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Review Article

The Role of Biochar in Ameliorating Disturbed Soils and Sequestering Soil Carbon in Tropical Agricultural Production Systems

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Agricultural soils in the tropics have undergone significant declines in their native carbon stock through the long-term use of extractive farming practices. However, these soils have significant capacity to sequester CO_2 through the implementation of improved land management practices. This paper reviews the published and grey literature related to the influence of improved land management practices on soil carbon stock in the tropics. The review suggests that the implementation of improved land management practices such as crop rotation, no-till, cover crops, mulches, compost, or manure can be effective in enhancing soil organic carbon pool and agricultural productivity in the tropics. The benefits of such amendments were, however, often short-lived, and the added organic matters were usually mineralized to CO_2 within a few cropping seasons leading to large-scale leakage. We found that management of black carbon (C), increasingly referred to as biochar, may overcome some of those limitations and provide an additional soil management option. Under present circumstances, recommended crop and land management practices are inappropriate for the vast majority of resource constrained smallholder farmers and farming systems. We argue that expanding the use of biochar in agricultural lands would be important for sequestering atmospheric CO_2 and mitigating climate change, while implementing the recommended crop and land management practices in selected areas where the smallholder farmers are not resource constrained.

1. Introduction

Evidence from the Intergovernmental Panel on Climate Change [1] is now overwhelmingly convincing that climate change is real, that it will intensify, and that the poorest and most vulnerable will be disproportionately affected by these changes. Climate change and variability, drought, and other climate-related extremes have a direct influence on the quantity and quality of agricultural production and, in many cases, adversely affect it. In particular, the influences of climate change on agricultural production are severe in developing countries because the technology generation, innovation, and adoption are too slow to counteract the adverse effects of varying and changing environmental conditions [2].

Agricultural intensification invariably has several negative impacts on the environment [3]. One of the major consequences of agricultural intensification is a transfer of carbon (C) to the atmosphere in the form of carbon dioxide (CO_2), thereby reducing ecosystem C pools. Agriculture contributes 10–12% of the total global anthropogenic greenhouse gas emissions [4, 5]. Tropical agricultural soils in particular have undergone significant depletion of their native carbon stocks but have considerable potential to act as CO_2 sinks through improved management practices [6, 7]. To this end, locally appropriate adaptation and mitigation strategies to increasing climate variability and climate change are urgently needed especially in vulnerable regions where food and fiber production are most sensitive to climatic fluctuations [2].

The implementation of improved land management practices to build up carbon stocks in terrestrial ecosystems is a proven technology in reducing the concentration of CO_2 in the atmosphere and lowering atmospheric CO_2 [8].

As a result, soil organic carbon sequestration in agricultural lands has recently drawn attention in mitigating increases in atmospheric CO_2 concentrations [5, 9].

Management practices to build up soil carbon must increase the input of organic matter to soil and/or decrease soil organic matter decomposition rate. At this point, it is worth to mention that the most appropriate management practices to increase soil carbon vary regionally, depending on both environmental and socioeconomic factors. In the tropics, increasing carbon inputs through improving the fertility and productivity of crop land and pasture is essential because climate change has negative influence on the livelihood of the vast majority smallholder farmers. In extensive systems with vegetative fallow period, planted fallows and cover crops can increase carbon levels over the cropping cycle [10]. Uses of no-till, green manures, and agroforestry are other beneficial practices to sequester soil C. Overall, improving the productivity and sustainability of existing agricultural lands is crucial to reduce the rate of new land clearing and the amounts of CO_2 emitted to the atmosphere.

Carbon sequestration in agricultural soils is frequently promoted as a practical solution to slow down the rate of increase of CO_2 in the atmosphere. To date, the bulk of research into agricultural production systems being net carbon sinks has been based on temperate based production systems that are quite different to those in the tropics. There is a need to improve our understanding on how land management practices affect exchange processes that lead to net removal of atmospheric CO_2 in the tropics. Therefore, we reviewed and analyzed the impacts of different land management practices such as agronomic practices, tillage, organic input management (i.e., addition of compost, manure, biochar, and other clay materials), and agroforestry as a means to increase carbon sequestration in agricultural soils of the tropics. Moreover, we reviewed the opportunities and constraints to adapt mitigation and adaptation options in the tropics with the goal of developing a possible framework for smallholder farmers to benefit from carbon markets.

