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Multi-year double cropping biochar field trials in Nepal: Finding the optimal biochar dose through agronomic trials and cost-benefit analysis

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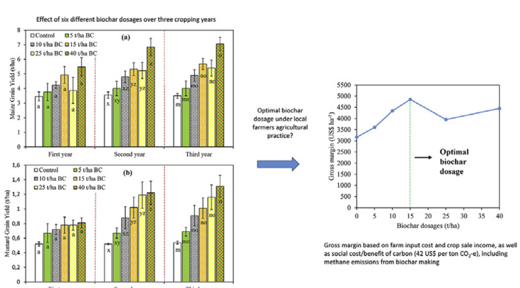
HIGHLIGHTS

- Field trials with six biochar doses were carried out in a silty loam soil, Nepal
- A maize-mustard field cropping system was applied over three years (six seasons)
- Biochar addition showed effects on crop growth during the second and third year
- Cost-benefit analysis included health cost, climate cost and agronomic cost
- The optimal biochar dose was 15 t ha^{-1} from an agronomic and economic perspective

GRAPHICAL ABSTRACT



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ABSTRACT

Poor water and nutrient retention are the major soil fertility limitations in the low productivity agricultural soils of Nepal. The addition of biochar to these soils is one way these hindrances can be overcome. In the present study, six different biochar doses (control, 5 t ha^{-1}, 10 t ha^{-1}, 15 t ha^{-1}, 25 t ha^{-1} and 40 t ha^{-1}) were applied to a moderately acidic silty loam soil from Rasuwa, Nepal and the effects on soil physicochemical properties and maize and mustard yield over three years (i.e., six cropping seasons), were investigated. Biochar addition did not show significant effects on maize and mustard grain yield in the first year, however significant positive effects ($p < 0.01$) were observed during the second and third years. During the second year, maize grain yield significantly increased by 50%, 47% and 93% and mustard grain yield by 96%, 128% and 134% at 15 t ha^{-1}, 25 t ha^{-1} and 40 t ha^{-1} of biochar respectively. A similar significant increase in yield of both crops was observed in the third year. Yields for both maize and mustard correlated significantly ($p < 0.001$) with plant available P, K^+, pH, total OC%, CEC, base saturation, and increased as a function of biochar addition.
On the basis of the measured crop yields for the various biochar doses, a cost-benefit analysis was carried out, and gross margin was calculated to optimize biochar dose for local farming practice. Total costs included financial cost (farm input, labor and biochar production cost), health cost and methane emission cost during biochar production. Health costs were a minor factor (<2% of total biochar preparation cost), whereas methane emission costs were significant (up to 30% of biochar cost, depending on the C price). Total income comprised sale of crops and carbon sequestration credits. The cost-benefit analysis showed that the optimal biochar application dose was 15 t ha^{-1} for all C price scenarios, increasing gross margin by 21% and 53%, respectively, for 0 and 42 US$

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per ton CO_2 price scenarios. In the current situation, only the 0 US$ price scenario is realistic for rural farmers in Nepal, but this still gives benefits of biochar amendment, which are capped at a 15 t ha^{-1} biochar addition.

1. Introduction

Biochar, the carbonaceous product from pyrolysis of biomass (Lehmann, 2007) has received much interest as it is able to abate two major global challenges, i.e., sustainable enhancement of soil fertility and climate change mitigation (Chan et al., 2008; Lehmann et al., 2006). Several studies have confirmed significant improvement of soil chemical properties such as increased soil pH, cation exchange capacity (CEC), exchangeable calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+) and soil organic carbon (SOC) upon biochar addition to soil (Chan et al., 2008; Lehmann and Rondon, 2006; Liang et al., 2006; Martinsen et al., 2014; Yamato et al., 2006). In addition, biochar amendment has shown positive effects on plant available water (Herath et al., 2013; Mukherjee and Lal, 2013; Obia et al., 2016) and microbial activity (Atkinson et al., 2010). Biochar has a recalcitrant nature and remains stable in soil for many years, thus, acting as an effective C sequestration technique combating climate change (Lehmann et al., 2006; Zimmerman, 2010). However, biochar addition does not have a uniform effect on soil fertility and carbon stability, and may vary with feedstock, pyrolysis condition, soil, climate, and crop type (O'Connor et al., 2018; Zhao et al., 2018).

A meta-analysis carried out by Jeffery et al. (2017), reported an average increase in crop yield of 25% mainly due to liming (increased pH) and nutrient addition effects of biochar in low fertile tropical soils. In a sentinel study from Sumatra, Indonesia, the addition of 20 t ha^{-1} increased soil pH (from 3.9 to 5.1) and reduced soil Al^{3+} concentration from 2.67 $cmol_c\ kg^{-1}$ (toxic level for plant growth) to 0.12 $cmol_c\ kg^{-1}$ (Yamato et al., 2006). Increased pH upon biochar addition is known to increase plant available phosphorous (P-AL) (Hale et al., 2013) and directly adds K^+ to tropical soils (Martinsen et al., 2014; Pandit et al., 2018). Soil nitrogen has also been observed to be higher in biochar-amended soils due to reduced leaching and absorption of N into biochar pores (Kammann et al., 2015; Laird et al., 2010).

The majority of biochar crop effect studies have been performed in field trials or pot trials that have been carried out for a single cropping cycle. However, longer-term studies with more cropping cycles are needed to examine the yield effect of biochar addition (Griffin et al., 2017).

Despite positive agronomic and environmental effects of biochar amendment in tropical soils (Jeffery et al., 2017), there are very few studies where explicit attempts were undertaken to analyze the feasibility of the biochar application i.e. agronomic, environmental and financial benefit of using biochar under small-scale normal farmer agriculture practice (Joseph, 2009). Financial return is often the main indicator used by farmers when they make decisions related to whether or not to adopt biochar amendment in their cropping system (Bach et al., 2016). Inadequate analysis of detailed cost-benefit effectiveness of biochar application may deter farmers from using biochar as a soil amendment (Joseph, 2009; Pratt and Moran, 2010). In addition, it is not easy to convince farmers from developing regions to adopt new farming practices (Bach et al., 2016). For example, though clean burn flame curtain kiln charring was introduced in Indonesia, farmers were reluctant to use this technology unless its financial and agronomic returns were made clear (Smebye et al., 2017). In a previous study, low profit was derived when only agronomic values were taken into account (Bach et al., 2016). Higher economic returns are achieved when soil carbon sequestration benefits of biochar are considered, as they offset biochar production costs that include negative environmental and health impact cost (gas and aerosols emissions) during biochar making (Sparrevik et al., 2014). However, considerations on various carbon price regimes are currently of an academic nature for rural Nepal, as the actual payment of such credits is not likely in the foreseeable future.

