagadougou, Burkina Faso, the same six crops received 1220 kg N, 250 kg P and 500 kg K in form of manure and mineral fertilizer (Manka'abusi et al. submitted). The observed loss of carbon demands innovative management options to maintain and increase carbon levels in soils (Predotova et al. 2010). One such option could be biochar (Fig. 1). This is carbonized biomass, which, when used as soil amendment, might address the problems of nutrient leaching and carbon depletion (Ding et al. 2016). During the carbonization process relatively labile carbon is converted into aromatic structures with very low decomposition rates (Kuzyakov et al. 2009). This facilitates not only the sequestration of carbon but may also lead to the stabilization of

Fig. 1 Carbonization of rice husks by farmers in the field using the Japan retort (a) and the ELSA barrel (b)

organic carbon and enhanced cation exchange capacity. It has been shown that the addition of biochar can increase nutrient use efficiency and reduce N loss (Steiner et al. 2008). Kimetu et al. (2008) used different organic resources to improve productivity in East African soils. The authors found the greatest improvement on the most degraded sites. Unlike other nutrient-rich organic amendments, biochar addition doubled yields even if nutrient provision was only minor. This indicates that benefits of biochar application to soils reach beyond the provision of nutrients.

There are several interacting mechanisms behind the increases in crop yields that biochar has been credited with, which express in different ways in different agricultural systems. The physico-chemical properties of various biochars are influenced by the feedstock they are made from and the conditions of the carbonization process (Steiner 2016). Elemental composition of the feedstock is, to an extent, reflected in the biochar (Gaskin et al. 2008). The recalcitrant, fixed carbon component of biochar is generally relevant to chemical, biological and physical soil properties. Macropores and micropores in the biochar structure can lower soil bulk density and enhance water availability, which can be particularly relevant for sandy soils (Novak et al. 2012).

While the yield-enhancing effects of soil-applied biochar have been demonstrated in many pot trials and on-station experiments, little has been done to examine the constraints of biochar production and their yield effects in farmers' fields. On-farm biochar production from crop residues is one potential way that farmers could supply biochar. The efficiencies of biochar production with various biochar stoves and feedstocks varies (Brewer 2012), and may also affect the practicability of biochar use in various farm situations.

The use of biochar in arable cropping systems in Africa is challenged by the vast areas of land and the limited availability of crop residues for biochar production. The application of biochar in effective quantities may thus be more feasible in intensive horticultural systems on relatively small plots. On-farm research using elements of participatory methodology is an appropriate way to investigate this. Collaboration and joint learning between farmers and researchers combines the concerns of both groups: a common strategy is for field trials to comprise a researcher-designed, farmer-managed experiment, sited on farmers' fields and gathering their opinion on researcher-defined technologies and parameters.

In view of the above this study aimed at conducting a semi-participatory assessment of simple biomass carbonization techniques and available feedstocks and measured the agronomic benefits for urban vegetable farmers in Tamale, Ghana, where urban horticulture is an important component of the local economy. Our objectives were firstly to evaluate the potential of on-farm biochar production from crop residues and secondly to investigate the relevance of this technology to farmers' economic realities.

2 Materials and methods

The experiment took place in Tamale, capital of the Northern region of Ghana. The site is a rapidly growing city, located in the Guinea Savanna agroecological zone, and experiences a monomodal rainfall pattern. The average annual precipitation of 1111 mm (Häring et al. 2017) is concentrated between June and September. The water table is low and there is no major local natural water body. Municipal water supply, drawn from the White Volta River 40 miles away, is intermittent. To set up the experiments, we used a semi-participatory approach and involved farmers from the design stage of the field trials. As a first step, different methods and different feedstocks for biochar production were tested under controlled conditions. Subsequently, the most promising technology was shown to the farmers to produce biochar themselves and use it in their vegetable fields. They managed the experiment after it was set up, applying biochar to beds and raising the crops to maturity and final market sale. Farmers collected qualitative and observational data, which were verified quantitatively wherever possible. Therefore, the data collection procedure was heavily weighted towards quantitative evaluation of farmers' observations about qualities that are useful to them in their context, following the approach of Hoffmann et al. (2007) to formalize the results obtained from farmers' life-long experiments.

