

Environmental and Socioeconomic Impacts of Utilizing Waste for Biochar in Rural Areas in Indonesia—A Systems Perspective

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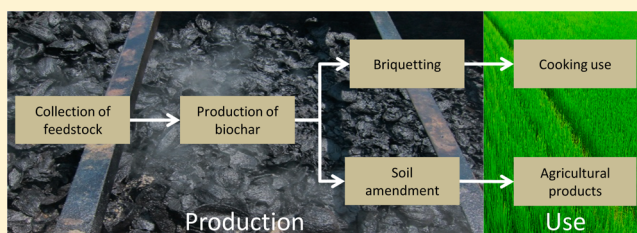
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S Supporting Information

ABSTRACT: Biochar is the product of incomplete combustion (pyrolysis) of organic material. In rural areas, it can be used as a soil amendment to increase soil fertility. Fuel-constrained villagers may however prefer to use biochar briquettes as a higher-value fuel for cooking over applying it to soils. A systems-oriented analysis using life cycle assessment (LCA) and cost benefit analysis (CBA) was conducted to analyze these two alternative uses of biochar, applying the study to a rural village system in Indonesia. The results showed

soil amendment for enhanced agricultural production to be the preferential choice with a positive benefit to the baseline scenario of -26 ecopoints (LCA) and -173 USD (CBA) annually pr. household. In this case, the positive effects of carbon sequestration to the soil and the economic value of the increased agricultural production outweighed the negative environmental impacts from biochar production and the related production costs. Use of biochar in briquettes for cooking fuel yielded negative net effects in both the LCA and CBA (85 ecopoints and 176 USD), even when positive health effects from reduced indoor air pollution were included. The main reasons for this are that emissions during biochar production are not compensated by carbon sequestration and that briquette making is labor-intensive. The results emphasize the importance of investigating and documenting the carbon storage effect and the agricultural benefit in biochar production-utilization systems for a sustainable use. Further research focus on efficient production is necessary due to the large environmental impact of biochar production. In addition, biochar should continue to be used in those soils where the agricultural effect is most beneficial.



INTRODUCTION

Use of biochar for climate change mitigation and agricultural purposes has gained increasing attention in the literature in recent years.^{1,2} Biochar is formed from incomplete combustion (pyrolysis) of organic material, and when biochar is added to soil, much of it remains stable and most of its carbon is retained from the short-lived carbon cycle.^{2,3} In addition, biochar can be beneficial for agricultural production since it can increase base saturation, water-holding capacity, and cation exchange capacity of the soil, depending on both soil and biochar properties.^{1–3}

The cost effectiveness of carbon abatement through biochar implementation use is highest in developing countries where low-cost technologies for production and use can be implemented.⁴ Studies show in addition that the highest potential for increase in crop production is in these areas where soil conditions are poor compared to industrialized

countries.^{5,6} Rural areas and farmers with limited resources will therefore potentially gain the most from applying biochar.

However, not all rural areas can expect promising results for agricultural purposes,^{6,7} and fuel-constrained villagers may want to use biochar in clean cooking solutions (briquettes) to achieve health, climate, and economic cobenefits due to lower emissions and exposure of toxic indoor smoke.⁸ Generalized conclusions about the beneficial use of biochar should therefore be avoided, and conclusions should be based instead on an overall systems perspective and inclusion of local conditions.⁹