In Nepal, low soil productivity (low P, organic C, base saturations, CEC), rain-fed subsistence farming systems, irregular rainfall patterns and a shortage of fertilizer has severely affected the status of crop production (Brown et al., 1999; Schreier et al., 1994). Farmers have poor access to chemical fertilizers and imported mineral fertilizers are quite expensive (Shrestha and Pandit, 2017). To cope with such challenges, it is essential to develop more efficient soil management strategies that increase crop production per unit of land (Brown et al., 1999). One alternative to overcome such limitations could be the application of biochar and farm yard manure (FYM) (Schmidt et al., 2017).

So far, the effect of biochar on soil fertility and crop production has only been studied for a single cropping season in one Nepalese soil (Schmidt et al., 2015, 2017). In addition, research on the optimal biochar dose and socio-economic aspects of biochar application are scarce. To fill this knowledge gap, the long-term fertility and economic effects of *Eupatorium* biochar amendments were investigated. A six-season trial for two crops (maize and mustard), at six different biochar doses amended to a moderately acidic silty loam soil of Rasuwa, Nepal, representative of significant parts of the country's agricultural land (Collins and Jenkins, 1996), was carried out. Biochar addition in this soil has been shown to have positive effects on maize biomass production in a greenhouse pot experiment, due to improved nutrient retention capacity (available P and K^+) (Pandit et al., 2017). In the present study, the optimal biochar dose was examined both with regard to agronomic effectiveness and financial profitability. To address the profitability, a cost-benefit analysis was carried out on the basis of the observed crop yield, including health and climate costs of gas and aerosol emissions from biochar production, as well as C sequestration benefits, using a variety of carbon prices from zero to full social cost of carbon (E.P.A. Fact Sheet, 2013). Previous studies that have taken both the climate cost of methane emissions and the health cost of aerosol emissions during biochar production in to consideration are scarce. Biochar stability was also investigated via a limited number of benzopolycarboxylic acid (BPCA) analyses, which represent the condensed aromatic C (pyrogenic carbon) content of soil.

2. Materials and methods

2.1. Study area

The experimental site (28°, 10″, 0′ N and 85°, 11″, 0′ E) was at an altitude of 1378 m above sea level (Fig. S1) in Rasuwa 115 km north of Kathmandu, Nepal. The study area receives 1850 mm average annual rainfall (receiving highest precipitation in June/July and lowest in November/December) and has a mean annual temperature of 15.4 °C (Rasuwa District Profile, 2013). Nepal has 75 districts. Each district is further divided into village development committees (VDC). The study area is within the Nilkantha VDC, which is one of the 18 VDC's in Rasuwa district. Nepal is divided into 5 development regions and the study area is in the central development region. Nepal is also divided into 14 zones and the study area is within the Bagmati zone, where common agronomic cereal crops encompass maize, mustard and wheat.

2.2. Biochar production

The invasive ubiquitous forest shrub *"Eupatorium adenophorum"* was used as a feedstock for biochar production. Shrubs of about 1–2 m high with stems up to 2 cm thick were cut. Eupatorium is unpalatable to livestock and has a negative impact on livelihood sustainability, food security and ecosystem management (Kunwar, 2003). In this study, *Eupatorium* feedstock was collected from community forest areas, farm uplands/lowlands and river banks (Image S1). The whole Eupatorium plant (feedstock), about 40 cm long, was used for making biochar. Following production, the biochar applied in <10 mm chunks, and was not ground or sieved. Biochar was produced with a traditional earth mound kiln (Image S2) with pyrolysis temperature of 450–500 °C. Elemental analysis of the Eupatorium was carried out using an *EuroEA Elemental Analyzer* and the biochar had an elemental content of 42.9% C, 1.4% H and 1.5% N (Table 1).

2.3. Experimental set up and cultivation practices

A private agricultural rain-fed upland area (Image S2) with low soil pH (4.6) and CEC (6.4 $cmol_c\ kg^{-1}$) was selected for the field trial (Table 1). Twenty-four plots of 10 m^2 each were established on a flat area without shading trees, with 1 m spacing between plots. Six treatments with four replications ($n = 4$) were assigned in four blocks in a completely randomized design (CRD). Six different biochar doses were used; 0 kg, 5 kg, 10 kg, 15 kg, 25 kg and 40 kg per 10 m^2 plot, equivalent to 0 ton ha^{-1} (control), 5 ton ha^{-1}, 10 t ha^{-1}, 15 t ha^{-1}, 25 t ha^{-1} and 40 t ha^{-1} respectively. Higher doses (25 t ha^{-1} and 40 t ha^{-1} biochar) are not realistic from a farmers perspective, but were included for scientific reasons, i.e., to provide more data points for correlations between biochar amendment rates, crop yields and soil characteristics. All treatments including the control received equal amounts of mineral fertilizer N (in the form of urea; 60 kg N ha^{-1} after 60 d) and farmyard manure (a composted mixture of cow manure and greenwaste, 30 t ha^{-1} wet weight) according to farmers practice. During land preparation, biochar and manure were spread evenly followed by tillage (15 cm soil depth) and harrowing practices in all treatment plots. Terracing and drains were built in the side of the plots to conserve the top soil of each plot and to prevent erosion. The field trial was set up in April 2014. Each year, maize was grown in the wet season (April to August) followed by mustard in the dry season (September to February). This cropping pattern (maize-mustard) was continued for three years (until February 2017).

After a week of land preparation, maize seed (*Arun variety*) was sown at a depth of 5–6 cm following 30 cm × 30 cm spacing within each treatment plot. Hand weeding was carried out twice (30 d and 60 d). Upon maturity, maize plants were harvested manually and a month after maize harvest, mustard seeds were broadcast in equal quantity in all 24 plots. Manure and N were applied each year during maize cultivation (first, third and fifth season) but not in the following cropping season (second, fourth and sixth season with mustard) according to farmers practice. Biochar was applied only once at the onset of the trials (April 2014; first year, first season) and was not applied in the subsequent seasons and years.

Table 1
Characterization of Eupatorium feedstock, biochar, manure and soil used in the field trial.

