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Life Cycle Assessment to Evaluate the Environmental Impact of Biochar Implementation in Conservation Agriculture in Zambia

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Supporting Information

ABSTRACT: Biochar amendment to soil is a potential technology for carbon storage and climate change mitigation. It may, in addition, be a valuable soil fertility enhancer for agricultural purposes in sandy and/or weathered soils. A life cycle assessment including ecological, health and resource impacts has been conducted for field sites in Zambia to evaluate the overall impacts of biochar for agricultural use. The life cycle impacts from conservation farming using cultivation growth basins and precision fertilization with and without biochar addition were in the present study compared to conventional agricultural methods. Three different biochar production methods were evaluated: traditional earth-mound kilns, improved retort kilns, and micro top-lit updraft (TLUD) gasifier stoves. The results confirm that the use of biochar in conservation farming is beneficial for climate change mitigation purposes. However, when including health impacts from particle emissions originating from biochar production, conservation farming plus biochar from earth-mound kilns generally results in a larger negative effect over the whole life cycle than conservation farming without biochar addition. The use of cleaner technologies such as retort kilns or TLUDs can overcome this problem, mainly because fewer particles and less volatile organic compounds, methane and carbon monoxide are emitted. These results emphasize the need for a holistic view on biochar use in agricultural systems. Of special importance is the biochar production technique which has to be evaluated from both environmental/climate, health and social perspectives.

INTRODUCTION

Biochar is charcoal from the incomplete combustion (pyrolysis) of organic waste. When mixed into soil, biochar remains stable and most of its carbon is thus removed from the short-term carbon cycle. Due to its alkaline nature, biochar can increase soil quality by increasing base saturation. In addition, especially in sandy soils, biochar can increase the water-holding capacity to alleviate water stress of plants. Lastly, biochar has a high cation exchange capacity, thus reducing cationic nutrient leaching when added to soil. All of these effects can increase seed germination, plant growth, and crop yield.[1−3]

This paper applies life cycle assessment (LCA) on agricultural biochar use in sub-Saharan Africa, perhaps one of the most feasible areas for biochar as a means of climate change mitigation and adaptation. Africa has been especially pinpointed for the use of biochar, since the biochar can be produced and used locally thus requiring minimum investments.[4−6] Economically, biochar can become an important factor for carbon credits within the clean development mechanism (CDM) and biochar may be of importance for adapting food production to a future drier climate.[7] Sub-Saharan African countries such as Zambia contain a significant portion of the continent's degraded sandy soils where the use of biochar may be especially relevant for agricultural purposes.[8]

From a climate change mitigation perspective, it would be beneficial to maximize the addition of biochar to soil, preferably using modern production technologies that have high efficiency

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and result in low emissions.[9] In reality, biowaste materials are a limited resource and their unrestricted use may exceed what can be supported locally without leading to negative impacts of deforestation and land degradation.[10] In addition, the assumption of using technologically advanced equipment for biochar production is probably too optimistic for Africa, given the economic status of small-scale farmers and the widespread use of primitive earth-mound kilns for traditional charcoal production in the continent.[11,12] Improved cooking stoves or retort kilns, despite being more costly than traditional production methods, can be more realistic options for replacing earth-mound kilns. Such technologies result in reduced airborne emissions of gases such as methane, carbon monoxide, volatile organic compounds, and also particulate matter.[7,11] In order to prove sustainable in an agricultural system, biochar will have to be beneficial not just for carbon storage, but must also be economically and socially compatible, therefore, human health effects, crop productivity, and resource use must be considered.

One common way to determine the relative impact between production systems occurring over the whole life cycle is to deploy LCA. With this method the inputs, outputs, and the potential impacts of a product system are compiled and evaluated throughout the product's life span.[13] LCA has been used on biochar systems previously, mainly to evaluate effects in highly industrialized, first-world systems focusing on greenhouse gas mitigation.[14−16] In tropical agricultural systems using rural biochar production methods, a spectrum of aspects has to be addressed in addition to greenhouse gases. Of special interest are the health aspects related to these traditional biochar production methods.[17]

In the present paper we have investigated the environmental impact of the use of biochar in small-scale conservation agriculture by conducting a life cycle assessment including ecological, health and resource issues. Based on the results, we discuss the use of biochar for agricultural purposes, not only from a greenhouse gas mitigating point of view but from a holistic perspective addressing several aspects simultaneously. To our knowledge this is the first paper combining all life-cycle aspects for the use of biochar in tropical agricultural systems.