Received: November 21, 2013

Revised: March 28, 2014

Accepted: March 30, 2014

Published: March 31, 2014

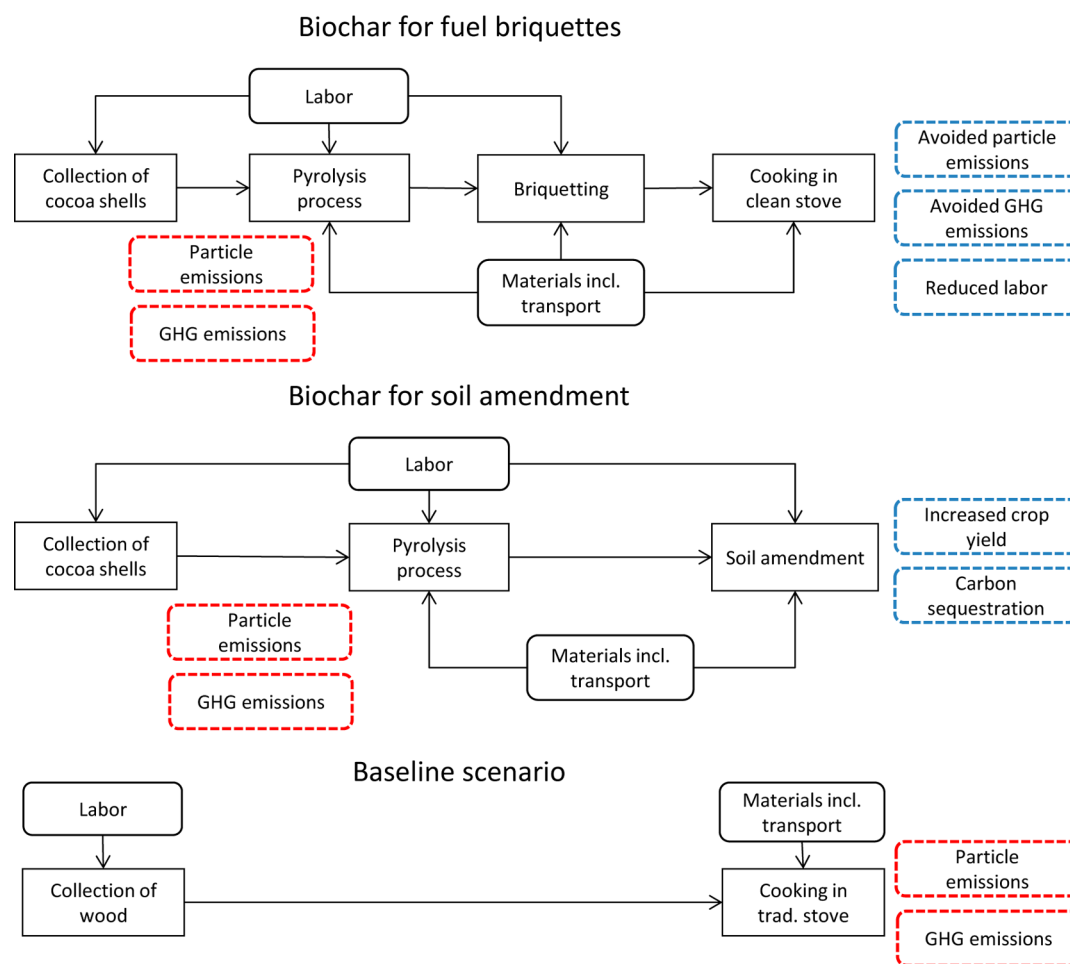


Figure 1. System boundaries for the study showing: (i) use of biochar as fuel briquettes in clean cooking stoves and (ii) use of biochar as soil amendment for enhanced agricultural production. These scenarios were compared to the baseline scenario based on cooking on wood in traditional stoves without the use of biochar. Red dashed boxes indicate negative impacts from the system; blue dashed boxes indicate positive impacts.

In this paper, we evaluated the environmental and socioeconomic impacts of implementing biochar in remote areas using a model case in Indonesia as an example. Environmental impacts were analyzed using life cycle assessment (LCA), whereas a broader set of socioeconomic impacts was assessed through cost-benefit analysis (CBA).

Individual LCA or CBA studies of biochar systems in tropical contexts are scarce,^{10–14} and this is to our knowledge the first study combining both methods in a comprehensive manner. Existing papers on LCA and CBA usually evaluate biochar applications in industrial countries, and the few that look at developing countries assess costs at an aggregated level only.^{10–13} In an earlier paper we performed the first full LCA for biochar amendment to soil in a tropical setting.¹⁴ The present study extends the analysis with the use of biochar as a fuel and a CBA of both alternatives.

A rural village in Sulawesi, Indonesia, was selected as a model system since it represents a typical local entity that may benefit from biochar use. The soils in the area are weathered and benefit agriculturally from biochar use. At the same time, wood for cooking is a limited resource and efficient fuel alternatives are desired. On a worldwide basis there are several million similar systems, and over 3 billion people rely on solid fuels including charcoal as their primary source of household energy.⁸ This makes the conclusions in the paper relevant for a large number of similar cases around the globe. The study exclusively used

biochar produced from biomass waste (cocoa shells). It is further based on the introduction of innovative technologies for biochar production and use, adapted to the rural village situation. This means the introduction of simple but efficient retort kilns for biochar production and affordable cleanly burning cooking stoves for biochar briquette use. On the agricultural side, the use of biochar is based on existing agricultural practices adding biochar as a complementary soil enhancer, thus requiring minimal investments in new technology.¹⁴

We discuss the use of biochar in rural areas from a systemic perspective evaluating both environmental and socioeconomic aspects of the two alternatives (biochar as a soil amendment and biochar as a briquette fuel).

■ MATERIALS AND METHODS

Case Description. We have based our study on on-site investigations executed by the United Nations Development program (UNDP) in the village Ngata Toro in central Sulawesi Indonesia during 2011–2013.¹⁵ The village has 2600 inhabitants, and their income is based on agricultural production, mainly cocoa in smallholder plots. Soils are mostly weathered oxisols, and agricultural products are cultivated on farmland that has gained productivity through the extensive use of fertilizer and lime. Given the right soil conditions, there is an excess of unproductive farmland in the area that could be used for additional production, for example of maize.