Properties	Feedstock	Biochar	Manure	Soil[a]
pH_{CaCl2}	–	9.3	–	4.6
pH_{H2O}	–	–	–	5.1
CEC ($cmol_c\ kg^{-1}$)	–	72	–	6.4
BS[b] (%)	–	–	–	74
Ca^{2+} ($cmol_c\ kg^{-1}$)	–	18	–	3.2
Mg^{2+} ($cmol_c\ kg^{-1}$)	–	13	–	1.2
K^+ ($cmol_c\ kg^{-1}$)	–	36	–	0.2
Al^{3+} ($cmol_c\ kg^{-1}$)	–	–	–	0.7
Ca/Al ratio	–	–	–	4.5
Total organic C %	42.9	70	30	1.6
Total H %	1.4	1.1	0.9	0.48
Total N %	1.5	0.46	1.6	0.18
Total P (g kg^{-1})	–	–	6.2	–
Total K (g kg^{-1})	–	–	25.3	–
Available P mg kg^{-1}	–	–	–	12
Surface area	–	74.6	–	–
Textural class	–	–	–	Silty loam[c]
Order	–	–	–	Inceptisol

[a] Soil test before operating field trial experiment.
[b] Base saturation.
[c] Silty loam with 33% sand, 50% silt and 17% clay.

2.4. Soil sampling and analysis

Before trial establishment, the soil was collected from 24 locations within the farm to make a composite sample that was analyzed for pH, CEC, total organic carbon % (OC %) and nitrogen (N %) (Table 1). The sampled soil was a silty loam Inceptisol (33% sand, 50% silt and 17% clay). After the fifth seasons harvest, three soil samples from different locations within each plot were collected to make a composite soil sample for each of the treatments (4 samples per treatment consisting of triplicate samples within the plot). Soil samples were collected from 5 to 10 cm depth with the help of a small auger. Soil samples were oven dried at 105° C for 24 h, passed through a 2 mm sieve and crushed (<2 mm) prior to analysis. Soil pH was measured in both water and 0.01 M $CaCl_2$ (1:2.5, solid to solution ratio) using an Orion 1 Ross pH electrode. For CEC, soil was extracted with 1 M NH_4NO_3 at pH 7 and the individual exchangeable cations (Ca^{2+}, Mg^{2+}, Na^+, K^+ and Al^{3+}) were measured using inductively coupled plasma optical emission spectrometry (ICP-OES). Exchangeable H^+ was determined by titration the extract with 0.02 M NaOH to pH 7. Total CHN analysis was carried out with a CHN analyzer (LECO, Truspec).

In order to explore the stability of the biochar under field conditions, soil from the control and 40 t ha^{-1} field aged biochar plots, along with the fresh non-aged biochar, were subjected to BPCA analysis following the methods of Brodowski et al. (2005) and Dittmar (2008) with modification. Briefly, samples were digested in 4 M trifluoroacetic acid (TFA, 105 °C, 4 h) to remove metals and polyvalent cations. Residue were then extracted in 0.5 mL of 65% HNO_3 at 170 °C for 8 h under high pressure and purified using Dowex cation exchange resin (50 W, 200–400 mesh). Finally, BPCA compounds (B3CA to B6CA with 3 to 6 carboxyl group substituents, respectively) were identified via HPLC-DAD using certified standards.

Plant available phosphorus (P-AL, mg kg^{-1}) and plant available water (PAW, vol%) were measured in three plots (control, 10 t ha^{-1} and 40 t ha^{-1}) to assess the effect of biochar addition on P availability and water retention capacity respectively. The other biochar doses were not included in these analyses due to financial constraints. Available (ammonium lactate extractable) phosphorus (P-AL) was measured according to Krogstad et al. (2008). For PAW measurements, soil sample rings were filled in the laboratory and saturated. Soil water was measured at different matrix potentials (pF 2, field capacity and pF 4.2, wilting point) using ceramic pressure plates (Martinsen et al., 2014; Obia et al., 2016).

2.5. Biochar and FYM characterization

Biochar samples (oven dried) were analyzed in the same way as soil samples, for pH, CEC and total CHN. In addition, biochar surface area was determined using a Quantachrome Autosorb1 surface area analyzer. N_2 adsorption isotherms were measured at 77 K and interpreted using the Brunauer, Emmet, and Teller (BET) theory. The biochar used in this experiment had a pH $_{CaCl2}$ of 9.3, an organic carbon content of 70%, CEC of 72 $cmol_c\ kg^{-1}$ and a surface area of 74.6 $m^2\ g^{-1}$ (Table 1).

Manure samples (oven dried) were analyzed for total CHN % as for soil samples. To determine total elemental P and K analysis, manure samples (0.25 g) were first decomposed in ultrapure nitric acid using an ultraclave at 260 °C and 50 bar. After decomposition, samples were diluted with deionized water to 50 mL and analyzed using a microwave assisted nitrogen plasma instrument (Agilent 4200) via selective atomic lines (213.618 nm for P and 769.897 nm for K). The manure had an organic carbon content of 30%, a total N content of 1.6%, a P content of 6.2 g kg^{-1} and a K content of 25.3 g kg^{-1} (Table 1).

2.6. Crop yield analysis

Upon maturity, maize and mustard plants were harvested manually from all plots on the same day. Maize and mustard above ground biomass and grain yield was measured immediately after harvest and dry weight was calculated after oven drying at 70 °C for 24 h.

2.7. Economic analysis of biochar amendment

Cost-benefit analysis of the application of biochar at six different doses for three subsequent years (2014 to 2017) under maize and mustard cropping system was performed on the basis of the agronomic results obtained. The agronomic costs included farm inputs (seeds, urea and manure) and labor for land preparation. Biochar production costs included labor for feedstock harvest and collection, kiln construction and operation as well as the health cost of gas (CO) and aerosol (smoke, $PM_{2.5}$) emissions during biochar making (analogous to Sparrevik et al. (2014)). The biochar was made by the farmers, as biochar with the intention of soil amendment use is never bought at market, in contrast to charcoal for cooking purposes. Health costs arising from the preparation of biochar are challenging to estimate, and calculations here are based on data for the health cost of indoor air pollution in Arcenas et al. (2010) and Malla et al. (2011), obtained using the methodology of Sparrevik et al. (2014). Arcenas et al. (2010) reported data for Indonesia, the Philippines and Timor Leste, the latter having a Gross Domestic Product far closer to that of Nepal than the other two. Health cost due to air pollution were comprised of around 50% (Arcenas et al., 2010) to 80% (Malla et al., 2011) of acute lower respiratory infections (ALRI), the rest dominated by chronic obstructive pulmonary disease (COPD). For Timor Leste the cost of indoor air pollution was calculated to be 15 to 60 US$ per household per year (Arcenas et al., 2010). Malla et al. (2011) summed the economic health benefits of switching to clean stoves in Nepal, and found these to be around 7 US$ per household per year, mainly as a result of time saved as sick people did not need to be taken care of. Assuming 2 h of daily indoor air pollution exposure through cooking (700 h per year), and 40 h of labor to make 1 ton of biochar, as well as the exposure from indoor cooking being equivalent to that of outdoor biochar making (a conservative estimate), the health cost of making 1 ton of biochar can be estimated to be 0.4 to 3.4 US$. In the calculations, a health cost of 2 US$ per ton biochar was assumed. This number is subject to a high degree of uncertainty, but this uncertainty is relatively low in comparison to the total cost of making biochar (144 US$ per ton).