Our experiment therefore contained components of "action research". It was not fully participatory because the researchers introduced the technology to the farmers, rather than responding to the farmers' predefined needs. Thus, it came somewhere between Pretty's (1995) 'functional' or 'interactive participation' and the 'on-farm testing' or 'consultative' types of participation described by (Lambrou 2001). The imperative to interact with farmers to influence the direction of the study means that participatory field trials are necessarily iterative processes. Therefore, preliminary observations informed our decisions about which parameters to measure.

2.1 Biochar production

We based our main biochar production technology on simple top-lit updraft gasifiers, described as an ELSA stove in a construction manual from the Biochar^{Plus} project (ACP-EU Cooperation Programme in Science and Technology II, G.C. FED/2013/330–236, Biochar^{Plus} 2015). We used a modified oil barrel with the same functionality as the ELSA stove as a gasifier (shown in Fig. 1a). Holes at the bottom of the barrel facilitated the flow of primary air from the bottom, and larger holes (6 × 6 cm inward-bent, L-shaped cuts) on the top sidewalls of the barrels facilitated the flow of secondary air. A 20-cm-wide opening was cut into the lid of the barrels and a 1-m tall chimney (riser, metal pipe) was added to the lid. The gasifiers were produced in triplicate [number of replicates (n) = 3] and used to carbonize different types of feedstock. Rice husks ($n = 9$), corn cobs ($n = 6$), wood shavings (n = 6) and peanut hulls (n = 9) were carbonized.

As a second method for biochar production, the "Japan open retort" was tested (Fig. 1b). This method is commonly used in Asia and consists of a chimney with a punched funnel (cone) at one end. The cone was produced using a 60 × 40-cm metal sheet. Approximately 2-cm holes were punched at 5 × 5-cm distances. A 60-cm-high chimney was attached to the cone. A small fire was lit inside the cone and the cone and lower part of the chimney were subsequently buried in rice husks; only the chimney protruded out of the rice husk heap. During constant turning with a shovel, the rice husks turn black and the pyrolysis gases are released through the chimney. The Japan open retort stove is designed for use soley with rice husks.

The carbonization of one feedstock using one or the other technology in triplicate was called a 'run'. Two runs were conducted and measured using the Japan retort. In total, 12 runs were completed using different feedstocks.

2.2 Biochar characterization

For each run, the volume and weight of the added feedstock and produced biochar was measured. The carbonization time was recorded and the conversion efficiency calculated, based on volume and weight of the materials and biochar yield per hour. Dry matter was determined by drying at 60 °C to constant weight. The produced biochar was analyzed for ash, volatile matter and fixed carbon content by proximate analysis following ASTM standards (D 1762–84) with modifications as outlined by (Mukherjee et al. 2011). Volatile matter was measured as the weight loss at 850 °C for 6 min, instead of the 950 °C for 11 min, as stated in the ASTM standards (D 1762–84). Ash content was measured after determination of volatile matter by heating the samples to 750 °C for 6 h. Fixed carbon was determined by the difference.

The pH and electrical conductivity of the biochars were measured in triplicate in deionized water with a biochar-to-water slurry ratio of 1:5 (w:v) following the DIN ISO standard 10390 for soil pH and conductivity measurements. Briefly, a biochar-to-deionized water ratio of 1:5 *w*/*v* was used after shaking with a glass rod for 30 min and allowed to settle for 5 min, after which the glass electrode (WTW, Ingold) with 0.01 M $CaCl_2$ is inserted in the slurry after calibration. One kilogram of rice husk biochar, produced in Ghana, contained on average 6 g of nitrogen, 0.9 g of phosphor, 1 g of potassium, 1.6 g of calcium and 1 g of magnesium (Häring et al. 2017).

2.3 Participatory selection of experimental sites

Five different farming communities near or within Tamale (Northern Ghana) were visited, and the suitability of their fields and their motivation to participate evaluated in April 2015. The main selection criteria were: site not prone to floods, availability of an irrigation source, the farmers' motivation and a minimum field size of 24 m^2. The selected study area is an open space northwest of the center of Tamale and the irrigation water source was potable water. Farmers irrigated crops using watering cans and hosepipes. Irrigation practice varied largely between seasons and crops, and slightly according to soil quality and individual capability. For lettuce, farmers tended to irrigate at least twice daily in the dry season (Oct/Nov–April/May), at dawn and dusk, using 60–90 l of water on each bed of 7–10 m^2. On very sunny days, additional midday irrigation could take place. In rainy season, farmers used the same amount of water after each rainfall event, i.e. every 1–2 days, to remove soil and other dirt from leaves. The experimental fields were established outside the area frequently flooded after heavy rain events close to the dam. The soils were classified as arenosols and lixisols according to the World Reference Base (WRB) classification (2015). Topsoil textures of the selected sites were sand or loamy sand. Lixisols had a sandy loam texture starting between 50 and 90 cm of soil depth.