Cooking is mainly conducted indoors, without chimney, by the use of traditional wood-fired stoves with locally collected firewood from the area. The potential for substituting wood with other sources is viable, and the interest in the use of biochar briquettes is high. The perceived advantage of briquettes over wood is the ability to regulate heat and the applicability toward simmering purposes. Using briquettes for more efficient cooking may also save valuable time spent collecting firewood.¹⁶ However, the availability of briquettes is currently limited.

Important raw materials such as wood and cocoa shells are collected freely and utilized in the village directly. Other resources such as crop seeds, fertilizer, and construction materials are typically transported 100 km by lorry to the village. A complete picture of the background material in the study obtained via our on-site investigations is given in SI Tables S1, S2, and S4.

Goal and Scope. In the combined LCA/CBA analysis, we compared the integrated impacts of utilizing waste cocoa shells in two different production-utilization systems, comparing them to a baseline scenario, Figure 1. Cocoa shell is a waste material with no alternative use, it is widely available and is an excellent raw material for biochar production with high CEC and high alkalizing effect.¹⁷ Specific production conditions would be expected to affect these parameters.

Since this study is conducted from a combined environmental and cost-benefit perspective, the annual impact from an average village household utilizing available cocoa waste was selected as the functional unit. This is in contrast to our previous LCA study¹⁴ which used “produced amount of agricultural products” as the functional unit. We further applied a consequential approach in the LCA comparing the alternatives to a baseline scenario representing today’s situation where wood is used for cooking in traditional stoves and where there is no use of biochar in agriculture. This approach corresponds well to the principles of CBA, which assesses costs and benefits of (small) changes compared to a baseline.¹⁸

System Boundaries. The system boundaries were concentrated to production and use of biochar, either as fuel briquettes for cooking purposes or as a soil fertility improvement for food production. The inflow to the system was thus the use of resources (including labor inputs in the CBA), where outflows are products and their potential impacts when used. The system produced two distinct outflows to the market: (i) biochar briquettes for fuel-efficient stoves and (ii) agricultural products (maize). These products substituted two other flows: (i) collected firewood for use in traditional stoves and (ii) maize produced without the use of biochar.

In order to incorporate the total effects we have expanded the system boundaries accordingly. For the briquettes produced, we assumed a replacement of wood for use in traditional cooking stoves resulting in reduced air emissions and reduced time spent on wood collection. For agricultural production, we also included increased agricultural yield on existing farmland, in addition to carbon sequestration from use of biochar as soil amendment.

Feedstock Collection. Our evaluation showed that feedstock in the form of wood (for cooking only) and cocoa shells for biochar production is readily available for manual collection at the local scale (0.9 and 5 tons/y respectively pr. household).

Wood collection was observed to take approximately 156 h pr household and year, 50% more time pr unit mass than collecting the more accessible cocoa waste. This material is usually left to decompose since the use of these hard, dry shells for compost is not attractive and is not a part of traditional practice.

Locally, few people have paid work in a traditional sense. Nevertheless, their time has productive value in alternative use. Thus, labor time was valued here as the average between the Gross Domestic Product per capita for the Sulawesi Tengah province (USD 0.79 per hour) and the national wage rate for production workers in animal husbandry and fishery below supervisory level (USD 0.64 per hour).¹⁹ External supervision/training costs were valued at USD 3.7 per hour.

Availability of local biowaste as feedstock was an important prerequisite for sustainable use, since transportation or negative impacts due to indirect competition for agricultural land would have significantly increased the negative environmental impacts.²⁰ We assumed no net emissions of carbon dioxide since the biogenic carbon uptake and release from the feedstock is taking place within approximately one growth season.²¹ No emission of other greenhouse gases (methane) during decomposition of organic waste was foreseen in the baseline scenario due to aerobic conditions and no stockpiling.²²

Production of Biochar. Both systems assumed use of simple production technologies based on retort technology for the production of biochar (Figure S1). This technology allows use of the thermal energy from combustion gases to sustain the pyrolysis process at a temperature of 300–400 °C, resulting in higher biochar yields and reduced air emissions compared to traditional kilns.²³

The environmental and health impacts from biochar production are almost exclusively associated with air emissions, especially methane and particulate matter from the production process (dust emissions from handling of char have not been observed to be a problem due to the biochar being moist and “flaky”). Whereas emissions from small scale cooking ovens are well documented,⁸ scientific evaluations of impacts from improved retort kilns are scarce. This paper used published emission factors¹⁴ including a biochar yield of 30%. The emissions, even if outdoors, give rise to health effects, and in the CBA were assumed to be 25% of the indoor air pollution effects from cooking.^{24,25}

The production process of biochar is relatively labor-intensive. We evaluated that one cycle of kiln operation with approximately 600 kg of dry cocoa shells yields ca. 200 kg useable biochar requiring 20 h of labor input. We also assumed a small amount of external supervision/training time per household (likely highest at the start). Around 15 households can share one biochar kiln (cost USD 1340 based on the inventor’s specifications²³) to produce the annual amounts of biochar. The investment costs were annualized using a discount rate of 10% and an assumed technical lifetime of 5 years. An annual maintenance cost (mainly to shift the bottom plate) equal to 10% of the investment was added.