2. Overview of Tropical Production Systems

In the tropics, farming systems have undergone major changes from hunting and gathering through fallowing to stationary cultivation systems during the course of history [11]. The changes in farming systems were mainly driven by the increase in human population and agricultural mechanization (e.g., [12]), the quality and availability of land resources (e.g., [13]), and access to markets (e.g., [12]). The decision-making environment in tropical agricultural systems is complex. The first factor that controls farmer's decision-making is the physical environment (e.g., [14]). The second can be called household characteristics (e.g., [15]), where uniform producers react in a uniform and rational manner during decision-making processes. The third factor that determine farmers' choice of production systems is the politico/economical frame conditions (e.g., [16, 17]).

Furthermore, farming systems may be differentiated into subtypes that continue to evolve along different pathways. For example, in systems under population and market pressure, some farms could successfully intensify and even specialize to produce for the market, whereas others could regress to low-input/low-output systems [17]. Moreover, in any one location within a farming system, different farms are likely to be at different stages of evolution because of differentiated resource bases, household goals, capacity to bear risk, and degree of market access, among others [15]. It is the sum of all farmers' decisions that will determine the quality of the future land resources in the tropics as there is a feedback mechanism between farmer's decisions and the quality of the natural resource base. The chain of linkages among population pressure, agricultural intensification, economic growth, societal well-being, and technical changes in agriculture and their subsequent environmental consequences are thus very complex in nature and causation and as a result are often difficult to analyze and understand.

3. Tropical Agricultural Production Systems and Soil Carbon

The key problem of tropical agriculture is the steady decline in soil fertility, which is due primarily to soil erosion and the loss of soil organic matter. Some soils in tropical agricultural systems are estimated to have lost as much as 20 to 80 $\mathrm{t\,C\,ha^{-1}}$, most of which has been released into the atmosphere [3, 18]. The low soil organic carbon content is due to the low shoot and root growth of crops and natural vegetation, the rapid turnover rates of organic material as a result of high soil temperatures and fauna activity particularly termites, and the low soil clay content [19]. In addition, soil erosion and the long-term cultivation using conventional tillage practices reduce soil carbon levels, and over time the soils have become degraded, often resulting in land abandonment [6, 20, 21]. For instance, a study in west African agro-ecosystem revealed that there is a tremendous SOC loss in agricultural lands due to soil erosion (ranging from 65 to 1801 $\mathrm{kg\,ha^{-1}\,yr^{-1}}$) compared to the loss of SOC (ranging from 6 to 13 $\mathrm{kg\,ha^{-1}\,yr^{-1}}$) in undisturbed ecosystems [19]. The loss of SOC could range from 9 to 65% depending on severity of soil erosion and soil types.

Furthermore, the burning of biomass or vegetation as a conventional land preparation method and the use of crop residues and cow dung as a source of energy have a net negative impact on the soil organic carbon and on the environment through the release of CO_2. For instance, in Ghana, Parker et al. [22] documented a 21% reduction in soil organic carbon because of biomass burning that resulted in the release of 1.4 $\mathrm{t\,CO_2\,ha^{-1}}$ to the atmosphere. A study in southern Asia also demonstrated that burning of 5–7 $\mathrm{t\,ha^{-1}}$ of rice residues causes air pollution through releasing 13 $\mathrm{t\,CO_2\,ha^{-1}}$ [23].

In the tropical agricultural systems, the removal of crop residues for or by livestock, either through grazing or cut and carry, is a common practice, which conflicts the use of crop residues and cover crops for soil improvement [24]. Smith et al. [5] showed that it was more likely to observe an effect of straw removal on SOC: (i) in the less fertile soils,

(ii) when greater quantities of residues were removed, and (iii) over longer periods. In line with this negative effect of residue removal on soil carbon, Nandwa [25] demonstrated that residue removal for off-farm use should consider only amounts that can be harvested without decreasing SOC levels. However, livestock are an important part of production in mixed farming systems and in the absence of alternative feed sources; farmers are usually unwilling to abandon this critically important one [25].