Novel for this work in comparison to previous work, is that the climate cost of CH_4 emissions (taking into account the 27-fold higher global warming potential of CH_4 compared to CO_2) during biochar making were taken into account (Smebye et al., 2017; Sparrevik et al., 2015). Here, CH_4 is assumed to be a 27 times stronger GHG than CO_2 and that on average 0.049 tons CH_4 is emitted per ton of biochar produced (Cornelissen et al., 2016; Sparrevik et al., 2015). Thus, the GHG from CH4-emissions in CO2-equivalents per ton biochar is $0.049*27 = 1.32$ CO2-e. The gas emissions from a flame curtain kiln were used in the cost-benefit analysis, as this novel production method is the one of choice in practice and far preferable to traditional kilns, due to low gas and aerosol emissions, as well as quick and easy operation (Cornelissen et al., 2016). However, financial costs of making biochar, agronomic effects of the resulting biochar, as well as methane emissions, have previously been reported to be similar for traditional and flame curtain kilns (Cornelissen et al., 2016). Only CO emissions and resulting health effects were shown to be higher for traditional kilns. Thus, the outcome of the cost-benefit analysis would not have been affected to a large degree by the choice of biochar production method (gross margins being maximally 5% lower, with the same trends between C price scenarios and biochar doses). Income was calculated from crop sale (both maize and mustard) and possible carbon sequestration benefits at various C prices. Effects on biomass production from the application of biochar were not included in the cost-benefit analysis, as biomass is mainly used for fuelwood or forage. There is no tradition of buying and selling the biomass of maize or mustard in Nepal. Thus, no standard price could be set for the biomass. Details of all costs are given in the SI (Table S3 and S4). Gross margin/profit of biochar-inclusive farming calculated as Total income - Total cost as a function of biochar dose, assuming no cost of carbon, as is the current situation. In addition, two carbon prices were used in calculations, the current voluntary carbon market price (US$ 6 per ton CO_2) as well as a medium “social cost of carbon”, SCC, of US$ 42 per ton CO_2 (SCC at 3% discount rate and emitted in 2020) (E.P.A. Fact Sheet, 2013).

2.8. Statistical analysis

Data were analyzed using R software version 3.2.2. Normality and homogenous variances of all data sets were tested with Shapiro-Wilk – and Levene's test, respectively. One factor fixed effect ANOVA model was used to assess the effect of biochar addition on soil properties and crop yield for all three-year harvest. Post hoc Tukey test (pair wise comparison at $P = 0.05$) was performed to assess the least significant difference (LSD) between the treatment means. Paired *t*-tests were used to assess the effect of biochar between three-year crop harvests grown in respective treatment plots. A linear regression model was used to identify the relationship between various soil physicochemical properties and crop yield (third year) at a given level of biochar addition.

3. Results

3.1. Effect of biochar addition on soil fertility

Soil pH $_{CaCl2}$ was significantly increased ($p < 0.001$) at all levels of biochar addition. Related to this, the average Al/Ca ratio was significantly reduced upon biochar addition above 10 t ha^{-1}, from a relatively low value of 0.21 without biochar addition. Soil CEC was significantly increased upon 40 t ha^{-1} BC addition compared to the control soil. Exchangeable base cations (Ca^{2+}, Mg^{2+}, K^+) were significantly increased at all levels of biochar addition; however, base saturation was already high without biochar addition (74%).

Biochar additions showed significant effects ($p < 0.001$) on plant available phosphorous (P-AL) which increased by 92% and 440% upon the amendment of 10 t ha^{-1} and 40 t ha^{-1} of biochar, when compared with the control soil, respectively (Table 2). Similarly, soil moisture retention at field capacity and plant available water were significantly increased upon 40 t ha^{-1} biochar addition compared to the control soil.

3.2. Effect of biochar addition on soil carbon (SOC)

Biochar addition showed significant effect on SOC at all levels of biochar addition except the lowest dose (5 t ha^{-1} BC). Assuming that biochar addition did not have, or only had minor effects on soil bulk density (around 3–5% per % biochar added, i.e. <10% for all biochar doses (Obia et al., 2016), the addition of manure containing 30% C to the soil with a C % of 1.6% should have resulted in 1.9% C in the control soil. Addition of biochar with 70% C and manure with 30% C to soil containing 1.6% C (Table 1) in the five treatment plots i.e. 5 t ha^{-1} BCE (0.25%), 10 t ha^{-1} BC (0.5%), 15 t ha^{-1} (0.75%) BC, 25 t ha^{-1} BC (1.25%) and 40 t ha^{-1} BC (2%), should have resulted in around 2.01% SOC, 2.25% SOC, 2.41% SOC, 2.66% SOC and 3.30% SOC, respectively. These values were fairly close to the measured values of 1.82%, 2.01%, 2.42%, 2.65% and 4.99% SOC respectively (Table 2). Thus, biochar addition resulted in additive effects on SOC over the relatively short time period of

Table 2
Soil properties at different biochar doses for soil samples taken after the 5th season (2.5 year); mean ± sd, $n = 3$. Different letters within the same column represent significant differences between soil properties for the various treatments according to a one factor ANOVA (post hoc-Tukey test, $P = 0.05$).

