Chapter

Diversified Agroforestry for Climate Change Adaptation and Mitigation in the Himalayan Region: Potential for Achieving Multiple Benefits

Roshan M. Bajracharya, Deepak K. Gautam, Ngamindra R. Dahal and Him Lal Shrestha

Abstract

Land management and forests are crucial to tackling the concurrent issues of sustainable food production and climate change. Conventional modern agriculture, converting forests and naturally vegetated landscapes to farms and rangelands, contributes significantly to elevate carbon in the atmosphere. Agroforestry systems offer potential for local communities to meet livelihood needs while simultaneously adapting to and mitigating climate change. Data from several studies conducted in nine districts of central Nepal between 2007 and 2017 were analyzed. Forests and agroforestry systems in three central Nepal districts had significantly higher total carbon stocks than agricultural soils (2–5 times) due to high above and below-ground biomass carbon and SOC stocks. The application of improved FYM compost, cattle urine and biochar in four districts increased average SOC by 2.75% over 6 years, translating to an increase of nearly 100 t ha^{-1} in SOC stock. Along with soil quality benefits, biochar and FYM compost improved the yields of soybean, potato, millet and Swertia chirayita yields which were significantly higher than in untreated plots. The flux of N_2O was significantly lower in biochar-amended soil compared to non-biochar. Crop diversification incorporating high-value horticultural and medicinal crops enhance economic returns as indicated by higher benefit-cost ratios for vegetable and Swertia chirayita than for cereals.

Keywords: agroforestry, diversified cropping, climate change, biochar, farmyard manure, sustainable soil management

1. Introduction

Farming communities in the hill and mountain regions of the Himalayas depend to a large extent on the soil and forest resources for their survival and livelihoods. The past several decades have witnessed ever-increasing pressures upon the land-based resources due to increased human and livestock populations. Intensified and commercial agricultural production with increased reliance on chemical fertilizers and pesticides has led to adverse ecological consequences of these unsustainable farming practices. Soil degradation and productivity decline are widespread in many parts of South Asia [1]. Moreover, the impacts of global climate change, causing higher mean annual temperatures and erratic, intense rainfall events, further threaten the livelihoods of small-holder mountain farmers [2, 3]. Therefore, approaches and systems to enhance and sustain production, while also improving resilience to climate change impacts are urgently needed in the Himalayan region. A combination of practices holds considerable potential to provide multiple benefits related to sustainable production along with supporting climate change adaptation and mitigation. These include crop diversification, incorporation of agroforestry species, use of biochar in conjunction with local farmyard manure and the adoption of appropriate soil and water conservation measures [4, 5].

Due to the increasing demands for food and fiber of a growing population, intensification of agriculture is unavoidable. Agricultural intensification can be defined as any cropping or animal husbandry system that increases the intensity or frequency of use of the same parcel of land, for instance, by growing a greater number of crops per year or grazing a higher number of livestock on the same land area than previously [6, 7]. If such intensification of production is done through the adoption of agrochemical use and mono-culture cropping, then over a period of a few decades, the organic matter content and fertility of the soil becomes depleted, leading to diminishing quality and productivity of the land. On the other hand, if intensification can be achieved in a sustainable manner, maintaining ecological balance, then both the livelihoods of farming communities and the environment could be preserved [5, 8, 9].

Agroforestry involves the inclusion of perennial plants on farm land in combination with annual crops. Often trees, such as, fruit or fodder species, are planted within or on the borders of the crop land with other annual cereal or vegetable crops grown in between. Agroforestry systems offer considerable potential as a climate adaptive strategy due to the diverse nature of crops with varying degrees of tolerance to soil, water, nutrient and climatic conditions [5, 10, 11]. Furthermore, the inclusion of perennial crops enables complimentary, as well as, synergistic effects in terms of productivity, while also capturing and storing carbon, thereby contributing to climate change mitigation [12–14]. These systems are likely to be particularly appropriate for mountain farming due to the steep topography, often shallow depth of soils and limited scope for supplemental irrigation.