There is a consensus among the literature that most of the tropical agricultural systems lead to the depletion of organic matter due to the long-term extractive agricultural practices and reduced organic inputs, which consequently make most of the agricultural systems unsustainable. Due to this, there is an urgent need to improve the management of organic inputs and soil organic matter dynamics in tropical land use systems. One desirable goal is the ability to be able to manipulate soil organic matter dynamics via management practices so as to promote soil conservation, to ensure the sustainable productivity of agroecosystems, and to increase the capacity of tropical soils to act as a sink for, rather than a source of, atmospheric carbon.

4. Land and Crop Management Practices for Soil C Sequestration

In the last two to three decades, several land and crop management practices have been advocated to restore soil organic carbon and reduce net emissions of CO_2 from the agricultural systems in the tropics [5, 26, 27]. Among others, practices that restore soil organic carbon and reduce net emissions of CO_2 include crop rotation, avoiding use of bare fallow, conservation tillage, management of organic inputs such as manure and crop residues, restoration of degraded agricultural lands, water management, and agroforestry (e.g., [28–34]).

Studies demonstrated that smallholder farmers can reduce greenhouse gas emissions and maintain carbon stocks in soil and vegetation at relatively low cost by implementing crop and land management practices (e.g., [27, 35–37]). However, a review by Giller et al. [38] and Sanchez, 2000 [39], identified a number of constraints that include a low degree of mechanization within the smallholder system, lack of appropriate implements, problem of weed control under no-till system, and lack of appropriate technical information that hinders large-scale adoption of the practices by the smallholder farmers. Woodfine [27] added that a key bottleneck to realizing the adoption of many mitigation practices is the availability of financing to catalyze initial change. Operationally, improved crop and land management practices may require more manual labor than conventional agricultural practices [40]. Optimizing these advantages and disadvantages can be a complex task which is in itself a disadvantage where there is a scarcity of trained personnel and extension workers to provide information and advice to farmers.

Furthermore, the temporal pattern of influence in mitigating the increase in CO_2 varies among practices and, in most cases, CO_2 emissions reduction resulted from the advocated practices are temporary [5]. For example, a study in Kenya documented that the residual effect of manure applied for four years only lasted another seven or eight years when assessed by yield, SOC, and Olsen P [41]. Effect of no-till practices are also easily reversed and lead to the release of CO_2 to the atmosphere as soon as the system started to be disturbed.

In sum, under present circumstances, recommended crop and land management practices are inappropriate for the vast majority of resource constrained smallholder farmers and farming systems [38]. However, this does not mean that mitigation practices advocated in the last two to three decades could not be one option that can offer substantial benefits for smallholder farmers in the tropics who are not constrained by resources and in certain locations where political, economical, and institutional frame conditions are relatively efficient. Identification of the situations when mitigation practices can offer major benefits is a challenge that demands active research [38].

5. Biochar as a Climate Change Mitigation Option

Biochar is a charcoal produced under high temperatures (300 to 500°C) through the process of pyrolysis using crop residues, animal manure, or any type of organic waste material [42]. The two main methods of pyrolysis are “fast” pyrolysis and “slow” pyrolysis. Fast pyrolysis yields 60% bio-oil, 20% biochar, and 20% syngas and can be done in seconds, whereas slow pyrolysis can be optimized to produce substantially more char (~50%), but takes on the order of hours to complete [43]. Depending on the feedstock, biochar may look similar to potting soil or to a charred substance. The combined production and use of biochar are considered a carbon-negative process, meaning that it removes carbon from the atmosphere [42, 44]. Studies suggest that biochar sequester approximately 50–80% of the carbon available within the biomass feedstock being pyrolyzed depending upon the feedstock type [45, 46].

6. Can We Produce Biochar Using Locally Available Technologies?

Biochar can be produced using locally made technologies, which can be affordable to the local farmers and easily adopted and used. One of such easy technologies is the use of biochar chamber made of stainless steel (Figure 1). This kind of technology only costs about $ 70 US per chamber (based on the amount of money invested to produce a chamber at Laos PDR), and the system operation and maintenance are quite easy and can be managed by the smallholder farmers in the tropics. We have also measured that it has the capacity to produce 83.3 (±4.2) kg of biochar from a rice husk with conversion efficiency of 48.1 (±2.1) % per 14.5 (±1.0) hours of burning. Other methods used to produce biochar in small quantity for use by the small-scale farmers that are described in http://www.biochar.info/ include carbon zero

Biochar chamber made of stainless steel

The chamber covered with rice husk and burning

Biochar produced after 14–18 hours of burning

Figure 1: The process of biochar production using biochar chamber made of stainless steel from a rice husk (photo by Wolde Mekuria).

experimental biochar kiln, simple two-barrel biochar retort, and simple two barrel biochar retort with afterburner.