Twelve farmers were highly motivated to participate and each of them received one carbonization barrel. Having identified in a focus group discussion that rice husks were the most abundant feedstock, they organized their transportation from a nearby mill. The farmers chose to plant lettuce (*Lactuca sativa*) on the experimental plots. Lettuce is a major cash crop for these farmers, and they perceived that increases in its yield could potentially give the highest economic return of all their crops. The agricultural innovation (biochar) rose expectations and therefore even farmers with less fertile soil and not familiar with lettuce decided to plant lettuce. Farmers did not necessarily perform a formal cost-benefit analysis when making this choice; they used their experience and expectation. This reflects the participatory element of the methodology, in that we were guided by farmer perceptions and imperatives, and also confirms the economic motivation of the farmers. Six farmers had fields on lixisols and the other six farmers had fields on arenosols.

2.4 Focus group discussions and observation

Focus group discussions were carried out and recorded in addition to informal conversations throughout the course of the work. One aim of the focus group discussions was to make plans in as a participatory a manner as possible with the farmers, for example, to identify crops and parameters that they found important and would like to measure, and to collect qualitative data on farmers' experiences and observations.

We held six focus groups throughout the course of the experiment. The first took place at the stage when the researchers were choosing the site in which the experiment would take place, on 27.04.2015. The last was held on 11.02.2016. Each was attended by up to 14 farmers. The farmer who spoke the best English acted as an interpreter, and two of the researchers had passable understanding of the local language.

One of the major aims of our study was to tap farmers' knowledge about their practice, in the sense that we asked them to identify parameters that mattered to them and their marketers in terms of making profit, and observe differences in these and other parameters between biochar and non-biochar treatments. Farmers identified important parameters (such as leaf color and stiffness) beyond those that we had originally set out to measure. This information was recorded through informal conversations with the farmers each time the site was visited.

2.5 Design of the field study

The experimental setup was a randomized split-plot design with 12 blocks, represented by the fields of the participating farmers. In the fields of all farmers four main plots (2 × 8 m) were established, which were split into two sub-plots (2 × 2 m) each. Only one side (sub-plot) received biochar; the other did not. Biochar was mixed into the topsoil (0–0.2 m). The farmers produced their rice-husk biochar themselves. From previous testing of the barrels by the researchers, the production capacity of the barrels was known, and the carbonization efficiency was fairly constant. Therefore, we asked the farmers to burn the barrel three times for each biochar plot and mix the biochar into the soil directly after production (on 23.05.2015). The three burns produced on average of 6.8 kg (Table 1) which corresponds to an application rate of 1.7 kg m^{-2}. Seeds were nursed on 17.5.2015. The fields were planted with lettuce on different dates for each farmer, between 8.6.2015 and 12.6.2015. The date of transplanting for each farmer was determined by rainfall and personal labor availability at an average planting density of 38 plants m^{-2}. In line with farmer practice, infilling (replacement of missing seedlings) took place on plots when drought and water shortage caused seedlings to die within the first week of growth. Apart from the addition of biochar, farmers applied their normal practice (NAP) on all plots. This NAP differed between the farmers but they were instructed to treat plots with and without biochar equally. This involved the irrigation practice outlined in section 2.3. Fertilizer was applied 2–3 times during the life of the crop, some days after transplanting, approximately 2 weeks later and possibly again a week later if growth was slow. Farmers preferred NPK fertilizers (15-15-15 or 23-10-10), but used ammonium sulfate or urea if these were unavailable. Application rates could be approx. 300 g of fertilizer per 7–10 m^2 bed. Weeding was practiced at least weekly. Farmers loosened soil around their crops after rainfall or at least weekly in the dry season. As these were the farmers' own commercial plots, there were differences in management between the plots. Such compromises are inherent to participatory