In addition to diversified cropping strategies through agroforestry, another environmentally friendly and sustainable approach for enhancing production while aiding in carbon sequestration is the use of on-site farmyard manure and locally prepared biochar. While the use of biochar in soils dates back thousands of years in South America and Australia [15, 16], its potential for promoting soil microbial activity, improving plant nutrient availability, increasing water retention and, thereby enhancing production has only gained scientific recognition in recent decades [3, 17, 18]. The beneficial effects of biochar reportedly arise from its high porosity, stability and longevity in soils, serving as a catalyst for increased microbial activity along with high water and nutrient retention capacity [17–19]. In the Himalayan region, biochar prepared from locally available waste biomass feedstock, such as, crop residues and weeds, could offer a low-cost, sustainable option to improve soil quality and livelihoods through increased crop productivity. Layek et al. [9] point out that in the Eastern Himalayas of India, where a type of slash-and-burn

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agriculture is practiced, the use of biochar could improve soil quality and crop production while also enhancing carbon sequestration. Even greater benefits of biochar to enhance crop yields may be achieved through the application of biochar enriched in nutrients such as nitrogen, phosphorous and potassium [20, 21].

2. Approach and methods

The present chapter is a compilation and re-analysis of the data and salient aspects of several studies carried out in the lower and mid-hills regions of Nepal located in the Central Himalayas. The studies were conducted in nine different districts of the central and mid-western development regions of Nepal during the period from 2007 to 2017. The study districts and locations are shown within the map of the country in **Figure 1**. Brief descriptions of the field trials and studies examined are provided below.

The effects of agroforestry and community-managed forests on the accumulation of carbon in both soil and biomass compared to conventional agriculture were evaluated in a study conducted in three districts of central Nepal. Four field plots each in three land use types, namely, agriculture (AG), agroforestry systems (AF) and community forests (CF), were sampled in Chitwan, Gorkha and Rasuwa districts [22]. These districts represented different agro-climatic zones with Chitwan in the tropical zone (100–300 m elevation range), Gorkha situated in the warm subtropical zone (at 1000–1200 m elevation) and Rasuwa lying in the warm temperate zone (at 1800–2000 m elevation). Soil organic carbon (SOC) and dry bulk density (BD) were determined using dry combustion [23] and core methods [24], respectively, for samples taken at four soil depths down to 1 m or bedrock, whichever was shallower. These included topsoil at 0–0.15 m depth, and three sub-soil layers at 0.15–0.30 m, 0.30–0.60 m and > 0.60 m depths. Using the SOC percent and soil BD, the total soil

Figure 1.
Map of Nepal showing the study districts (shaded in gray). Source: *https://www.worldatlas.com/r/w960-q80/upload/d6/7b/0c/provinces-of-nepal-map.png*.

OC stocks were calculated using Eq. (1) [25]. The above and below-ground biomass carbon stocks were also determined using the allometric method according to Chave et al. [26]. The above-ground tree biomass (AGBT) was calculated using the diameter at breast height (DBH) and the total height of the tree (h) as given in Eq. (2).

The biomass carbon of leaf-litter, herbs and grasses was determined by destructive sampling over an area of 1 m^2, and oven drying in the laboratory; calculations were done according to the formula in Eq. (3). The below-ground root biomass was taken according to the root-to-shoot ratio of 1:5 as suggested in MacDicken [27].

$$\text{SOC stock}\left(\text{t ha}^{-1}\right) = \text{SOC}^{*}\ \text{BD}^{*}\ \text{H}^{*}\ 10^{4} \tag{1}$$

Where, SOC = soil OC %; BD = soil dry bulk density (Mg/m^3); H = thickness of soil layer sampled.

$$\text{AGTB} - \text{C stock}\left(\text{t ha}^{-1}\right) = 0.059^{*}\ \delta^{*}\ \text{DBH}^{2} * \text{h} \tag{2}$$

Where, δ = wood specific gravity (g cm^3); DBH = diameter of tree at breast height (cm); h = tree height (m).

$$\text{LHGB} - \text{C stock}\left(\text{t ha}^{-1}\right) = \text{Wf}^{*}\ \text{Wd}^{*}\ 10^{4}/\text{A}^{*}\ \text{Ws} \tag{3}$$

Where, Wf = fresh weight of leaf-litter-herb-grass sample; Ws = wet weight of subsample; Wd = oven dried weight of subsample; A = sampled area (m^2).