Briquetting. For the briquetting option, briquettes were foreseen to be produced manually using two metal molds (USD 0.25) with biochar and cassava flour (used as binder) as raw materials. The briquettes were used for cooking, and the surplus char was sold and used locally. Our evaluation showed that the briquetting process is highly labor intensive involving manual biochar drying and crushing, mixing with binder, molding, drying, and packaging.¹⁵ This process was evaluated to take around 15 min per kilo briquette, plus 4 h supervision pr. household and year.

Biochar Addition As a Soil Amendment. Biochar may be used as a method for carbon storage and increasing crop yield. From a GHG perspective two soil processes were included: (i) sequestration of carbon in the soil due to biochar amendment

and (ii) GHG emission due to soil management. Other soil related emissions such as difference in soil organic carbon (SOC) release or uptake due to agricultural use were excluded since the agricultural practice remains the same for all cases.

The cacao shell biochar was measured to consist of 70% carbon²⁶ of which 80% was assumed to remain as stable carbon in the soil after amendment.³ We here selected a hundred year's perspective on environmental impacts from greenhouse gases.²⁶

These values are probably realistic and conservative during present conditions and soil type, even though the stable carbon fraction and residence time are reported to vary with both biochar type, formation temperature, and soil conditions.^{27,28} To acknowledge this uncertainty in biochar C stability, this factor was subjected to sensitivity analysis.

Priming effects, i.e., effects on natural organic matter stability due to the presence of biochar, were not explicitly considered in our evaluation, since there is no scientific consensus whether biochar could lead to increased²⁹ or decreased organic matter content.³⁰ A recent extensive modeling exercise indicated that the negative effects on C stocks are probably negligible, whereas the positive effects could be significant.³¹

Greenhouse gas emissions from soil management were included by addressing nitrous oxide formation from nitrification and denitrification of added synthetic N fertilizer.³²

The annual production of biochar will subsequently determine the maximum land area for cultivation with biochar amendment. Addition rates for biochar depend on local soil conditions, application method, biochar type, and leaching to subsoil.^{14,33} We based our LCA and CBA on a combination of locally obtained experimental data utilizing an addition of 10 tons pr. ha and literature values suggesting an annual leaching rate of biochar to the subsoil of 12%.^{7,15} This gave an average required annual addition rate of 1.2 ton biochar pr. hectare in order to sustain a positive agricultural effect over time. Uncertainty exists as to what extent the biochar leaching data for a rice system⁷ can be extrapolated to maize systems; however, no more data are currently available.

We used the locally applied addition rates of 75 kg fertilizer, 75 kg urea, and 20 kg of seed pr. ha pr. year. Biochar was added together with fertilizer in growth basins to utilize the biochar most effectively.⁶ This does not involve significant additional labor since the process was done in a single step. Forty hours extra net labor per ha including preparation of the biochar prior to amendment was assumed for the CBA. Yield effects will be discussed under "agricultural products".

Cooking Fuel. We assumed that replacement of fuel wood with biochar briquettes was followed by briquette use in energy-efficient stoves (USD 3.3, if produced locally¹⁹), by both household and surplus briquette buying customers. Such stoves exhibit an improved thermal effect of 10–30% compared to traditional wood stoves, whereas the combustion efficiency is increased by 3–8%.³⁴ Emission factors for cooking stoves vary depending on type and fuel (Table S3). We conservatively assumed the same emission factors for improved biochar stoves as for traditional wood stoves and used the IPCC recommended values (Table S3). We further assumed a 50% more energy-efficient use of biochar than of wood. This value is slightly higher than experimental values and supported by the superior simmering behavior of biochar compared to wood, thus saving more fuel than a standard boiling test will show.³⁵

Agricultural Products. Field experiments substantiate an increase in yield from biochar application of 20% (from 6.5 t/ha to 7.8 t/ha) compared to the use of synthetic fertilizer (NPK)

and Urea alone,¹⁵ Figure S2. A meta-analysis by Jeffery et al.³³ showed that the effect of biochar on crop yield is variable, ranging from –28% to +39%, with a grand mean of +10%. Therefore, we chose to do a sensitivity analysis on crop yield response to biochar amendment. Due to the selection of the functional unit, we allocated the positive impacts from increased harvest to the CBA alone. No impacts have been identified for the harvest process (manual process and no transportation). For comparison with our previous LCA work in Zambia¹⁴ a calculation using an alternative functional unit has been performed (Figure S3).