Soil	Treatments					
Properties	0 t ha^{-1} BC (control)	5 t ha^{-1} BC	10 t ha^{-1} BC	15 t ha^{-1} BC	25 t ha^{-1} BC	40 t ha^{-1} BC
pH_{H2O}	5.14 ± 0.02a	5.29 ± 0.01b	5.24 ± 0.02b	5.46 ± 0.01c	5.55 ± 0.02d	5.70 ± 0.03e
pH_{CaCl2}	4.62 ± 0.01a	4.74 ± 0.01b	4.73 ± 0.01b	4.92 ± 0.01c	4.94 ± 0.02c	5.11 ± 0.03d
CEC ($cmol_c$ kg^{-1})	6.40 ± 0.28a	6.45 ± 0.10a	6.68 ± 0.09a	7.02 ± 0.38a	7.18 ± 0.17a	8.38 ± 0.52b
BS[a] (%)	74.3 ± 4.5a	76.0 ± 5.2a	80.7 ± 2.4a	91.0 ± 2.6bc	92.7 ± 2.5bc	96.3 ± 0.6c
Ca^{2+} ($cmol_c$ kg^{-1})	3.22 ± 0.05a	3.54 ± 0.06b	3.73 ± 0.07c	4.47 ± 0.24d	4.61 ± 0.00e	5.74 ± 0.48f
Mg^{2+} ($cmol_c$ kg^{-1})	1.22 ± 0.04a	1.31 ± 0.00b	1.38 ± 0.00c	1.66 ± 0.00d	1.73 ± 0.00e	1.96 ± 0.04f
Na^{+} ($cmol_c$ kg^{-1})	0.03 ± 0.01a	0.04 ± 0.01a	0.04 ± 0.02a	0.04 ± 0.02a	0.03 ± 0.00a	0.05 ± 0.01a
K^{+} ($cmol_c$ kg^{-1})	0.21 ± 0.00a	0.23 ± 0.01b	0.26 ± 0.02b	0.27 ± 0.01b	0.30 ± 0.00c	0.38 ± 0.01d
H^{+} ($cmol_c$ kg^{-1})	0.92 ± 0.34d	0.78 ± 0.05d	0.61 ± 0.21 cd	0.36 ± 0.19bc	0.25 ± 0.17b	0.00 ± 0.00a
Al^{3+} ($cmol_c$ kg^{-1})	0.71 ± 0.02e	0.58 ± 0.01c	0.65 ± 0.01d	0.22 ± 0.01a	0.26 ± 0.01b	0.25 ± 0.01b
Al/Ca (molar ratio)	0.21 ± 0.01c	0.17 ± 0.01b	0.18 ± 0.01b	0.05 ± 0.00a	0.05 ± 0.01a	0.05 ± 0.01a
Ca/Al (molar ratio)	4.67 ± 0.15a	6.03 ± 0.15a	5.73 ± 0.06a	20.67 ± 1.53bc	17.97 ± 0.75b	23.30 ± 2.60c
Total OC %	1.81 ± 0.01a	1.82 ± 0.01a	2.01 ± 0.02b	2.42 ± 0.01c	2.65 ± 0.01d	4.99 ± 0.01e
Total N (%)	0.18 ± 0.01bc	0.15 ± 0.01a	0.16 ± 0.01ab	0.18 ± 0.01bc	0.17 ± 0.01bc	0.20 ± 0.01c
Total H (%)	0.48 ± 0.01a	0.50 ± 0.01ab	0.51 ± 0.00ab	0.49 ± 0.01a	0.52 ± 0.01b	0.55 ± 0.01c
Available P (mg kg^{-1})	12.5 ± 0.6a	–	23.3 ± 0.6 b	–	–	65.3 ± 0.8 c
FC[b] (vol%)	29.8 ± 1.8a	–	29.9 ± 1.3a	–	–	35.0 ± 0.7b
Wilting point (vol%)	9.0 ± 0.15a	–	8.78 ± 0.64ab	–	–	9.75 ± 0.39b
PAW[c] (vol%)	20.82 ± 1.97a	–	21.18 ± 0.78a	–	–	25.55 ± 0.54b

[a] Base saturation.
[b] Field capacity.
[c] Plant available water.

2.5 years used in this experiment. The exception to this was the 40 t ha^{-1} amendment and is likely due to heterogeneity issues than significant negative priming (Whitman et al., 2015).

BPCA analysis provides information on the proportion of condensed aromatic C in soil, and serves as a measure of pyrogenic C. On the basis of the calibration that around 24% of condensed C is converted into benzenepentacarboxylic acid (B5CA) and benzenehexacarboxylic acid (B6CA) during the nitric acid oxidation (Bostick, in revision), there should have been 91.6% condensed carbon in the pure biochar, 0.50% in the non-amended soil, and 3.7% in the soil amended with 40 t ha^{-1} biochar after 2.5 years (Table 3). Thus, 3.7–0.5 = 3.2% of the condensed C can be attributed to the added biochar, similar to the amount of biochar C originally added to the soil (4.99–1.81 = 3.18%, Table 2). This suggests that almost all condensed C in the biochar survived after five seasons (2.5 years) of aging under field conditions. The degree of aromatic condensation in the biochar can be represented by the ratio of B5CA/BC6A (Schneider et al., 2010), as B5CA is formed from less condensed components than B6CA compounds. In the aged soil, the B5CA/B6CA ratio of the biochar was 0.53. This was higher than the corresponding value for the fresh biochar (0.35), indicating that the aged biochar was less condensed, and perhaps more oxidized, than the fresh biochar (Table 3).

3.3. Crop yield

In the first year's harvest, biochar addition did not show a significant effect ($p > 0.05$) on maize (Fig. 1a) or mustard grain yield (Fig. 1b), however significant effects ($p < 0.01$) on biomass of both crops were observed (Fig. S1). Significant effects of biochar addition on both crops' grain yield were observed during the second year's harvest (Fig. 1, Table S1). Maize grain yield increased by 50% (5.3 ± 0.4 t ha^{-1}), 47% (5.2 ± 0.5 t ha^{-1}) and 93% (6.8 ± 0.6 t ha^{-1}) for the 15 t ha^{-1} BC, 25 t ha^{-1} BC and 40 t ha^{-1} BC addition respectively, compared to the control soil (3.5 ± 0.2 t ha^{-1}) (Fig. 1a). Similarly, mustard grain yield increased by 96% (1.02 ± 0.14), 128% (1.19 ± 0.18 t ha^{-1}) and 134% (1.22 ± 0.16 t ha^{-1}) at 15 t ha^{-1} BC, 25 t ha^{-1} BC and 40 t ha^{-1} BC addition respectively, compared to the control (0.52 ± 0.01 t ha^{-1}) (Fig. 1b). In addition to these biochar treatments (15 t ha^{-1} BC, 25 t ha^{-1} BC and 40 t ha^{-1} BC amendment), biochar addition at 10 t ha^{-1} BC also showed significant effect on mustard biomass production during the fourth season (second year's harvest) (Fig. S1b). Similar significant trends to those observed for the second year's harvest were observed for both maize and mustard crop yield (Fig. 1, Table S1) and biomass production (Fig. S1, Table S2) during the third year's harvest (seasons 5 and 6).

Table 3
BPCA composition of fresh biochar and aged biochar in the 40 t ha^{-1} plots (after 5 seasons) and the control soil.

Treatments	B5CA[1]	B6CA[a]	Pyrogenic C[b]	B5CA/B6CA
	mg BPCA per g soil		%	
Fresh biochar	57.3	163.5	91.6	0.35
Control soil	0.53 ± 0.03	0.68 ± 0.06	0.5	0.78
40 t ha^{-1} aged biochar	3.1 ± 0.3	5.8 ± 0.4	3.7	0.53

[a] Benzenepentacarboxylic (B5CA) and benzenehexacarboxylic (B6CA) acids.
[b] (B5CA + B6CA)∗4.1/10.