In addition, in The Netherlands, a "Twin-retort" carbonization process has been developed to address charcoal production efficiency and emission problems [47]. The traditional charcoal production systems used in the past such as charcoal production in open pits, earthen kilns, and traditional charcoal mounds, as carried out in rural areas, are inefficient. In most cases, weight efficiency of the traditional charcoal production systems carried out in rural areas ranged from 10 to 15% indicating that seven to ten kilograms of wood are required to produce one kilogram of charcoal [47]. Reumerman and Frederiks [47] documented that the efficiency of "Twin-retort" carbonization process is more than double compared to the tradition charcoaling processes. This indicates the possibility to reduce emissions with at least a factor of two.

We argue that the possibility to produce biochar using simple and locally available technologies speeds up the adoption of biochar production systems and its use as a climate change mitigation measure and improving agricultural productivity provided that obstacles that may halt rapid adoption of biochar production systems include technology costs, system operation, and maintenance [42]. Although biochar research and development are in their early stage, interest in biochar as a tool to mitigate the increase in CO_2 and improve agricultural productivity is growing at a rapid pace across the tropics.

7. Biochar, Soil C, Soil Fertility, and Productivity

Soil amendment with biochar has been proposed as a means to sequester C (Table 1) and improve soil fertility. Application of charcoal to soils is hypothesized to increase bioavailable water, build soil organic matter, enhance nutrient cycling, lower bulk density, act as a liming agent, and reduce leaching of pesticides and nutrients to surface and ground water [48–51]. Leach et al. [52] also documented that application of biochar to the soil enabling increases in agricultural productivity without, or with much reduced, applications of inorganic fertilizer. Furthermore, Harley [53] indicted that biochar is a promising amendment for ameliorating drastically disturbed soils due to its microchemical, nutrient, and biological properties (Table 2). Biochar-based strategies are thus being seen to offer valuable routes to building sustainable agricultural futures, particularly for resource poor farmers for whom soil fertility and water availability are seen as key constraints on crop production and food security [52].

The extent of the effect of biochar on crop productivity and soil carbon sequestration is, however, variable due mainly to the different biophysical interactions and processes that occur when biochar is applied to soil, which are not yet fully understood [59]. For instance, in nitrogen limited soils, application of high rates of biochar may affect growth negatively due to immobilization effect [46]. Moreover, feedstock and pyrolysis conditions (temperature, holding time, etc.) may affect both stability and nutrient content and availability of biochar [59–61]. Given how inconsistent biochar impacts on yields and soil carbon sequestration are and how little is known about their longer-term impacts, farmers who are to use biochar on their fields are taking considerable risks such as a possible reductions in crop yield during the early cropping seasons.

Thus, we argue that care should be taken on the amount and type of biochar added to the soil for restoring degraded soils. In addition, it is crucial to detect the consequent soil organic carbon accumulation and increase in crop yields under different soil and climatic conditions. Long-term studies on biochar in field trials are also required to better understand biochar effects and to investigate its behavior in soils, thereby reducing the associated risks.

Table 1: Effects of biochar sourced from different biomass on soil C.