Life Cycle Assessment Method. Inventory values from Ecoinvent 3.0 were used to compile the aggregated life cycle inventory of the alternatives. Emission data for biochar production and stove use are case-specific and based on literature values^{14,32} (Tables S2 and S3). The significance of the potential environmental impacts of the aggregated inventories was evaluated with the ReCipe impact model. This method incorporates 17 impact categories considering damage to health and ecosystems, as well as depletion of resources.³¹ This study highlighted two specific categories: (i) *climate change impacts*: aggregated potential damage of GHG including human and ecosystem effects and (ii) *emissions of particulate matter*: human effects from inhalation of fine particulate matter on a regional and global scale. The other end point impact categories are of less importance in biochar production-utilization systems¹⁴ and are only presented in the SI. In order to facilitate the comparisons to the CBA an LCA end point method with "world setting" normalization and "hierarchical" weighing of impact categories was used as the primary impact assessment method (Figures S4 and S5 and accompanying methodological explanations). The result was then a dimensionless index (ecopoint).

Cost Benefit Analysis. All costs and benefit components were valued in monetary terms on a household basis for the two alternatives compared to the baseline. Costs reflect the alternative value (opportunity costs) of resources used, and benefits reflect the welfare improvements experienced. Physical effects and resource use were evaluated (or "weighted" in LCA terminology) in monetary terms using either (adjusted) market prices or prices calculated based on other sources to reflect true social costs and benefits. All costs and benefits were normalized on an annual, per household basis and expressed in USD, 2012 units.

Costs included the following: (i) *technology investment costs* for the kilns, clean stoves, and briquette molds and (ii) *biochar and agricultural production costs* in form of labor and supervision/training.

The benefit components (that may be positive or negative depending on the scenario analyzed) included the following: (i) *health effects* (indoor and outdoor); (ii) *climate effects*; and (iii) *other economic benefits*.

In addition, there may be changes in cooking experience using briquettes, either positive (efficiency) or negative (cultural challenge of adapting to a new way of cooking¹⁶). This net benefit is thus highly uncertain and thus in our case assumed to be zero.

For health effects we used a general procedure for quantification and valuation³⁶ earlier applied to Indonesia by Acrenas.³⁷ The annual number of mortality and morbidity cases in Indonesia attributed to Acute Respiratory Infections for children was estimated with the human capital approach (i.e., present value of future foregone earnings). Chronic obstructive pulmonary disease (COPD) in women caused by solid fuel use for indoor cooking were estimated from values of statistical life

(VSL) adjusted from Mrozek and Taylor.³⁸ Morbidity was valued using cost of illness estimates (i.e., annual medical treatment costs and value of time lost); details in Table S4.

The climate effects, based on the emission/sequestration midpoint data from the LCA, were valued using the central US EPA estimate of the social cost of carbon (expected damage from emissions based on integrated climate-economic modeling) of USD 47.6 per ton CO₂.³⁹ This is a conservative value that does not include all important damages due to data and modeling limitations.³⁹ On the other hand, this expected damage is far from reflected in current carbon markets (e.g., the clean development mechanism or the European Emission Trading scheme) where CO₂ prices are as low as 1.34 USD per ton.

The direct economic agricultural benefit of increased maize production was valued using the current market price of maize in the area (USD 177 per ton).

Uncertainties. Uncertainties are connected to the variability in the inventories and methods due to data quality and inherent assumptions.⁴⁰ For the LCA, the inherent standard deviation values in Ecoinvent 3.0 were used for uncertainty predictions complemented with study-specific uncertainty assessments. Ecoinvent addresses uncertainties by determining the standard deviation of each inventory value through a mathematical aggregation of individual uncertainty sources (Pedigree method).³⁰ Monte Carlo simulation was then used to calculate standard deviation for each data point across their corresponding uncertainty range.

Use of end point indicators, normalization, and weighing will naturally introduce methodological uncertainties not seen in non-normalized unweighted midpoint methods.^{41–43} However, even though many parameters may be uncertain, experience shows (SI Figure S5) they are likely to result in similar over- or underestimation for all considered alternatives and are thus unlikely to affect the final ranking.^{14,44} For comparison and for input values for the CBA we also performed calculations using non-normalized unweighted midpoint data, see SI Table S6. This model addresses impacts from a hierarchic decision maker's perspective as the end point model.