The use of sustainable soil management practices, such as, improved compost and farmyard manure (FYM), cattle urine, crop residue mulching and biochar are reported to have beneficial effects on soil quality and fertility. This ultimately translates to increased productivity and higher crop yields, which contribute to greater incomes and better livelihoods for farming communities. A study in four districts of central and mid-western Nepal evaluated the increase in soil organic carbon over a period of 6 years of adoption of these practices by farmers [28]. Soil from 16 farmer fields in Baglung, Kavrepalanchok, Sindhupalchok and Syangja districts was sampled at 0–0.15 m and 0.15–0.3 m depths representing the crop rooting zone. The soils were air-dried, sieved through a 2 mm sieve and analyzed for SOC using the loss-on-ignition dry combustion method. The increase in SOC contents over the six-year period was calculated and the potential for carbon sequestration was determined.

In separate trials in five districts of central Nepal, the application of biochar prepared from locally available crop residues, weeds and grass biomass in combination with FYM compost was studied. The quality of biochar made by pyrolysis at low temperatures (350 to 470°C) using different feed stocks, namely, coffee pulp and husks, leaf-litter/grass, rice straw, Eupatorium sp., and wood sawdust, along with the quality of local FYM compost was determined. The organic C contents, pH, total N, available P, available K and cation exchange capacity (CEC) were determined for biochar, FYM and soil from the farm fields using standard methods. The effects of the local biochar and FYM on soil properties, as well as, crop growth and yields were evaluated for coffee agroforestry and vegetable crops in Bhaktapur, Kavrepalanchok, Lalitpur, Rasuwa and Sindhupalchok districts of central Nepal between 2012 and 2017 [29, 30].

An economic analysis was done to determine the benefits to farm income of cultivating vegetable crops and medicinal plants in smallholder farm fields in Rasuwa district during 2016–2017. Cost-benefit analyses were done for crops including millet (the main cereal crop grown in the district), radish, garlic and Swertia chirayita (medicinal plant). The benefit-cost ratio was calculated to determine the estimated profitability of each crop type.

3. Results and discussion

Based on sampling and quantification of carbon stocks under agricultural fields, agroforestry systems and community forest plots, it was observed that the total carbon stocks accumulated in forests were expectantly highest (by 2 to 5 times), followed by agroforestry systems (approximately 2–3 times higher than agriculture) and least in agricultural lands in three districts in central Nepal (**Table 1**). While soil carbon stocks were variable, with farm fields in Chitwan having significantly higher SOC stocks than the other two districts, biomass carbon stocks were highest for community forests, followed by agroforestry plots. Agricultural plots, on the other hand, did not accumulate biomass carbon as the fields are planted to annual crops which are harvested and all biomass removed each cropping season. The variability of SOC stocks may be due to farming practices, amounts of organic residues returned to the soil and farmyard manure applied, as well as, the soil depth, which was highest in Chitwan district. The influence of organic matter management under different agricultural practices and variability in soil OC contents and stocks have been reported in a number of studies [4, 9, 22, 31, 32].

As shown in **Figure 2**, the distribution of below-ground carbon stocks, including root-biomass carbon and SOC, depended on the depth of sampling. Although the total below-ground carbon stocks were generally higher for forest soils, the difference was not significant when topsoil (0–0.3 m) alone was considered. However, when quantified to greater depths, the below-ground carbon stocks were considerably higher for both community forest and agroforestry plots. This is presumably due to the contribution of root biomass carbon of perennial crops and trees under agroforestry systems and in forests. Increased SOC contents under agroforestry systems have been observed in other studies as well [13, 33–35].

District	Land Use[$]	SOC stock	Biomass C stock	Total C stocks
Chitwan	AG	208.9 ± 37.9	—	208.9
	AF	244.2 ± 44.1	81.3 ± 17.8	325.5
	CF	354.4 ± 129.0	172.3 ± 49.6	526.7
Gorkha	AG	63.0 ± 12.9	—	63.0
	AF	88.0 ± 17.0	63.2 ± 21.7	151.2
	CF	252.5 ± 64.6	75.9 ± 14.9	328.4
Rasuwa	AG	127.1 ± 17.8	—	127.1
	AF	152.5 ± 9.5	262.4 ± 62.8	414.9
	CF	150.0 ± 17.7	420.3 ± 92.8	570.3

[$] *AG = Agriculture; AF = Agroforestry; CF = Community Forest.*

Table 1.
Carbon stocks (t ha^{-1}) under three land uses in three central districts of Nepal.