3.4. Cost-benefit analysis through agronomic trials

Gross margin per ha cropped land was observed to be highest (4848 US$) for 15 t ha^{-1} biochar addition, when calculated based on the medium social cost of CO_2 (42 US$ per ton) (Fig. 2c), taking into account the CH_4 emission cost during biochar production and income/benefit when amending it to soil (C sequestration) in the respective plot. Without a carbon price, gross margin still peaked at a biochar dose of 15 t ha^{-1}, but at a lower value of around 3832 US$, and showed a sharper decrease with increasing biochar dose above 15 t ha^{-1}. All numerical data can be found in the SI (Tables S3 and S4). Biochar produced from freely available *Eupatorium* and using a flame curtain soil pit kiln costs around 144 US$ per ton biochar including labor, packaging, storage and transportation (Table S3). During biochar production, health cost (acute respiratory and chronic obstructive pulmonary diseases) was also considered, and amounted to US$ 30 for 15 t ha^{-1} biochar addition (Table S4). In comparison, C emission cost (in terms of CH_4) were as high as US$ 118 to 834 for 15 t ha^{-1} biochar, at C prices of 6 and 42 US$ per ton, respectively. This showed that the GHG cost of methane emissions during biochar production outweighed the negative health effects.

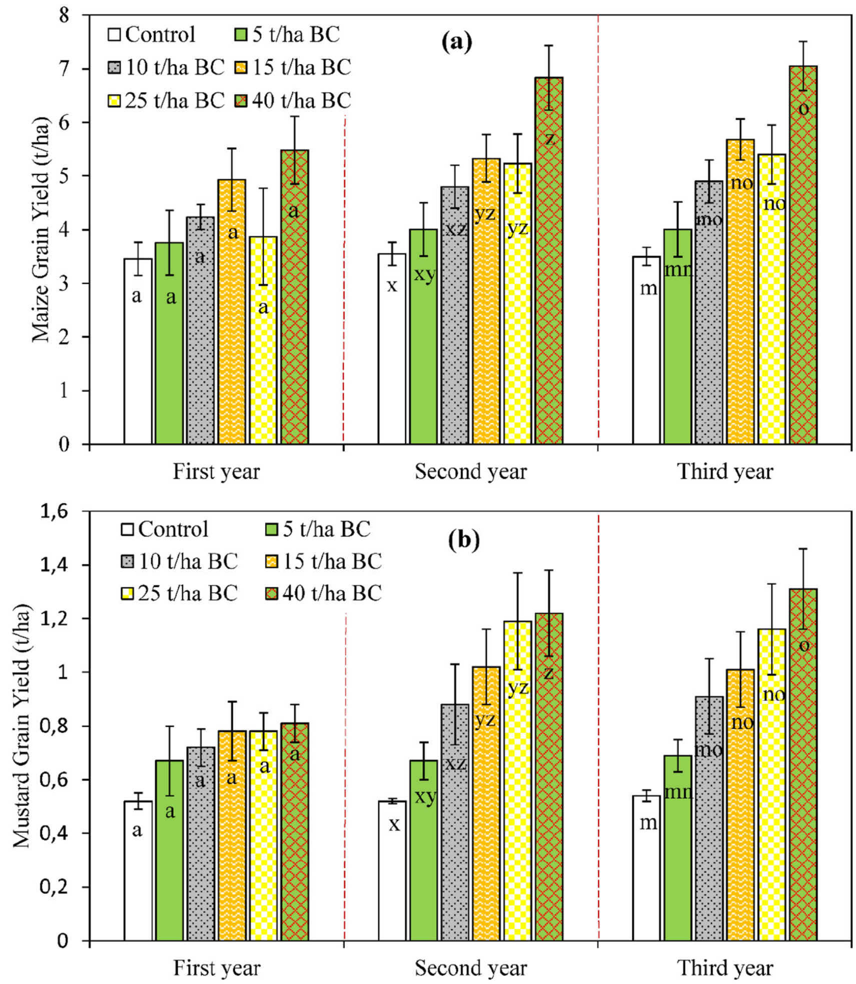

Fig. 1. Effect of biochar addition on grain yield of maize (*fig a*) and mustard (*fig b*) over a period of three cropping years; mean ± SE, $n = 4$. Different letters inside a bar of each treatment represents significant differences between various treatments in a respective year following one factor ANOVA (post hoc-Tukey test, $p = 0.05$).

4. Discussion

In this study, biochar addition showed a significant effect on grain yield of both maize and mustard of the second and third year's harvest, but not during the first year's harvest (Fig. 1, Table S1). Both crop yields gradually increased with increasing biochar dose over 10 t ha^{-1} (Fig. 1, Table S1). In accordance with this, Major et al. (2010) reported increased maize yield in repeated years (after first year) with the amendment of 20 t ha^{-1} biochar, an effect that was not mirrored for a biochar dose of 8 t ha^{-1} in a four-year field trial (maize-soybean rotation) in a Colombian savanna Oxisol. Similarly, another field study carried out in Wales by Jones et al. (2012) reported significant effects of biochar on foliar N uptake and grass crop production only in the second and third year's harvest (not first year) at high biochar additions (25 t ha^{-1} and 50 t ha^{-1}) when applied in a Cambisol. These results indicate that biochar requires a certain degree of aging in soil before it exerts its positive effect on crop yield. Haider et al. (2016) reported that aged biochar was more effective than fresh biochar for nutrient capture and delivery, a property which may lead to increased crop yield over time. This observation may be explained by a recent study reporting the slow formation of an organic coating on the surface of biochar following aging in a compost media which increased nutrient retention (Hagemann et al., 2017). In the experiment here, a similar phenomenon may have occurred over time in the presence of the repeatedly applied manure.

Biochar amendment (10 t ha^{-1} and 40 t ha^{-1}) significantly increased soil available P (P-AL) (Table 2), which resulted in significant positive effects on both maize ($R^2 = 0.95$, Fig. S3a) and mustard grain yield ($R^2 = 0.92$, Fig. S4a) in this soil. In our previous study with the same soil and crop (maize) but under greenhouse conditions, P-AL appeared to be one of the most important growth limiting factors, which was effectively alleviated upon biochar addition (increased P-AL from 11 mg kg^{-1} at control to 84 mg kg^{-1} at 2% w:w biochar addition) thereby increasing maize biomass production (Pandit et al., 2018). In the present study, P-AL increased from 12.5 to 65 mg kg^{-1} upon biochar addition (40 t ha^{-1}) (Table 2), reaching the value (50–70 mg kg^{-1}) that is required for better crop growth (Krogstad et al., 2008). Improved P availability in low fertility acidic soil upon biochar addition has been reported by Hale et al. (2013), which has also been shown to have a positive effect on crop production in P-deficient soils (Asai et al., 2009). In addition, biochar amendment increased soil moisture at field capacity and PAW by 5% compared with the control soil (Table 2), but only at 40 t ha^{-1}, thus, moisture was not expected to be the main growth-limiting factor in this soil, in line with our greenhouse observations (Pandit et al., 2018). In the much drier climate of Zambia, Martinsen et al. (2014), reported positive effect of biochar addition (10 vol%) on crop yield, where PAW increased from 18.2% to 22.3%.