Table 1 Carbonization characteristics, and feedstock and biochar properties of two different carbonization methods and four different waste biomass sources

Feedstock	Feedstock properties			Biochar properties							Carbonization characteristics								
	n	BD DM	H_2O %	*n*	VM %	Ash %	FC %	pH	EC µS	BD BC	*n*	Time (min.)	Vol. FSt (dm^3)	Vol. BC (dm^3)	Weight FSt (kg)	Weight BC (kg)	Eff. ww %	Eff. vv %	Yield kg h^{-1}
Corn cobs	3	0.16	13.2	6	10.2	22.6	67.2	8.7	3480	0.13	6	46.8	180	41.3	28.0	5.4	19.0	23.0	7.3
Peanut hulls	9	0.10	9.7	9	12.3	13.0	74.7	8.7	3151	0.08	9	44.7	144	44.3	13.8	3.6	24.3	30.7	4.9
Rice husks[1]	6	0.11	10.9	6	16.6	50.7	34.9	6.4	385	0.16	3	79.0	108	31.3	12.0	5.0	39.5	29.0	3.8
Rice husks[2]	6	0.11	13.3	9	5.8	64.3	30.0	8.8	414	0.11	9	34.4	54	21.0	5.8	2.3	33.3	38.9	4.2
Wood shavings	6	0.05	11.6	6	15.7	15.7	68.2	9.6	4610	0.07	6	31.8	180	20.1	8.9	1.4	15.5	11.2	2.7

[1] Japan open retort, [2] Biochar produced with a modified oil barrel. *BD*, bulk density (g cm^{-3}); *DM*, dry matter; *VM*, volatile matter; *FC*, fixed carbon; *EC*, electrical conductivity; *min*, minutes; *FSt*, feedstock; *BC*, biochar; *Eff*, efficiency; *ww*, per weight; *vv*, per volume. Not all biochar samples were analyzed; therefore the number of replicates (*n*) differs

research, in order to be able to obtain farmers' observations on the interactions of the technology with their practice.

2.6 Measurements

Plant diameter of lettuce and mortality after infilling was measured 3 and 4 weeks after planting and the fresh biomass recorded after harvesting by a marketer. We also collected information on the qualities that farmers and marketers found desirable in lettuce, and gained their qualitative opinions on the difference between the biochar and non-biochar plots in terms of these. One desirable characteristic cited by farmers was leaf stiffness. We therefore designed a field assay where we measured the strength of different leaves by placing coins with different weights on them and measuring the weight required for the leaf to bend. We also recorded the value of the produce by noting what the marketers paid when they harvested lettuce from each farmer, and asking then to apportion the money between the different biochar and non-biochar beds. A greener leaf color on biochar plots was observed by both the farmers and researchers. In order to corroborate this finding, the total N content of the lettuce plants was analyzed by combustion (Vario MAX CHN Elementar Analysensysteme GmbH, Hanau, Germany). Bulk density of the soil was measured by taking soil samples of a certain volume, measuring dry weight and stone content. Soil moisture content was measured before irrigation and 10 min, 6 h, 12 h, 24 h and 48 h after irrigation using a soil moisture meter (FieldScout TDR 100, Spectrum Technologies, Inc., Aurora, IL, USA) with 7.5-cm rods.

2.7 Statistical analysis

The biochar production methods were compared using a *t* test and the different feedstocks for biochar production using a General Linear Model (GLM) and combined with a Tukey-HSD post-hoc-test. Yield parameters were compared using a paired *t* test (with and without biochar). The soil moisture data was analyzed with a repeated measurements general linear model (GLM) and paired *t* test for individual measurement times. All statistical analysis were done with IBM SPSS Statistics vers. 20.

3 Results and discussion

3.1 Biochar production and characterization

A comparison between the two carbonization methods was possible with rice husks because the Japan stove was designed for this feedstock. The obtained yield per hour and carbonization efficiency did not differ significantly (Table 1), although the Japan retort required more and constant attention and thus was more labor intensive.