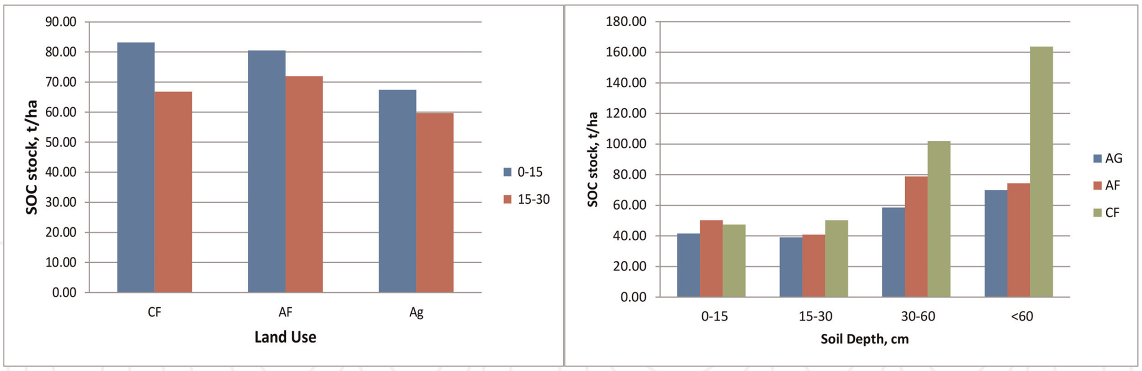

Figure 2.
Distribution of below-ground carbon stocks at different depths within the topsoil (0–0.3 m), in Rasuwa district, left; and the entire soil profile, right, in Chitwan district.

Farm fields in four districts of central and mid-western Nepal, namely, Kavrepalanchok, Sindhupalchok, Baglung and Syangja, were monitored over a period of 6 years to evaluate the effect of sustainable soil management practices that focused on organic and nature-based approaches to increase soil organic matter and fertility. As shown in **Table 2**, the mean baseline SOC contents of the four study districts were low, ranging from less than 1 percent to about 2.3 percent. After 6 years of adoption of the improved FYM/compost and cattle urine application practices on the farm plots, mean SOC contents increased significantly in all districts from about 2.5 to more than 6 percent. This represented a range of about 2-fold to more than 4-fold increase in SOC contents in the farm fields over the 6-year period. Assuming an average soil bulk density of 1.2 Mg m^{-3}, the average increase in SOC stock in the topsoil (0.3 m layer) would amount to nearly 100 t ha^{-1} over 6 years. The results indicate that such sustainable soil management practices can improve not only the quality and fertility of agricultural soils but also contribute significantly to carbon capture and sequestration. Such improvements in soil properties and increased carbon accumulation as a consequence of restorative soil management practices have been shown in numerous other studies [3, 16, 29, 36].

Other studies examining the properties and influence of locally prepared biochar on both the soil and crop production suggested improvements over conventional farming practices. The local biochar was made using a variety of different waste biomass feed stocks such as coffee waste, weeds (Eupatorium sp.), leaf-litter, grass and wood sawdust. Pyrolysis at low temperatures in a locally constructed dual chamber biochar stove over periods ranging from 3 to 10 hours (depending on moisture contents of feed stock) yielded 35 to 50 percent by weight of the resultant biochar as can be seen from **Table 3**. The highest quantities of biochar resulted from leaf-litter and grass, as well as, coffee pulp and rice husk feed stocks at about 50 percent of the initial weight of the biomass.

Biochar has a number of beneficial effects when applied to the soil. This can be seen from the properties of the biochar given in **Table 4**. Biochar tends to be alkaline in nature and hence can moderate the soil pH in acidic soils. The highest pH was observed for biochar made from Eupatorium sp., a local nuisance weed, which resulted in pH greater than 10. The next best feed stock from a pH standpoint was leaf-litter and grass, which yielded biochar with about 9.5 pH. With regard to best overall properties including organic matter, nitrogen and phosphorus levels, Eupatorium along with leaf-litter and grass, as well as, wood sawdust biochar appeared to be favorable (**Table 4**). It should be noted, however, that biochar does

District	Initial SOC %	3-year SOC %	6-year SOC %	Increase in SOC %
Kavreplanchok	0.68	1.36	2.99	2.31
Sindhupalchowk	1.19	1.31	2.45	1.26
Baglung	1.60	3.72	4.96	3.36
Syangja	2.29	2.97	6.37	4.08
Means ± SD	1.44 ± 0.86	2.34 ± 1.20	4.19 ± 1.81	2.75 ± 1.23

Table 2.
Soil organic carbon contents in the crop root zone (0–0.3 m depth) over 6 years of sustainable soil management practices in four districts of Nepal (n = 16).