For the CBA, the relative standard deviation factors from the LCA for the underlying greenhouse gas emissions were used. In addition, standard deviation factors of 50% were applied for the physical effects considered most uncertain (i.e., number of health cases, additional labor time in biochar application) and 25% for relatively less uncertain effects (i.e., labor time in wood and waste collection and in briquette and biochar production).

Sensitivity Analysis. For the LCA, the climate change impacts and particulate matter formation are determined by the efficiency in, and emissions from, the production of the biochar (both alternatives) and the use of fuel (briquetting alternative). The carbon sequestration is depending on the amount of stable carbon in the soil. All of these factors were therefore subjected to a sensitivity analysis where each of the factors was systematically varied by $\pm 50\%$ to the values used in the main scenario (stable carbon was maximally truncated at 100% and varied between 40% and 100% C stability in absolute numbers).

The CBA results will depend on the efficiency of the biochar production (kiln efficiency) and the subsequent effects on health. In addition, crop productivity based on the addition of biochar to soil can vary significantly.³³ In our case, we have divided this into (i) agricultural production rate, which is effected both on the agricultural effect of the biochar, and (ii) the necessary amendment rate (lower rate will give more productive land for cultivation). In addition, we included variation in carbon stability

and the subsequent effect on social cost. All of these CBA related factors were also subjected to a systematic $\pm 50\%$ variation of values.

RESULTS AND DISCUSSION

Environmental Impacts. Resulting values from the LCA are given in Figure 2. A complete overview of all end point results is in Table S5 and of midpoint indicators in Table S6.

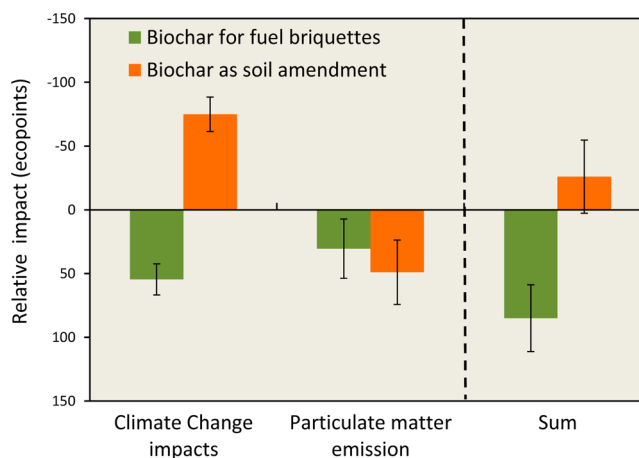


Figure 2. Annual normalized and weighted impacts (ecopoints) for the two biochar alternatives. The solid bars show impacts relative to a baseline scenario. The error bars show standard deviations based on Monte Carlo simulations. Climate change impacts and health effects from particulate matter emissions are highlighted in the figure. Negative values mean reduction of impact, i.e. an improvement compared to today's situation, whereas positive values represent larger impacts than today.

The results showed a significantly larger environmental impact of the use of cocoa shell for briquette production than for cooking purposes. The main reason is the necessity to produce the biochar with associated emissions of particles, methane, and carbon monoxide, before being able to utilize it for cooking purposes. In this case, these impacts are not outweighed by the more efficient use of biochar as a fuel compared to traditional wood stoves. In contrast, addition to soil presented an environmentally friendly alternative with reduced impact compared to today's situation. The positive effect was almost exclusively associated with sequestration of carbon in the soil and reduced climate change impact, which was only partly nullified by the negative impact of methane and particle emissions. The particulate matter emission effect was more negative for the soil amendment alternative than for the briquette alternative. This is caused by the fact that traditional stoves were used for cooking in the soil amendment alternative, emitting more smoke than the improved briquette stoves. The midpoint calculations confirmed the results by giving the largest difference to the baseline for the categories *climate change* and *particulate matter formation*. Looking at the results using food production as a functional unit¹⁴ only enhances the differences (Figure S3).

The results illustrate the sustainability dilemma of biochar for cooking purposes.⁴⁵ Even though more efficient production and use of biochar is an important and welcome step toward reduced life cycle impacts, a "sustainable biochar vision" could only be realized via soil amendment and an agricultural component.⁴⁶

Costs and Benefits. Results from the cost-benefit analysis are provided in Figure 3. Annualized per household, the