■ MATERIALS AND METHODS

Case Description. We have used biochar in combination with conservation agriculture techniques instead of combining it with conventional agriculture. Conservation agriculture aims to achieve sustainable and profitable agriculture especially for smallholder farmers through the use of minimal soil disturbance, permanent soil cover and crop rotations.[18,19] Especially important for life cycle impacts in the currently studied form of conservation agriculture are the deployment of soil dry-season preparation with minimum tillage methods to minimize soil disturbance and precision fertilization to maximize the utilization of nutrients in the soil. Agricultural residues are used for soil protection. In addition, herbicides are used for land management instead of manual weeding techniques. This is in contrast to conventional rural farming, which is based on land preparation through scrub burning, manual tillage, hand weeding, and broadcasting of fertilizers.

The LCA has been conducted using measured field data from an ongoing project directed at assessing the use of biochar in Zambia.[20] This project is testing biochar as a complement to the above-described conservation farming (CF) practice in five Zambian locations for maize production, evaluating effects on soil physics, soil chemistry, and crop growth. In CF all cultivation is done in growth basins which are constructed during the dry season followed by seeding and precision fertilization in the basins just before the first rainfall. This is in addition an excellent opportunity for efficient biochar addition since the material can be added precisely, reducing the required amount of biochar compared to conventional broadcasting. More details and illustrative pictures of CF practice are given in the Supporting Information (SI), Figures S1 and S2.

Zambia can be divided into four ecological regions varying in soil characteristics, landform and climatic characteristics.[21] All field sites are situated in region II, which exhibits similarities in landform and climatic conditions. In the LCA we used data from three of the five field sites in the project representing various soil conditions, Figure 1.

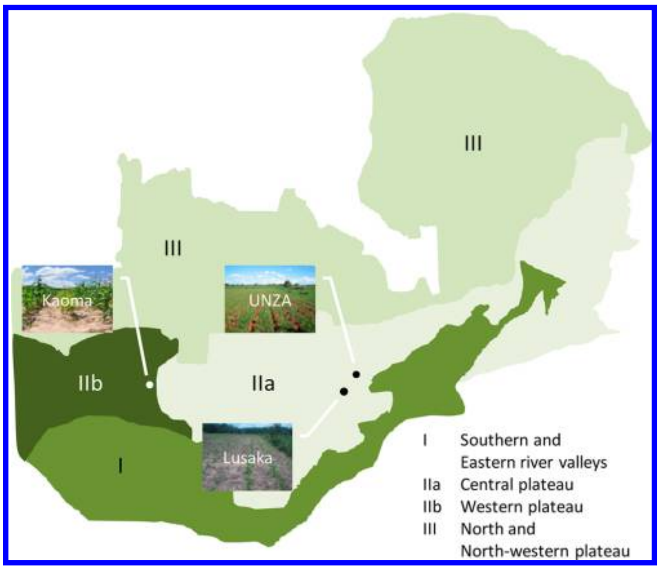

Figure 1. Field sites in relation to the agro-ecological regions in Zambia.[21] Region IIb (coarse sandy degraded soil) showed the strongest crop yield effects of biochar application.

The Kaoma site is situated in western Zambia region IIb, an area of coarse sandy degraded soil, whereas the other sites are situated in area IIa with red oxisol (UNZA north of the capital Lusaka) and clay loam (within Lusaka). The other two sites not considered in the present study, Shimabala and Mkushi, were very similar to Lusaka and UNZA, respectively, both with respect to soil characteristics and agronomic effect of biochar. SI Table S1 gives more details about the field trials and SI Table S2 presents data on soil characteristics from the sites.

In addition to soil variability the sites were selected based on their different response to biochar amendment on crop yield: (i) Kaoma, with strong effect on crop yield (>+300%); (ii) UNZA farm where moderate crop yield effects were observed (+30−40%), and (iii) Lusaka, where a slightly negative effect (−10%) of biochar was observed, Table 1.

Biochar corresponding to a general application rate of four tons per hectare was distributed in the field trial growth basins together with fertilizer with rates as described in Table 1. The results have been compared to fertilized controls without biochar addition. The plots have not been limed, in order not to mask the effect of biochar. This may lead to lower yield than recommended CF practice where addition of lime is used for pH adjustment. We have also estimated yield for conventional

Table 1. Grain Yields (tons/ha) for the Three Sites Evaluated in the Present Study, With and without Biochar Addition[a,b]

method	Kaoma[d]	UNZA[e]	Lusaka[e]
conventional agriculture[c]	0.6 ± 0.1	1.7 ± 0.8	5.8
conservation farming	0.9 ± 0.1	2.6 ± 1.2	9.1
CF and biochar 4 t/ha	3.8 ± 0.5	3.7 ± 1.1	8.2

[a]Mean values of harvests 2011 and 2012 (Kaoma and UNZA), 2011 for Lusaka. [b]Estimated values for conventional agriculture with the same addition of fertilizer are included. [c]Estimated yield 63% of that from conservation farming.[22] [d]Addition of 140 kg/ha of NPK fertilizer 10:20:10 and 140 kg/ha of urea 46:0:0:0. [e]Addition of 280 kg/ha of NPK fertilizer and 280 kg/ha of urea.

agriculture from literature values[22] using the same fertilizer rates and cultivation techniques as in the field trials.