The rice husk biochar produced with the Japan retort had a lower ash content but much higher content of volatile matter (Table 1, $p < 0.05$); the content of fixed carbon did not differ significantly. The higher volatile matter of biochar produced with the Japan retort is likely a consequence of the slow smoldering fire, lower temperature (Enders et al. 2012) and release of pyrolysis gases which are not burned (Steiner 2016). The volatile matter might be responsible for the surprisingly low pH (6.4) of the rice husk biochar produced with the Japan retort. The bulk density of rice husk biochar produced in the barrels was lower. This was either also caused by the higher volatile matter content or is a consequence of the constant stirring during carbonization.

The different feedstocks carbonized in the ELSA barrel differed in their properties such as bulk density and particle size, influencing their carbonization efficiency. A certain volume of wood shavings (0.05 g cm^{-3}) had only half the weight of peanut hulls or rice husks. The corn cobs weighed three times as much (0.16 g cm^{-3}). This explains the significantly longer carbonization time of a full load of corn cobs (46 min) compared to wood shavings (31 min) and the significantly higher yield per hour (7.3 kg h^{-1}) compared to wood shavings (2.7 kg h^{-1}). Peanut hulls had a relatively high conversion efficiency. Rice husks had the highest carbonization efficiency (biochar output/feedstock input, volume or weight), however, only because of the high ash (mineral) content of rice husks. Therefore, the ash content of the resulting biochar was also very high (60%). Consequently, the fixed carbon content of rice husk biochar was the lowest (31%). Although having the highest ash content, rice husk biochar had the lowest electric conductivity. The ash consists mainly of silicon, which has little influence on the electric conductivity. A rather large proportion of the minerals in carbonized rice husks seem to be insoluble in water. The ash content of rice husks is 87–97% silica (Kapur 1985), indicating low levels of basic cations such as Ca, Mg, K and Na.

3.2 Biochar production in the field

The density and particle size of the feedstocks influenced how fast and efficiently they carbonized. However, discussions with farmers showed that availability is more important in deciding which feedstock can be used. Farmers determined in a focus group discussion that the most commonly available feedstock in the study environment was rice husks. At harvest, corn cobs were slightly more plentiful, but were also in demand as household fuel. They were less available in some sites than in others, because the farmers here sold their maize fresh rather than allowing it to dry before removing dents from the cobs. The availability of wood shavings was limited. Peanut hulls could be another option to consider for the future, but they were rarely disposed of at one point, and gathering them was harder than obtaining rice husks from a large waste heap beside a mill. The availability of different feedstocks is possibly one of the most important determinants of the appropriateness of each kiln. The Japan stove had been designed exclusively for rice husks. The ELSA barrel, however, worked better with larger items such as corn cobs that packed less densely. It could only require half the volume of rice husks as of any other material, because the rice husks packed too closely together and reduced the gas flux for effective gasification.

The nature of the stove also had other implications. Farmers had diverging opinions about the utility of each stove, rooted in the abovementioned seasonal availability of various feedstocks and related to different annual fertilization strategies. One farmer preferred the Japan retort because it could combust larger quantities of the available rice husks. His strategy would be to produce biochar in large quantities in the dry season and use it throughout the year. He was one of the farmers who declined to produce biochar in the rainy season because the feedstocks they could obtain were too wet. Another preferred the barrel because it could combust a variety of feedstocks, and therefore could be used throughout the year.

Individual labor availabilities also played an important role. The ELSA barrel required two people to turn it over to remove the biochar after carbonization had finished, but did not require supervision during the charring, whereas the Japan stove had to be constantly turned but required only one person (Fig. 1).

Along with feedstock availability, seasonal labor availability, rather than stove efficiency or the physicochemical properties of the biochar produced, could ultimately determine which equipment is used. In Kenya, Mugwe et al. (2009) similarly found that labor availability was a major factor influencing the uptake of innovations.

3.3 Agronomic effects of biochar

The diameter of plants growing on plots with biochar was approximately 1 cm wider than on plots without biochar ($p < 0.001$). Plant mortality was not significantly affected by biochar application. Biochar improved the fresh matter yields of lettuce significantly, with a wide range between farmers. Farmers' individual yields ranged from 0.5 to 7.4 t ha^{-1} and from 0.9 t to 10.7 t ha^{-1} for plots without and with biochar, respectively. The average yield without biochar was 2.4 t ha^{-1} compared to 4.0 t ha^{-1} with biochar (Fig. 2).