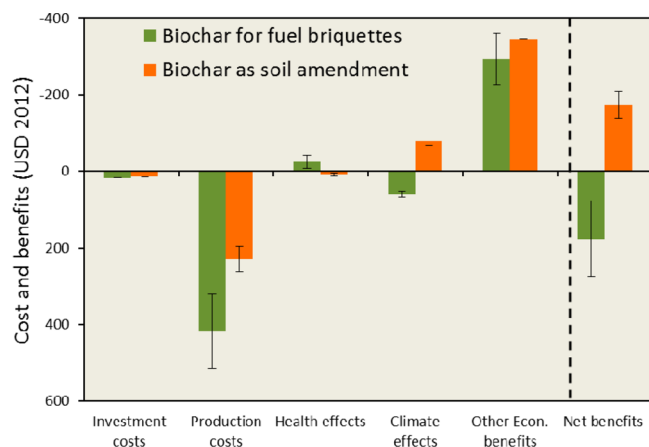


Figure 3. Annual costs (positive numbers on y-axis) and benefits (negative numbers on y-axis, bars pointing up) per household for the two biochar alternatives (USD 2012). The figure divides the effects into investment costs, costs of biochar production and briquetting, indoor and outdoor health effects, climate effects, and other economic benefits from increased maize production and fuel benefits in terms of saved wood collection time. Negative values mean benefits (or savings); positive values are costs.

investment costs were almost the same for the two alternatives, most of which was due to the investment in the retort kiln. The production costs were higher for the cooking alternative due to the time-consuming process of briquetting. Both alternatives had a health cost from (outdoor) biochar production, but this effect was more than compensated in the cooking use alternative by avoided higher health costs of using traditional wood stoves. Note that since the CBA specifically addresses local health costs related to particulate matter, the results were different from the equivalent category in LCA, which addressed health impacts from a regional-global perspective. The climate benefits were the largest in the agricultural alternative, consistent with the LCA, but the relative importance was less here since they only represent a monetized value, not the actual impacts. Finally, economic benefits in the form of agricultural and fuel benefits were positive for both alternatives.

Since all effects were capitalized in USD 2012 values, they can be summed into a net benefit measure indicating the overall welfare effect per household and year. The biochar as a soil amendment option has a net social benefit of USD 173 per household and year and is the preferred option. The briquetting alternative has a net cost of USD 176 per household and year. The benefit of fuel savings and positive health effects are not large enough, by a relatively large margin, to outweigh the costs (mainly time used making briquettes).

Sensitivity Analysis. For the LCA reduced kiln efficiency in the agricultural soil amendment alternative quickly led to this alternative becoming inferior to the baseline scenario since the sequestered amount of carbon no longer outweighed the toxic gas emissions during biochar production (Figure 4). The results stress the importance of an efficient pyrolysis process to reduce the environmental impacts of biochar production-utilization systems. Similarly, less stability of biochar in the soil showed negative impacts (Figure 4). This effect is nonlinear since the amount of stored carbon is limited by the produced amount of biochar.

The briquette alternative was relatively insensitive to changes in the input variables. Independent of improvements in biochar production or briquette use, the briquetting alternative remained

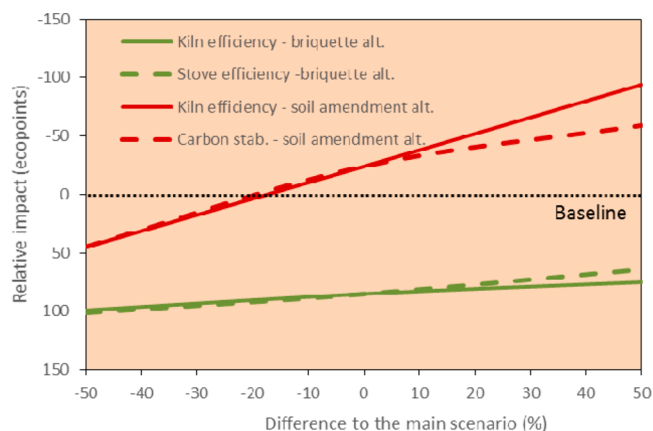


Figure 4. Relative change in environmental impacts compared to the main scenario (Figure 2) for $\pm 50\%$ variation in kiln efficiency (both alternatives), stove efficiency (briquette alternative only), and carbon stability (soil amendment alternative).

nonbeneficial compared to the baseline, because both the main impact factors (climate change and particulate emissions) gave negative impacts (Figure 2), in contrast to the main impact factors for the soil amendment alternative (positive climate impact, negative particulate matter impact).

An alternative to the use of biochar for briquetting purposes could therefore be the continued use of wood in more fuel-efficient stoves. Assuming the same fuel efficiency for wood stoves as for the biochar stoves, this alternative gives 4% less impact than the current practice, since particulate emissions from biochar production can be avoided. This is approximately equivalent to a scenario where LPG is used for cooking (based on an average annual use of 11 kg/household/day and emission data from Table S3).^{47,48}

For the CBA, the briquette alternative (sensitivity analysis not presented in a figure) involved a relative high net cost (negative benefit) in the current case study. Only a reduction in the costs of briquetting would result in this alternative having a net social benefit. In addition, the health effects due to cleaner cooking practice and time saving in avoided wood collection would need to increase substantially. The health effects have been conservatively assessed here due to the use of standardized methodology, but even if cardiovascular effects, pulmonary diseases, and cancer were included and updated (and possibly higher) value estimates were used, it is not likely that these benefits would be high enough to outweigh the cost.