Country	Soil type	Treatment	Application rate	Changes in soil C*	Source	Remark
Philippines	Gleysols	Rice husk biochar	41.3 t ha^{-1}	12.9 g kg^{-1}	[54]	After 3 years
Philippines	Nitosols	Rice husk biochar	41.3 t ha^{-1}	12.4 g kg^{-1}	[54]	After 3 years
Thailand	Acrisols	Rice husk biochar	41.3 t ha^{-1}	0.51 g kg^{-1}	[54]	After 3 years
Ethiopia	Nitosols	Maize stalk biochar	5 t ha^{-1}	0.71%	[55]	Incubation trial
Ethiopia	Nitosols	Maize stalk	10 t ha^{-1}	0.77%	[55]	Incubation trial
South Africa	Acidic sandy soils	Pinewood sawmill biochar	10 t ha^{-1}	8.11%	[56]	Pot trial
India	Vertic ustropept	*Prosopis* biochar	5% of the incubated soil	4.5 g kg^{-1}	[57]	After 90 days of incubation
Kenya	Ferrasol	Acacia tree biochar	50 t ha^{-1}	0.7%	[58]	Greenhouse experiment

*Changes in soil C refers to the increase in C due to addition of biochar against the control plots.

8. Potential of Biochar to Mitigate the Increase in CO_2

Studies have shown that cover crops, mulches, compost, or manure can be effective in enhancing soil organic carbon pool and agricultural productivity in the tropics (e.g., [29, 34, 62]). The benefits of such amendments are, however, often short-lived, especially in the tropics, since decomposition rates are high, and the added organic matters are usually mineralized to CO_2 within only a few cropping seasons. Organic amendments therefore have to be applied intermittently to sustain soil productivity. In case of agricultural lands converted to no-tillage systems, stored carbon can be released once we convert no-tillage back to conventional tillage. Therefore, carbon sequestered by these crop and soil management practices is generally considered only temporarily sequestered from the atmosphere and associated with a high risk of rapid or large-scale leakage [44].

Management of black carbon (C), increasingly referred to as biochar, may overcome some of those limitations and provide an additional soil management option. Once biochar is incorporated into soil, it is difficult to imagine any incident or change in practice that would cause a sudden loss of stored carbon indicating that biochar is a lower-risk strategy than other sequestration options [44]. Thus, biochar could be a potentially a powerful tool for mitigating anthropogenic climate change as the carbon in biochar, it is claimed, resists degradation and can sequester carbon in soils for hundreds to thousands of years [26, 44, 54, 63, 64]. The half-life of C in soil charcoal is in excess of 1000 yr [65]. Laird et al. [49] presented an interesting graph that compares the stability of organic input added as residue biomass and biochar (Figure 2).

> According to Laird et al. [49] (Figure 2) “For the Biochar example, about 40% of the C is lost at time 0 when the biomass is pyrolyzed, 10% of the total C is lost to mineralization over a few months, and the remaining 50% of the total C is stable for millennia. For the Residue example, the half-life of the residue C is assumed to be 6 months and 99% of the C is lost to mineralization after 4 years. The biochar scenario results in a C debit for the first 6 months and a C credit thereafter relative to the residue scenario”. This indicates that biochar is a highly stable form of carbon and as such has the potential to form an effective C sink, therefore sequestering atmospheric CO_2 [59].

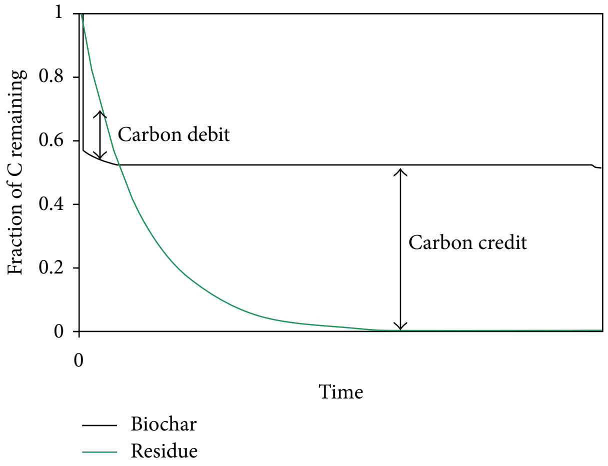

Figure 2: Impact of biomass pyrolysis with soil application of biochar on the amount of original biomass C remaining in the soil relative to the amount of C remaining in the soil if the same biomass is returned to the soil as a biological residue (source: Laird et al., 2009 [49]).