All farmers ($n = 8$) had marketable plants on the biochar plots ($n = 32$) but not on the plots without biochar ($n = 24$). Excluding farmers with non-marketable yields, average yields were 3.1 t ha^{-1} on plots without biochar and 5.0 t ha^{-1} on plots with biochar. On a researcher-managed trial in Tamale, an increase of 15% in lettuce yield was measured when soils received 20 t of rice husk biochar per hectare (Akoto-Danso et al., in submission). It is unlikely that improvements in soil fertility are the only reasons for such an increase. It seems plausible that the biochar additions increased

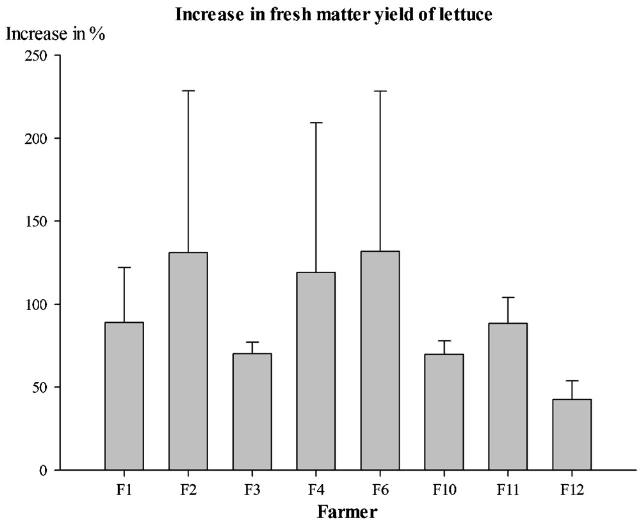

Fig. 2 Increase in yields due to biochar application in comparison to farmer's practice (FP). The twelve participating farmers are F1 to F12. Each farmer had four plots with and four plots without biochar and the proportional yield increases are compared to FP without biochar. Vertical bars indicate +/− one standard error of the mean ($n = 4$)

the farmers' attentiveness towards plots with biochar. Biochar improved early plant growth and this visible difference might have enhanced the attention of the farmers. This is corroborated by three findings from interviews and observations. Firstly, farmers concentrate their resources, primarily fertilizer, water and time used for weeding and loosening soil, where they yield the highest returns. Secondly, they observed that there were less weeds on plots with biochar, although there is no reason why the growth of weeds should be suppressed while crops grow better. Thirdly, farmers have a local practice of loosening the soil with a sharp home-made tool, allowing water and air infiltration to reach plant roots. Farmers observed during this loosening and during weeding that it was easier for them to break soil crusts on biochar plots. The silt-rich soil in the study site was characterized by a labile soil structure which is susceptible to surface crusting. It is known that organic matter can reduce surface crusting (Le Bissonnais and Arrouays 1997). Thus, it is possible that work time was more productive on plots with biochar, and farmers also invested more time and effort on biochar plots. This behavioral biochar effect might be enhanced by the fact that entire beds are sold and not individual salad plants. If a bed does not promise a marketable yield, it is likely abandoned or managed with less effort.

The farmers not only produced higher yields with biochar, but also sold their crops for a higher price. The average value for lettuce on plots without biochar was 2.3 (SE = 0.4, $n = 32$) Ghana cedi (GHS, 1 GHS = approx. 0.25 USD at the time) and on BC plots 5.6 GHS (SE = 0.8, n = 32). This is rather remarkable and was not only explained by the higher yields but also by a better appearance (quality) of crop. The improved qualities noted by farmers and marketers on biochar crops included stiffer leaves, which were preferred by consumers because they were perceived to promise a better shelf life. The farmers felt the lettuces with their hands, and discovered that the plants on the biochar fields were firmer than those on the non-biochar fields. During the marketing of the harvested lettuce, the market women confirmed these differences in toughness. Leaf stiffness, measured in terms of weight applied before the leaf bent, was 0.12 Newton for lettuce grown without biochar and 0.22 Newton for lettuce grown with biochar.

The marketable yield was described by the market women as those leaves that are deep green, spotless, broad, firm, fresh and pest and disease free. Leaves with these qualities did not necessarily command a higher price in the market but market women were more eager to buy them at the farm gate because they were less likely to lead to losses from waste. Farmers noted that, as well as having firmer leaves, the spots that appeared on lettuce in the dry season were less plentiful in biochar fields, and that the color was a deeper green, although total N analysis did not show a higher N concentration of plants growing on biochar plots.