For the agricultural soil amendment alternative, the relationships between the value of carbon stability and kiln efficiency, and the agricultural effect of biochar and soil amendment rate, respectively, are of specific interest (Figure 5). The uncertainty ranges of low (USD 1.34) and high end (USD 268) carbon prices (values) are included in the figure, as this value and the potential inclusion of biochar in the global carbon market may be important for the viability of small-scale biochar systems. However, the results show relative robustness to variation in both input data and carbon prices. Only a 30% reduction in the benefits combined with a low carbon price will give negative net benefits of the soil amendment alternative. In practice this means that agricultural use of biochar is independent of carbon credit support in this case. The sensitivity analysis showed the largest benefit resulted from more efficient utilization of biochar (reducing the soil amendment rate), thus allowing the use of biochar on more farmland which will multiply the harvest and

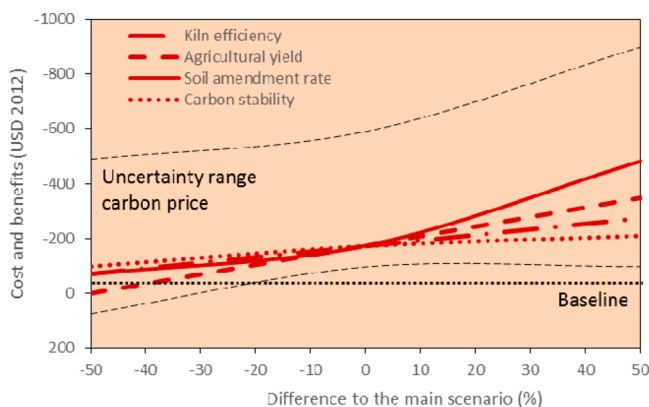


Figure 5. Relative change in net benefits to the main scenario (Figure 3) for $\pm 50\%$ variation in kiln efficiency, agricultural production rate (harvest), and soil amendment rate of the biochar for the agricultural alternative in the CBA analysis. The maximum uncertainty range for the investigated sensitivities using a low end (USD 1.34) and a high end (USD 269) carbon price is marked in the figure (main scenario: carbon price USD 47.).

benefits accordingly. One should however be aware that availability of agricultural land might be limited, and, as a result, this effect is possibly not feasible in practice.

Implications for Management. This study showed that the environmental benefits of biochar use for agricultural purposes exceed those of the use of biochar briquettes as cooking fuel in a production-utilization system for rural applications. Even though the use of biochar briquettes can be beneficial due to low emissions during food preparation, in an overarching systems perspective the summation with the emissions from biochar production renders this scenario inferior to a baseline scenario of not utilizing the cacao shell biowaste at all. This conclusion is supported by the cost-benefit analysis where the production costs outweigh the benefits of avoided wood collection and saved health costs. Fuel wood users may perceive social benefits in transition to briquettes.¹⁶ However, under such conditions subsidized LPG use due to its energy density may represent an even higher user benefit.^{47,49}

The results further emphasize the importance of investigating and documenting the carbon storage effect and the agricultural benefit in biochar production-utilization systems for sustainable use. Without these two components in place, the use would be neither environmentally friendly nor socioeconomically beneficial. Interestingly, based on our results, biochar projects do not seem to be dependent on the inclusion of carbon credits in order to be socioeconomically beneficial, on the condition that the biochar is used as a soil amendment, not as fuel briquettes.

Further focus on efficient biochar production is necessary due to the large environmental impact from the production of biochar and the sensitivity of overall systems impacts connected to this factor (Figure 4). We propose the development and introduction of highly efficient retort kilns with low air emissions to overcome this challenge.

In addition, for biochar to be sustainable it should continue to be used in poor soils where the agricultural effect is largest.⁵⁰ Since this effect is highly variable, the results emphasize the need for comprehensive system assessments of impacts before the introduction of small-scale biochar projects in rural areas.^{6,14}

■ ASSOCIATED CONTENT

📄 Supporting Information

More detailed information about the LCA/CBA assumptions and detailed results. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

The authors would like to thank the Norwegian Research Council for the support to the study (grant agreement 203901, program NorGlobal). Important field data has been collected by Heri Tabadepu and Robin Svensson of the UNDP. The provision of data by the Indonesian Soil Research institute (ISRI) and cooperation from Dr. Neneng Nurida and (Jubi) Jubaedah is greatly appreciated. Dr. Kristin Aunan, Bjorn Larsen, and Dr. Haakon Vennemo have provided very useful comments to the CBA, especially evaluation of health effects. Dr. Sarah Hale has been helpful in reviewing the manuscript.

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