The present LCA compared biochar produced via three different methods using maize cobs as raw material: (i) earth mound kilns without gas recovery; (ii) larger retort kilns where the pyrolysis gases are refed through the pyrolysis zone, both enhancing the process by delivering combustion heat as well as combusting the methane and carbon monoxide otherwise emitted, and (iii) micro top-lit up-draft (TLUD) stoves allowing the use of the gas flame for cooking purposes. The biochar used in the actual field trials was produced by traditional earth-mound kilns. Complementary TLUD stoves[23] were handed out to farmers in order to investigate the spontaneous interest in using improved production technology, but in the introduction phase not enough biochar was produced for the trials. For the LCA it is assumed that biochar produced by different technologies will have similar chemical properties substantiated by analysis of pH (8.1 ± 1.1) and cation exchange capacity (CEC) (21.5 ± 2.0) from different biochars, SI Table S3.

Goal and Scope. The goal and scope of the LCA analysis were to compare the environmental impact of CF to that of conventional farming and to estimate whether biochar produced through different methods may prove beneficial in a complete life-cycle perspective. Five cases were considered: (a) conventional farming; (b) conservation farming without biochar addition; (c) conservation farming with biochar addition produced in earth-mound kilns; d) conservation farming with biochar from retort kilns, and (e) conservation farming with biochar from TLUD stoves. These cases will for a decision maker illustrate the life cycle impacts from different agricultural techniques (conventional vs conservation) in a rural setting, and how biochar application with different relevant production techniques (TLUD, retort kiln, traditional kiln) will affect these impacts.

System Boundaries. The currently applied LCA centered the system boundaries around two main processes; *biochar production* and *soil application*. The inflow to the system was thus the use of resources and energy, where outflows were emissions, resource use and land use. *Biochar production* included the complete resources connected to production of kilns and stoves including transportation, whereas impacts from the pyrolysis process were limited to subsequent air emissions. Secondary effects such as replacement of other biomass sources and subsidiary health effects due to changed cooking practices were considered to be outside the system boundaries. *Soil application* included all annual resources required to produce the maize and the impacts associated to transport these resources to the agricultural sites. We addressed biochar application on established agricultural land and impacts connected to land preparation were considered to be outside system limits due to uncertainties in how the land was opened. Both conventional agriculture and conservation farming were performed through rural practices not involving mechanized equipment for cultivation or harvest. Carbon storage due to the local application of biochar was considered to be within the system boundaries since it originates from the local agricultural process.

The processes within the LCA, methodologies and more detailed assumptions will be described in the following sections and the SI.

Functional Unit. Since this study was conducted from an agricultural perspective, the functional unit was selected as impact per produced ton of maize per year.

Inventory Analysis. The life cycle inventories, that is, the aggregated environmental data collected for the modeled system are given in Table 2.

Table 2. Life Cycle Inventory for Conventional Agriculture and Conservation Farming with and without Biochar Addition[a]

inflow	unit	conventional agriculture	conservation farming	CF and biochar
Materials				
seeds	kg	20	15	15
fertilizer NPK (10:20:10) − mass of N in the form of NH_4NO_3	kg	14/28	14/28	14/28
fertilizer NPK (10:20:10) − mass of P in the form of P_2O_5	kg	28/56	28/56	28/56
fertilizer NPK (10:20:10) − mass of K in the form of K_2O	kg	14/28	14/28	14/28
fertilizer Urea (46:00:00) − mass of N in the form of $CO(NH_2)_2$	kg	64/128	64/128	64/128
herbicide − glyphosate	kg		5.1	5.1
herbicide − cyanazine	kg		0.41	0.41
herbicide − atrazine	kg		0.91	0.91
Biochar and Soil Emission Related Processes				
agricultural residue burning	kg	1100		
biochar added	kg			1000
carbon stored (CO_2 equiv)	kg			(−2200)
soil N_2O emissions	kg	0.81/1.62	0.81/1.62	0.81/1.62
transportation				
lorry transport	$t \times km$	160/300	159/299	159/299

[a]Stacked values represent high and low fertilizer addition. Values are given per ha for one growth season.