Feedstock type	Wt, of feedstock (kg)	Wt. of biochar produced (kg)	Fuel used (kg)	Time of pyrolysis (hours)	Biochar yield ratio
Coffee pulp and husk	7.35 kg	3.50	8	10	0.48
Leaf litter and grass	3.4	1.75	1.05	3	0.51
Eupatorium sp.	4.45	1.55	2.5	3.5	0.35
Rice husk	1.41	0.75	4	5	0.53
Wood sawdust	2.5 kg	1	3.5	4.5	0.40

Table 3.
Biochar is produced from various feedstock types under the low-temperature pyrolysis (temperature range maintained at 350–470°C).

not provide nutrients directly to crops, rather, it enhances microbial activity by providing sites with high nutrient and moisture contents for their growth, thereby, enabling the release of nutrients for crop use. Furthermore, due to the high OM contents of biochar and the stability of this OM, biochar can enhance carbon sequestration in soils over extended periods of time. The beneficial effects of biochar on soil properties have also been reported by other researchers [31, 37–40].

Farmers in the hills and mountains of the Himalayas have traditionally used locally prepared farmyard manure or compost as a means of fertilizing and replenishing the soil with organic matter and crop nutrients. In recent decades, however, increasing

Feed Stock Type	pH	Organic Matter (OM) %	Total Nitrogen mg kg^{-1}	Available Phosphorus mg kg^{-1}	Exchangeable Potassium mg kg^{-1}
Coffee pulp and husk	8.41	39.57	4865	1335.5	350
Leaf litter and grass	9.49	35.525	17,465	3848	209.61
Eupatorium sp.	10.25	62.34	4392.5	3259.5	81.87
Rice husk	9.07	25.295	3080	1867	244.25
Wood	8.66	68.54	1120	519	206.2

Table 4.
Biochar properties are produced from five types of biomass feed stocks.

reliance on chemical fertilizers in order to produce commercial crops around the year with an intensified cropping cycle has led to declining soil quality and productivity. Research in several districts of central Nepal, including Lalitpur, Kavrepalanchok, Sindhupalchok, Bhaktapur and Rasuwa, has suggested that the application of a combination of FYM compost and biochar could improve soil quality, while simultaneously enhancing crop yields, particularly those of vegetable crops and medicinal plants.

Analyses of locally prepared FYM compost samples from three districts revealed that this organic form of fertilizer is rich in macro- as well as micro-nutrients (**Table 5**). Apart from having high amounts of organic matter ranging from about 15 to 65 percent, the FYM compost is also high in nitrogen, available phosphorus and available potassium, which are the three most common nutrients required by plants in large amounts. The values in FYM ranged from about 4000 to 7000 mg kg^{-1} for total N, about 5300 to 12,000 mg kg^{-1} for available P and approximately 200 to 300 mg kg^{-1} for available K. These values are considered high to very high as a source of plant available macro-nutrients. Moreover, the analyzed FYM samples also contained considerable amounts of iron, manganese, copper and zinc, which are micro-nutrients required in only trace amounts by crops.

The properties of soils after 2 years of amendment with biochar as compared to soil in control (non-biochar) plots clearly indicate improvements in a number of soil properties (**Table 6**). The SOC content, soil pH and CEC of biochar treated soils were significantly higher than for untreated soils as seen from the analysis of variance F-test and P values. The bulk density was weakly significantly lower ($P < 0.10$) for biochar-amended soil compared to the control. The crop macro nutrients, namely, total N, available P and available K were not statistically significantly different for biochar-amended soil, but the values were, nonetheless, somewhat higher than for the control soil (**Table 6**).