In addition, biochar amendment improved soil chemical properties such as soil pH, OC%, CEC and exchangeable base cations (Ca^{2+}, Mg^{2+}, K^{+}) (Table 2). These measured soil chemical parameters were positively correlated with biochar doses (Fig. S3). Biochar addition showed increased soil pH and reduced amount of Al^{3+} at all doses compared to the control (Table 2), but even in the control treatment, the Al^{3+} content was below the level where negative effects on plant roots can be

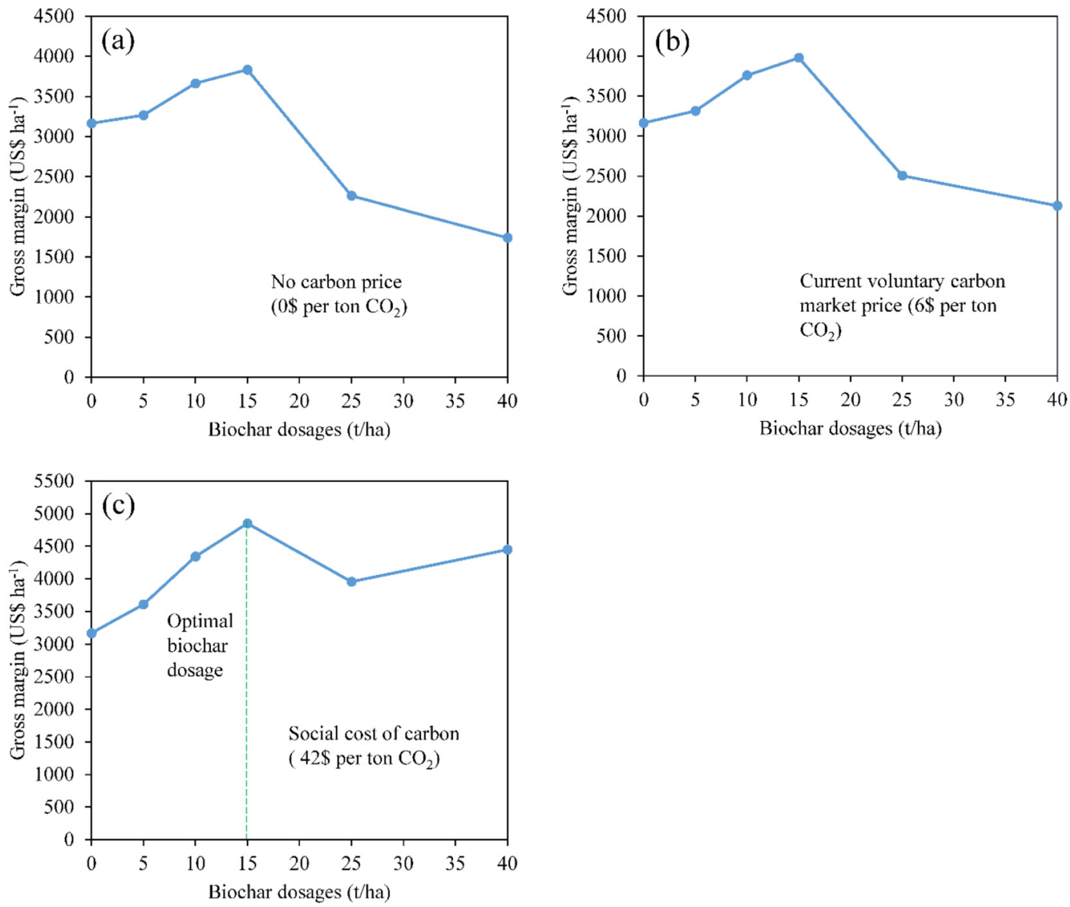

Fig. 2. Gross margin of single biochar application at different levels, with varying carbon prices; a) no carbon price, b) voluntary market price (6$ per ton CO_2) and c) medium social cost of C price (42$ per ton CO_2) under maize and mustard cropping system over a three-year period.

expected (around 0.7 $cmol_c\ kg^{-1}$) (De Wit et al., 2001). Therefore, soil acidity alleviation is not expected to be the reason for the increased crop yields in the presence of biochar. In addition, SOC was increased at all levels of biochar addition with the exception of 5 t ha^{-1} (Table 2), indicating the stability of C in the biochar over 2.5 years (Kuzyakov et al., 2014; Wang et al., 2016). However, on the basis of this dataset, it cannot be concluded whether the biochar was stable, or whether negative priming compensated for possible biochar decomposition. In multi-season field trials, Jones et al. (2012) reported increased soil pH upon biochar addition (50 t ha^{-1}) by 0.32 units. In the same study, higher total SOC in the whole soil profile was observed over time due to very little effect of biochar on soil mineralization. On the other hand, long term field studies have shown a gradual reduction of available exchangeable base cations (Ca^{2+}, Mg^{2+}, K^+) over time from the soil surface layer to lower horizons through leaching, however, values still remained higher than in control soils (Jones et al., 2012; Major et al., 2010; Steiner et al., 2007). In this study, the measured soil exchangeable nutrients (Ca^{2+}, Mg^{2+} and K^+) sampled after the fifth season (2.5 years) from the biochar amended treatments were higher than those in the control soil (Table 2), illustrating the effect of biochar on improved chemical soil fertility was sustained for at least 2–3 years in this soil.

Soil parameters such as exchangeable K^+, pH, OC%, CEC and BS% were found to have significant beneficial effect on both maize (Fig. S3) and mustard grain yield (Fig. S4) as a function of biochar addition (5th and 6th seasons). Our previous mechanistic study (pot trial) in a similar soil revealed higher amounts of soil K upon biochar addition, which had a significant positive relationship with maize growth (Pandit et al., 2018). Another field trial conducted by Gautam et al. (2017) in a similar silty loam soil from Rasuwa, reported increased K upon biochar addition (5 t ha^{-1}), also shown to be beneficial for crop production. Similarly, a positive effect of biochar addition (10 vol%) on K availability and crop yield was observed in low productive tropical soils from Zambia (Martinsen et al., 2014). With respect to a pH effect on crop yield, our previous study with the same soil, showed that biochar addition increased soil pH, which led to a greater amount of available P, and contributed to increased crop yield (Pandit et al., 2018). That finding implied that there was a nutrient effect rather than liming effect of biochar. No similar mechanistic experiments were carried out in the present trial, as the replicated multi-season, multi-dose approach was the maximum achievable in a remote rural location, and as the greenhouse experiment was carried out using the same soil as the one in the present work.