The bulk density of the soil was not influenced by biochar addition, but the moisture content, which is generally low in the sandy soil, was significantly higher (Fig. 3). There was only a small difference in volumetric moisture content between the treatments, but the size of the difference should be seen in relation to the soil and crop characteristics. Without plants the difference might even be larger, as the larger plants on biochar plots consume more water and counteract the measured differences. Novak et al. (2012) suggested that biochar has a propensity to improve moisture content of soils, conjecturing that this could be more useful in sandy soils such as found in the study area.

One of the most important findings for farmers was that lettuce grown on plots where biochar was incorporated was able to last up to 2 days longer on the field after maturity, without wilting.

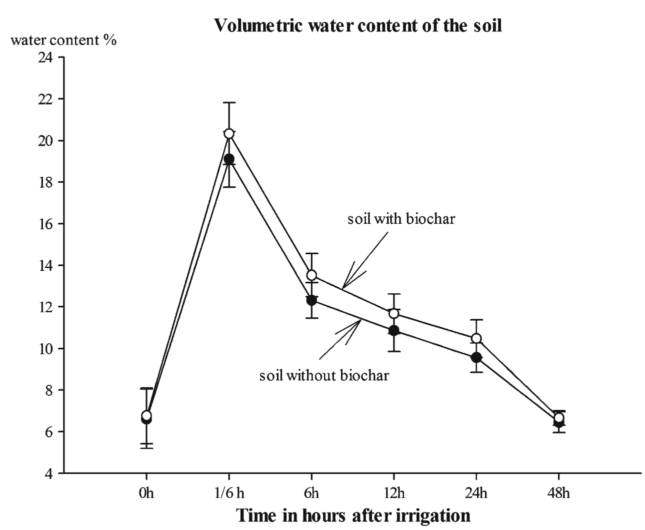

Fig. 3 Volumetric moisture content before (0 h) and after irrigation, means and +/+ one standard error ($n = 24$). Significant differences between FP and FP + biochar were found at 6 h and 24 h (paired t test) and for the entire time using repeated measurements GLM

The farmers described this as 'buying time'. They explained that this was especially important in the season when lettuce was abundant in the market and it was difficult to find a buyer. It allowed them to negotiate with marketers in order to get a better price. This commonly happened in the *Harmattan season*, the cool, windy and dry period that falls between November and February, and was the most important factor, more so than the other quality characteristics above, in determining price. The longer stay of matured lettuce could possibly be related to the ability, noted by farmers, of soil amended with biochar to retain moisture longer.

3.4 Biochar production costs

In this experiment, yield increased when biochar was added to FP. However, this entailed additional costs. The cost of an ELSA barrel was 140 GHS (32 USD) and that of the Japan retort 60 GHS (15 USD). An individual farmer's payback time for using this technology would depend on the endurance of the equipment and biochar, the number of beds they cultivated in this time and the application rate. Data from interviews indicated that farmers could earn a profit of 12–23 GHC per bed, after costs of fertilizer and other inputs were accounted for. Farmers such as those who participated in our experiment cultivated 6–10 beds of lettuce per month. The average yield increase from biochar application was 93% (Fig. 2). Such farmers could therefore expect to recoup the cost of an ELSA barrel in 2 months and a Japan stove in 1 month, while making 12 GHC profit per bed.

The results of such a conventional cost-benefit analysis should be treated with caution and in combination with other data already presented. In particular, the results above on marketable yield show that bed price is not the only element relevant to farmers and marketers economic reality: marketers could select beds appearing to contain fresher, greener and stiffer lettuces with the expectation that they would have a longer shelf life. Making a financial cost-benefit analysis is also less relevant when farmer labor is not costed, and absolute affordability of a tool is more likely to be a decisive factor in its adoption than efficiency or payback time. The duration of the study was not long enough to estimate the life-time of the carbonization devices. They are still functional after 2 years of use, however, the frequency of use will influence the durability.

A question for future research thus remains the balance between profit and labor cost, and also the potential reductions in the necessary fertilizer costs that could contribute towards offsetting labor costs. It is unknown how much of the yield effect in this case was from biochar's own nutrients, retained nutrients from fertilizer, improved soil physicochemical properties or farmer reactions to the technology.