The above results indicate, therefore, that the use of FYM compost prepared on-farm from animal manure mixed with crop residues, leaf-litter and used animal bedding materials serves as an environmentally friendly and sustainable means of restoring soil fertility and overall quality. The enhancement of crop yields due to the application of biochar and organic fertilizers is corroborated by many studies around

Analyzed parameters	Sampled District		
	Lalitpur	Kavrepalanchok	Sindhupalchok
pH	10.77	6.19	8.25
Organic Matter (%)	65.29	15.19	27.23
Total Nitrogen (mg kg^{-1})	7009	4005	6160
Available Phosphorus (mg kg^{-1})	5273	12,061	5333
Available Potassium (mg kg^{-1})	294.1	199.5	196.7
CEC ($cmol_c$ kg^{-1} soil)	67	75	139
Iron (Fe) (mg kg^{-1})	26.60	41.67	2.50
Manganese (Mn) (mg kg^{-1})	17.18	117.9	105.5
Copper (Cu) (mg kg^{-1})	2.64	2.50	3.50
Zinc (Zn) (mg kg^{-1})	10.77	11.50	30.17

Table 5.
Properties of farm yard manure compost prepared locally by farmers.

Soil Property	Control (± SD)	Biochar Tmt. (± SD)	F-test/Signif.
SOC (%)	2.88 ± 0.97	5.07 ± 2.27	25.95**
Bulk density (Mg m^{-3})	1.70 ± 0.23	1.60 ± 0.25	3.47†
Soil pH	5.68 ± 0.43	6.13 ± 0.45	6.09*
CEC ($cmol_c$ kg^{-1})	47.3 ± 11.7	58.6 ± 10.1	6.82*
Total N (mg kg^{-1})	2360 ± 659	2640 ± 426	0.6 ns
Available P (mg kg^{-1})	248 ± 133	302 ± 160	2.16 ns
Available K (mg kg^{-1})	208 ± 39	253 ± 68	1.38 ns

Note: *†, *, ** indicate significance at the 10, 5 and 1 percent levels, respectively.*

Table 6.
Selected properties for biochar-amended and non-biochar (control) soil in three districts of Central Nepal (n = 12).

the world [39, 41–44]. While increasing the rate of biochar application to soil generally led to increased yields, an optimum application rate of 15 t ha^{-1} was proposed by Pandit et al. [45]; as the cost increased with higher rates, the incremental yield did not support the application of higher amounts of biochar.

A field trial on smallholder farm fields in Rasuwa district indicated that the application of FYM compost at a rate of 20 t ha^{-1} mixed with biochar at a rate of 5 t ha^{-1} had significant effects on increasing the yield of a number of crops over the application of FYM alone to the soil (**Table 6**). Yields of mustard seed were highly significantly ($P < 0.01$) different between the two treatments, while those of potato and the medicinal plant Swertia chirayita were significantly different ($P < 0.05$). Although the yields of garlic and radish were only weakly significantly different ($P < 0.10$) between biochar+FYM and FYM alone, the yield values were notably higher for the former by about 25 to 66 percent (**Table 7**).

Another trial in Bhaktapur district also indicated that the combination of FYM compost with low rates of biochar applied to the soil prior to planting led to generally higher yields for crops like garlic, chili, radish and soybean (**Figure 3**). The yield of soybeans grown in soil with biochar+FYM applied was significantly higher, by about 56 percent, than that of soybeans grown in soil with FYM compost only. While the yield differences for the other crops, namely, garlic, chili and radish, were not significant, the yields of the crops grown in soil with biochar+FYM were slightly higher

Crop Type	FYM Compost	Biochar + FYM	P-value/Signif.
	(t ha^{-1})		
Garlic	3.0 2.1	5.0 3.9	0.066†
Potato	6.6 2.4	8.0 3.1	0.012*
Radish	9.0 3.0	11.6 5.2	0.058†
Mustard (seeds)	0.3 0.1	1.3 0.4	0.001**
Swertia chirayita	2.0 1.4	3.04 2.4	0.039*

*†, *, ** indicate significance at the 10, 5 and 1 percent levels, respectively.*

Table 7.
Yields of different crops grown with farmyard manure compost alone and with biochar plus FYM compost in Rasuwa district.