The positive effects of improved soil CEC and BS on crop yield upon biochar addition (Fig. S3) is in line with many previous field studies carried out in low fertile acidic tropical soils (Cornelissen et al., 2013; Martinsen et al., 2014; Yamato et al., 2006). Soil inorganic N (NO_3^- and NH_4^+) was not considered in this study, as the amount of extractable NO_3^- and NH_4^+ did not reveal a significant effect on maize biomass production in a similar soil under controlled greenhouse conditions (Pandit et al., 2018). Overall, the positive crop yield effect upon biochar addition was possibly due to collective effects of improved soil properties (available P, K, pH, OC%, CEC and BS%) in this soil. These soil parameters were also strongly correlated with crop yield (Figs. S3 and S4). In this study, individual soil parameters or the most important growth limiting factors were not assessed. Results of this study allow the conclusion to be reached that biochar addition had a significant positive effect on soil properties and crop yield. For more stringent mechanistic conclusions, our previous greenhouse trial paper using the same soil is referred to Pandit et al. (2018).

4.1. Cost-benefit analysis

Currently there is no possibility for payment of C credits to farmers and thus, the price of CO_2 was set to zero in the main scenario used here. In this scenario, gross margin was observed to peak at 3832 US$ per ha (Fig. 2a), however, the incentive for biochar use from the farmer's perspective is small as the difference in gross margin between no biochar amendment (3163 US$ over 3 y) and optimal biochar amendment rate (15 t/ha; 3832 US$ over 3 y) was 21%. Gross margin was drastically reduced for higher biochar doses (25 t ha^{-1}and 40 t ha^{-1}) under the zero CO_2 price regime as the increase in crop yield was not worth the investment of adding such high amounts of biochar. At a voluntary market C price of 6$ per ton CO_2 (Fig. 2b) as well as at a medium social cost of CO_2 price of 42 US$ per ton (Fig. 2c), gross margin also peaked at 15 t ha^{-1} biochar with the clearest incentive for making biochar at the 42 US$ CO_2 price (gross margin for 15 t ha^{-1} biochar 4848 US$ ha^{-1} over 3 years, and for no biochar 3163 US$ ha^{-1}; a difference of 53%). Based on the significant effect of biochar applied at 15 t ha^{-1} on maize crop (Fig. 1a) and mustard crop (Fig. 1b) in a subsequent year along with higher a gross margin, this study suggests the optimal biochar dose under local farmers practices is 15 t ha^{-1}. It should be noted that this conclusion is true for this particular soil/biochar/farming system combination, and several multi-season field studies are needed to identify the long-term agronomic, financial and C sequestration benefits of biochar in Nepalese soil. In the current situation, only the 0 US$ price scenario is realistic for rural farmers in Nepal, but still gives benefits of biochar amendment, topping at a 15 t ha^{-1} biochar addition.

This is one of the first studies taking into account both the climate cost of methane emissions and the health cost of CO and aerosol emissions during biochar production. However, these are not costs that are directly felt by the farmer making the biochar. Thus, the direct incentive for the farmer to make biochar is actually higher than represented in the graphs in Fig. 2 for those cases where the C price is higher than zero. For example, for biochar doses of 0 and 15 t ha^{-1} at a medium social cost carbon price, the gross margin excluding these costs not directly felt by the farmer, was calculated to be 3163 US$ and 5712 US$ respectively (instead of 3163 and 4848 US$, respectively), a difference of 80% (Table S4).

4.2. Implementation

One ton of biochar can be produced from around four to five tons of dry Eupatorium (20–25% conversion efficiency) by the farmers themselves on their farmland. In Nepal, *Eupatorium adenophorum*, an invasive shrub regenerated naturally in forest, farm upland and riverbanks and is found in abundant quantities. Invasion of *Eupatorium* is an enormous problem (Kunwar, 2003). Transitional zones and swamp forest are being invaded by dense monospecific stands of *Eupatorium*, which have little understorey except for *Eupatorium* seedlings. No commercially viable application has been found for Eupatorium (Kunwar, 2003). However, Eupatorium can be considered a sustainable feedstock to produce good quality biochar at a relatively low cost, thus turning a pest into a potential resource. A relatively high application rate of 15 t ha^{-1} could be surmountable for smallholder farmers because average land holding size in Nepal is small (around 0.7 ha, CBS, 2001/2002). In addition, biochar remains effective in soil for longer periods and does not need annual re-application. Thus, 15 t ha^{-1} biochar application seems feasible in Nepalese farming. Biochar can be produced using the novel, innovative, clean and cheap pyrolysis method of choice, flame curtain pyrolysis kilns (Kon-Tiki). These kilns were first developed in Switzerland in 2014 (Schmidt and Taylor, 2014). In flame curtain kilns biomass is pyrolyzed layer by layer in a conically formed metal kiln or soil pit that reaches a final pyrolysis temperature of about 600–700 °C (Schmidt et al., 2015). The biochar below the upper pyrolysis layer prevents oxygen from entering and the combustion zone forms a flame curtain that allows clean burning to occur, reducing aerosol (smoke) and gas emissions. Feedstock is added until the pit is filled and the pyrolysis process is stopped either by quenching with water or soil (Schmidt et al., 2015). The revolutionary aspect of the flame curtain soil pit kiln is that it is free of cost (except labor charge to dig the pit), is clean, easy and provides a fast mode of operation (Cornelissen et al., 2016).

5. Conclusion and recommendation

Biochar addition in a three year agronomic trial with maize and mustard farming was found to be economically viable. Among various biochar doses, the optimal amount was found to be 15 t ha^{-1} based on agronomical (crop yield), economic (cost benefit analysis) and environmental (C sequestration) considerations. For a zero C price regime (i.e., without payment for C sequestration, the current situation), gross margin was improved by around 21%, and drastically reduced for biochar doses exceeding 15 t ha^{-1} (25 t ha^{-1}and 40 t ha^{-1}), thus, the observed increased yield was not worth the investment of adding such high amounts of biochar. An increased margin of 21% obtained through biochar amendment, and up to 50% when a price is put on the carbon sequestered, would significantly improve the socio-economic status of poor farmers in Nepal where 25% of rural household are still living below the poverty line (average household income <1000 US$ per year, NLSS, 2011).

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2018.05.107.

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