Current analyses suggest that there is global potential for annual sequestration of atmospheric CO_2 at the billion-tone scale (109 t yr^{-1}) within 30 years [59]. Woolf et al. [66] also indicated that annual net emissions of carbon dioxide (CO_2) could be reduced by a maximum of 1.8 Pg CO_2-C equivalent (CO_2-C e) per year (12% of current anthropogenic CO_2-C e emissions; 1 Pg = 1 Gt) and total net emissions over the course of a century by 130 Pg CO_2-C e, without endangering food security, habitat, or soil conservation. In addition, Gaunt and Lehmann [67] documented that emission reductions can be 12–84% greater if biochar is put back into the soil instead of being burned to offset fossil fuel use. Furthermore, the application of biochar once in every ten years to the estimated 15×10^9 ha of cropland worldwide would

Table 2: Role of biochar in ameliorating drastically disturbed soils [53].

Limiting factor	Variable	Problem	Short-term treatment	Long-term treatment	Role of biochar
Physical	Soil structure	Soil too compact	Rip or scarify	Vegetation	Decreased soil bulk density, increased infiltration, and decreased erodibility
	Soil erosion	High erodibility	Mulch	Regrade vegetation	
	Soil moisture	Too wet	Drain	Wetland construction	
		Too dry	Organic mulch	Tolerant species	Increased water retention due to surface area and charge characteristics
Nutritional	Macronutrients	Nitrogen deficiency	Fertilizer	Nitrogen fixing plants, for example, leguminous trees or shrubs	Yield increases Slow nutrient release Soil organic matter stabilization Retention of released nutrients Increased microbial activity Habitat for mychorrhizal fungi hyphae
		Other deficiencies	Fertilizer	Fertilizer, amendments, tolerant species	
Toxicity	pH	Acid soils (<4.5)	Lime	Tolerant species	Designed for alkaline surface charge
		Alkaline soils (>7.8)	Pyritic waste, organic matter	Weathering, tolerant species	High CEC for Na retention
	Heavy metals	High concentration	Organic matter, tolerant cultivar	Inert covering, tolerant species	High surface area and cation exchange capacity allows for metal retention
	Salinity	EC > 4 ds/m pH < 8.5, SAR < 13	Gypsum, irrigation	Weathering, tolerant species	Mixed with gypsum to reduce soil structural issues
	Sodicity	EC < 4 ds/m, pH > 8.5, SAR ≥ 13	Gypsum, irrigation	Weathering, tolerant species	Nutritional values as described High CEC for Na retention

result in a CO_2-equivalent gain of 0.65 Gt C yr^{-1} [68, 69]. These in turn indicate that biochar sequestration could be one option to change bioenergy into a carbon-negative industry [44].

9. Opportunities and Constraints for Mitigating Carbon Emissions in Tropical Agricultural Production Systems

In the tropics, soil organic carbon in the agricultural landscape has been depleted through the long-term use of extractive farming practices [18, 70, 71]. Most agricultural soils have lost 30 to 40 t C ha^{-1}, and their current reserves of soil organic carbon are much lower than their potential capacity indicating that there is great technical potential to increase soil carbon in agricultural soils and reduce greenhouse gas emissions. According to Lal [71], most soils have a technical or maximum sink capacity from 20 to 50 t C ha^{-1} that can be sequestered over a 20-to-50-year period. The greatest potential for sequestration is in the soils of those regions that have lost the most soil carbon. These are the regions where soils are severely degraded and have been used with extractive farming practices for a long time. Among developing countries, these regions include Sub-Saharan Africa, South and Central Asia, the Caribbean, Central America, and the Andean regions [71]. Among others, converting degraded soils into restorative land and adopting practices such as no-till, organic C input management such as additions of manure, compost, biochar, and agroforestry are practices that can increase the soil carbon pool in the tropics [71].

The literature reveals that in the last two to three decades that enabling and encouraging broader adoption of mitigation options were advocated through market-based mechanisms. This could create the catalyst necessary to elevate agriculture's role as a key part of a global approach to mitigating climate change. However, soil C sequestration through the advocated crop and soil management practices currently does not fit under emission trading (ET), the clean development mechanism (CDM), or joint implementation (JI), and neither Article 3.3 nor 3.4 of the Kyoto Protocol specifically include soil carbon as an option [72]. According to Lehmann [44], some of the reasons why soil C sequestration through crop and soil management practices is not allowed into trading markets under current agreements include (1) the net withdrawal of CO_2 through the advocated crop and soil management practices is usually short-lived, (2) accountability of the process of C sequestration is not straightforward, and monitoring and certifying the changes in C stocks are difficult and costly, and (3) the processes of C sequestration also associated with rapid or large-scale leakages. Sohi and Shackley [26] also pointed out that decomposition rate may increase with climate change making soil carbon stores vulnerable to "feedback." Only a small proportion of added organic matter stabilized for longer time, and accumulation rate diminishes with time resulting in inefficient use of organic resource after equilibration.