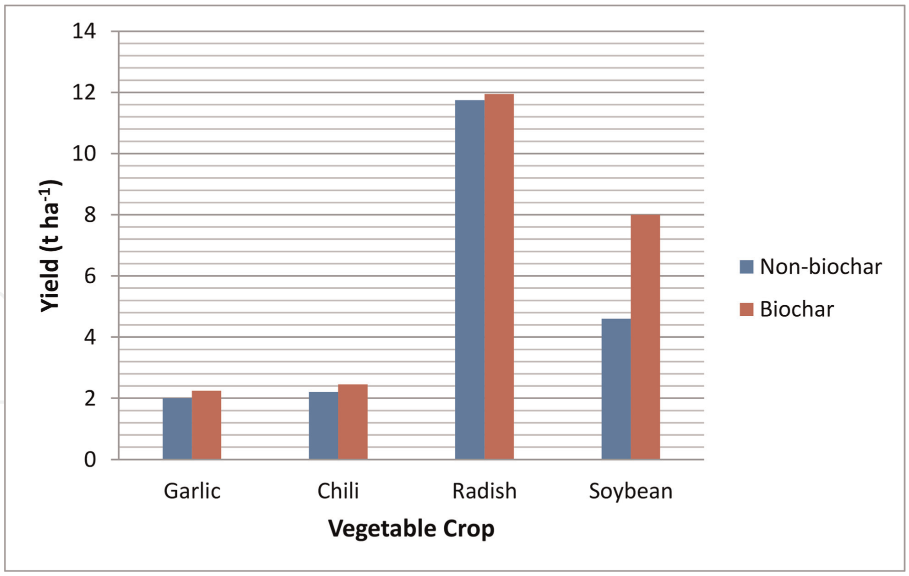

Figure 3.
Yields of vegetable crops grown with and without biochar in Bhaktapur district.

than that for crops grown in soil with only FYM compost (**Figure 3**). Similar results have been reported by researchers in other studies [36, 39, 41, 46]. The application of low doses of biochar enhanced by treating with cattle urine was also found to be effective in increasing yields of a number of vegetable and cereal crops by Schmidt et al. [42, 43].

Apart from the yield benefits of the use of biochar in agricultural and agroforestry soils, another study in Bhaktapur district where biochar was applied to farm plots at low rates (4 to 8 t ha^{-1}) showed a distinct reduction in the emission of greenhouse gases. The monitoring of carbon dioxide, nitrous oxide and methane, using the static chamber method over a period of 2 months during the early growing season, showed lower emissions of the gases from biochar-applied soil than from control plots that received no biochar (**Figure 4**). While the results were not statistically significantly different for CO_2 and CH_4, the emission of N_2O was significantly higher ($P < 0.05$) from soil in non-biochar plots as compared to biochar-amended plots. Other studies have also shown significant reductions in NO_2 and CO_2 from biochar applied soils as reported by Stavi and Lal [4]. On the other hand, increased N_2O emissions from agricultural soils and acidification have been shown to result from intensified crop production with the use of chemical fertilizers [47]. Therefore, the amendment of the intensively cultivated soils with biochar could be a potential measure to alleviate excessive GHG emissions.

Considerable research and scientific evidence have established that agroforestry systems and the incorporation of perennial plant species in agriculture have many environmental and ecological benefits in terms of soil quality, biodiversity, climate mitigation, etc. However, less work has been done evaluating the economic advantages of agroforestry crops, especially, high-value medicinal plants. A study in smallholder farm fields of Rasuwa district in central Nepal compared the total revenues from and costs of cultivating a number of different crops including cereal crops, vegetables and medicinal plants. The results clearly showed that medicinal plant cultivation, such as Swertia chirayita, gave significantly higher returns with a benefit-to-cost ratio of 2.45. On the other hand, growing common cereal crops like maize and millet actually led to a loss, whereas, vegetable crops such as radish were marginally