3.5 Evaluating biochar technology in context

A visit to the field site a year after the experiment ended revealed that two of the 12 participant farmers had produced and applied biochar since the end of the experiment, showing that some individuals had assessed it as a relevant technology. Participatory models of smallholder innovation emphasize the role of demand in driving technological innovation and adoption (Scoones and Thompson 2009), and therefore pose that a technology such as biochar is not likely to be adopted by all farmers who come into contact with it. For the remaining 10 farmers in the sample, indications were that their existing soil management practice sufficed, and they did not consider that the work entailed in producing biochar was recouped by the benefits.

The best solution for individual farmers was dependent on the interaction of labor and feedstock availability, in relation to seasonal market trends, and quality, as well as yield imperatives. The combination of these factors seemed to mean that rice husk biochar was most practicable for these farmers, and their choice between the Japan and ELSA stoves would be made according to available labor and feedstock, each determined seasonally.

The degree of market orientation of farmers likely plays a role in their reaction to technology. These farmers were typically profit-oriented, yet risk averse. This was seen in their negotiations with researchers over how to run the experiment. They chose lettuce as the test crop because it was a commercial crop and they were interested in the effects of biochar on their cash income: these farmers concentrated their resources where they yield the largest returns.

The process of carrying out this experiment on-site reinforced the importance of acknowledging the structural landscape of a given farming situation. Participating in farm practice gave the researchers first-hand experience of the structural resource constraints that farmers have to contend with, and the importance of a technology being practicable in situations of dearth. One of the challenges that the farmers faced in this area was frequent water shortage which led to the death of plants on some of the experimental fields in hot weather. Such conditions can, however, indicate important reasons that a particular technology is deemed appropriate at a certain point in space or time: this water constraint emphasizes the relevance of biochar's apparent ability to retain soil moisture. Irrigation water is especially critical for farmers in Tamale, where average rainfall is moderate, but concentrated in a single season, making dry-season vegetable farming dependent on irrigation. With no viable groundwater sources in the vicinity, farmers such as those in the study site rely on municipal supplies of potable water. Section 2.3 described the diurnal watering patterns necessary in the dry season, and the reasons for maintaining irrigation even in the rains. These irrigation patterns become impossible when municipal water supplies are interrupted for more than 24 h, something which happens every month to 3 months in the study context.

This result highlights biochar effects that may not have occurred in a controlled experiment, and shows the importance of semi-participatory on-farm trials. Scientific field trials often control for side conditions which are a key component determining the performance of a technology under on-farm conditions. One of the values of research with a participatory element is the extent to which it can show how technology interacts with real structural constraints. Our research was carried out in an agricultural system well-suited for biochar application. We involved farmers' perceptions in agronomic research on biochar, which is lacking after more than a decade of biochar research. From this, we are able to identify the effects of biochar that have relevance to their economic situation.

4 Conclusions

Biochar has potential for use by urban West African vegetable farmers, and doubled yield on average in our participatory field trial on lettuce. There may be some potential for such farmers to produce their own biochar on-farm, although various factors must be considered in deciding whether this methodology is appropriate in a particular context. The type of feedstock available will have implications for the type of carbonization technology used and for biochar quality. There likely will be different appropriate technologies in different seasons and for different crops. Other factors that determine whether and how on-farm biochar production and use is practicable include availability of resources, including labor and infrastructure, market quality and yield imperatives, and social relations, for example, between farmers and marketers. Benefits related to soil physical qualities are likely to be as important as those relating to soil chemistry and fertility. Further, the agronomic effects might also be linked to biochar-induced management changes.

Assessments of the complex interaction of various agronomic, economic and social factors involved in decisions about on-farm biochar technology is missing after more than 10 years of biochar research. Our novel, interdisciplinary and semi-participatory approach has succeeded in identifying some of the advantages and possible modes of use of biochar technology for West African small-scale horticulturalists. This implies that a systems approach should be taken for future research in this area.

Next steps should be to investigate mechanisms for some of the useful effects of biochar that were identified here, such as higher soil moisture, and the differential importance of this effect for various market and non-market crops, with varying perishability. Quantitative measurements of other potentially beneficial qualities, such as preferred color, could also be made. Finally, farmer-led production of the biochar production apparatus could also be investigated, alongside their willingness to pay for such technology.

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