Yet, considering soil carbon as a commodity and creating another income stream for resource poor and small size land holders are essential prerequisite to widespread adoption of recommended management practices in the developing countries where the problems of food insecurity and soil/environmental degradation are extremely severe. Realizing these incomes would necessitate substantially greater policy support and investment in sustainable land uses than is currently the case [73]. Furthermore, while soil and crop management practices that enhance soil carbon pool in general clearly offer economic and ecological advantages, the development of robust systems compliant with stakeholder needs and requirements is constrained by our limited understanding of the tradeoffs between subsistence requirements, acceptable risks, and the costs involved [74].

10. Can We Integrate Biochar into Trading Markets under Current Agreements?

Funding from carbon trading is argued to be essential to finance the research and development necessary to discover and exploit the full potential of crop and soil management practices to contribute to climate change mitigation and to enable wider adoption of the practices to sequester carbon at globally significant levels [52]. When it comes to including biochar in emission-trading schemes, the issues of permanence, land tenure, leakage, and additionality are less significant for biochar projects than for projects that sequester C in biomass or soil through management of plant productivity [44]. This is because biochar carbon sequestration might avoid difficulties such as accurate monitoring of soil carbon, which are the main barriers to inclusion of agricultural soil management in emissions trading [44, 75]. In addition, no complex predictive models or analytical tools are required, as is the case with other soil sequestration approaches. The source of biochar additions can easily be identified by soil analyses, if desired for verification under carbon-trading schemes.

We argue that there is a great potential to allow the associated emission reductions through using biochar into trading markets under current agreements, because emission reduction units obtained due to the use of biochar can easily be accounted, monitored, and verified. In addition, climate change is real that it will intensify, and there is an urgency not only to identify but also to implement solutions. Biochar sequestration does not require a fundamental scientific advance, and the underlying production technology is robust and simple, making it appropriate for many regions of the world [44]. Furthermore, the possibility to produce biochar using locally available technologies (Figure 1) even makes it more appropriate for the resource poor smallholder farmers living throughout the tropics.

11. Considerations in Upscaling Biochar

Recognizing that biochar technology is in its early stages of development, there are many concerns about the applicability of the technology in the tropics. Three issues are feedstock availability, biochar handling, and biochar system deployment. To date, feedstock for biochar has consisted mostly of plant and crop residues, a primary source of energy and livestock feed for the smallholder farmers in the tropics. Thus, there is still sustainability concerns related to supplying feedstock for large-scale biochar production. The ideal time to apply biochar and how to ensure that it remains in place once applied and does not cause a risk to human health or degrade air quality is also a concern. Furthermore, developing a "one size fits all" biochar system would also be a challenge as biochar systems are designed on the feedstock to be decomposed and the energy needs of an operation [42].

The literature indicates that biochar can be effective in improving soil organic C, nutrient cycling, and crop yield (e.g., [49]). However, biochar production involves removal of crop residues from agricultural lands and would increase risk of accelerated erosion. Thus, determination of sustainable crop residue removal rates and implementation of additional conservation practices such as contour cropping, conservation tillage, and cover crops in agricultural lands are crucial. Furthermore, competition with food production and induced land use change would diminish the carbon sequestration potential even for a strategy as promising as biochar [75]. As biochar carbon sequestration depends on revenues from carbon trading, it is important to ensure that large-scale biochar application on agricultural lands will not lead to depleting the terrestrial carbon stock as it reduces the economic viability of biochar.

We argue that it is important to consider issues such as feedstock availability while promoting biochar as climate change mitigation option in the tropics as the farming system in the tropics is dominated by mixed crop-livestock production systems. Under such system there is always a competition in the use of crop residues for soil amendments or for livestock feed. However, this conflicting issue can be resolved by arranging alternative feedstocks to feed the livestock.

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