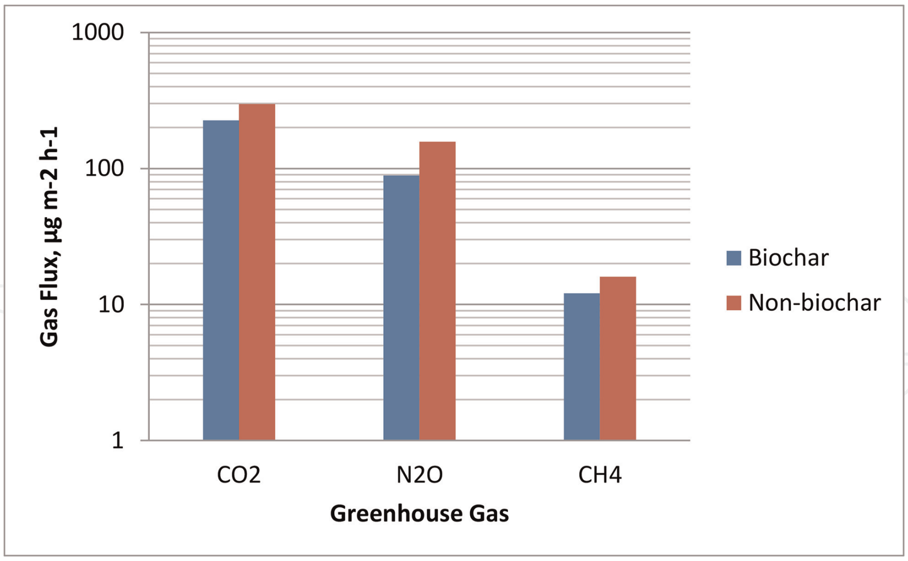

Figure 4.
Emissions of three greenhouse gases from soil with and without biochar amendment in Bhaktapur district.

Crop	Production	Total Revenue	Total Variable Cost	Gross Margin	Benefit:Cost Ratio
	(t ha^{-1})	(1000 X NPR‡)			
Maize	1.57	62.90	135.73	−72.83	0.46
Millet	0.69	27.52	136.81	−109.29	0.20
Radish	9.83	147.42	136.81	16.81	1.13
Swertia chirayita	393.13	1179.38	481.98	69.40	2.45

‡*Note: Currency exchange rate at the time of study was approx. USD 1 = 102 NPR.*

Table 8.
Cost–benefit analysis for various crops produced by smallholder farmer in Rasuwa district.

profitable (**Table 8**). The economic benefits of diversified cropping and inclusion of horticultural crops have also been reported by Shah et al. [44].

4. Conclusions

The results of a number of field trials conducted in several districts in central Nepal demonstrate that agroforestry, crop diversification and the adoption of various sustainable soil management practices hold considerable potential for enhancing land productivity, increasing crop yields and improving the livelihoods of local farming communities. Agroforestry systems are particularly suitable for mountainous regions and can contribute to climate change adaptation and resilience of hill communities while also increasing SOC accumulation and carbon stocks, thereby, helping to mitigate climate change. Trees outside of forest have been reported to substantially enhance carbon sequestration whether as traditional agroforestry practices or simply trees planted on farms and homesteads [48]. Forests and agroforestry systems typically contained significantly higher total carbon stocks than agricultural soils (by 2 to 5 times) due to the high above and below-ground biomass carbon as well as SOC stocks.

Sustainable soil management practices such as the application of improved FYM compost, cattle urine and biochar in four districts led to an increase in SOC contents by 2.75 percent on average, which could amount to nearly 100 t ha^{-1} of increase in SOC stocks over a 6-year period. In addition to soil quality benefits, the application of biochar and FYM compost improved the yields of a variety of crops with soybean, potato, mustard and Swertia chirayita yields being significantly higher than for untreated plots. Biochar has the potential to contribute to the mitigation of climate change by enhancing carbon sequestration in soil due to its inert nature and longevity in soils, as well as, by helping to reduce emissions of greenhouse gases from soil [49]. The flux of N2O was observed to be significantly lower in biochar-amended soil as compared to non-biochar soil. This was presumably due to the effect of biochar on soil chemistry, moisture conditions and microbial activity [4, 32].

The adoptability of sustainable agricultural practices depends to a large extent on economic returns. Diversifying crops with the inclusion of high-value horticultural and medicinal crops could lead to better economic returns as seen from the relatively higher benefit-cost ratios for vegetable and Swertia chirayita than for cereal crops. Therefore, adequate technical, financial and institutional support to farmers in developing countries and mountainous regions are needed to encourage and promote climate resilient and environmentally sound agricultural and land use practices.

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Conflict of interest

The authors declare no conflict of interest.

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