Table 3. Life Cycle Inventory for Open Burning and Biochar Production[a]

inflow	unit	open burning	traditional kiln	retort kiln	TLUD
Materials					
steel (low alloy)	kg			2.5×10^{-4}	6.8×10^{-4}
bricks	kg			0.1	
Emissions					
CO	g	34.7	223	162	93.7
CH_4	g	1.2	44.6	36.5	3.7
VOC	g	4.0	92.6	23.9	31.7
NO_X	g	3.1	0.063	0.005	4.8
N_2O	g	0.07	0.15	0.01	0
PM_{10}	g	3.7	22.8	4.2	6.6
SO_2	g	2.0			
PAH[b]	mg	18.6			
PCDD/F[c]	ngTEQ	0.5			
Transportation					
lorry transport	t × km			1.25×10^{-4}	3.4×10^{-4}
transoceanic freight ship	t × km				5.7×10^{-3}

[a]Values are given per kg product (dry biomass for open–burning and produced biochar for the three kiln alternatives). [b]Polycyclic aromatic hydrocarbons. [c]Polychlorinated dibenzodioxins and furans.

Data have been taken from mixed sources including results of interviews, literature data and experimental results from biochar addition to the research plots.[20] For more details, see SI Tables S4–S7. All seeds, fertilizers and herbicides were assumed to be delivered from a regional supplier and transported to the site by lorry (same distances to all sites, assumed equal to the distance of Lusaka to Kaoma). Ecoinvent 2.2 was used as data source for the description of inventory process except for the emission data for open-burning and biochar production which were generated from emission values (SI Tables S8–S11).

Greenhouse gas emissions from soil management were included by addressing nitrous oxide formation through the processes of nitrification and denitrification when adding synthetic fertilizer to the soil.[24] The nitrogen-poor and dry soils in the cases studied here are not expected to emit significant amounts of nitrous oxide themselves and no additional emissions of nitrous oxide are therefore foreseen. Possible effects of N_2O suppression resulting from biochar addition are ignored in the present analysis for simplicity.

Different tilling practices may in addition affect the fluxes of soil organic carbon in agricultural systems. These differences are most prominent immediately after land opening and will decline over time.[25] We conservatively assumed steady-state levels for the analyzed system, meaning that no difference in soil organic carbon (SOC) release or uptake were assumed between conventional agriculture and conservation farming. SOC values are therefore not included in the LCA.

Inventory data for burning of agricultural waste and for biochar production are described separately in Table 3 (more details in SI Tables S8 to S11). In conventional agriculture the maize stover is left behind after harvest and burnt as agricultural waste together with remaining scrub and weed. In conservation farming the stover residue is used as a soil cover without burning. Grains are separated from the cobs outside the field and when the cobs are not used as raw material for biochar production assumed to decompose. In the LCA we assumed no net emissions of carbon dioxide in either case since the biogenic carbon uptake and release is mostly taking place within a growth season. We however addressed and included other particle and gas emission effects from agricultural residue burning, Table 3.

Published emission field data for biochar producing stoves and kilns are limited and thus a data set was established from literature values most representative for the different technologies in a field situation. These limitations both in number of available studies and the different fuels and stove combinations introduced uncertainties in the used emission data. These uncertainties were incorporated in an uncertainty analysis. Here we have assumed that our data material, as far as possible, represented the relevant stove or kiln type. However, it was not possible to account for differences in feedstock. As shown in SI Table S12 the assumption of similar feedstock gave approximately 3 times lower uncertainty than a random variation of both feedstock and stove type (SI Table S13).

We calculated no net carbon dioxide emissions from biochar production assuming equality in biogenic uptake and emission release. Based on experimental data a carbon content of 74% in the biochar was used, of which 80% was assumed to remain as stable carbon in the soil.[26] For the life cycle impact of the biochar-producing equipment, field experience substantiated an assumption of a four year lifetime for equipment with a total production of ten tons of biochar for a retort kiln and one ton for a TLUD, SI Tables S14 and S15. An earth-mound kiln does not require any produced material and therefore does not yield any equipment impacts.

There are three major assumptions in the study that need further clarification and have been specifically addressed in the sensitivity analysis of the LCA.

First, the annual maize harvest yield of conventional farming was assumed to be 63% of that of CF. This ratio was based on a large-scale Zambian field study, in which maize yields were compared for CF and conventional agriculture, reporting average yields of 4.4 ton/ha for CF (no lime) and 2.8 ton/ha for conventional agriculture (hoe cultivation),[22] SI Table S16. However, the effect of CF on crop yield is the subject of debate, due to substantial variations in results between different studies.[27]

Second, in the field trials a single biochar addition of four tons per ha has been used. This addition will however exceed the available waste biomass from cobs from a production season. Previous studies have in addition found that biochar may leach to the subsoil at the rate of 50% in a period of 4 years

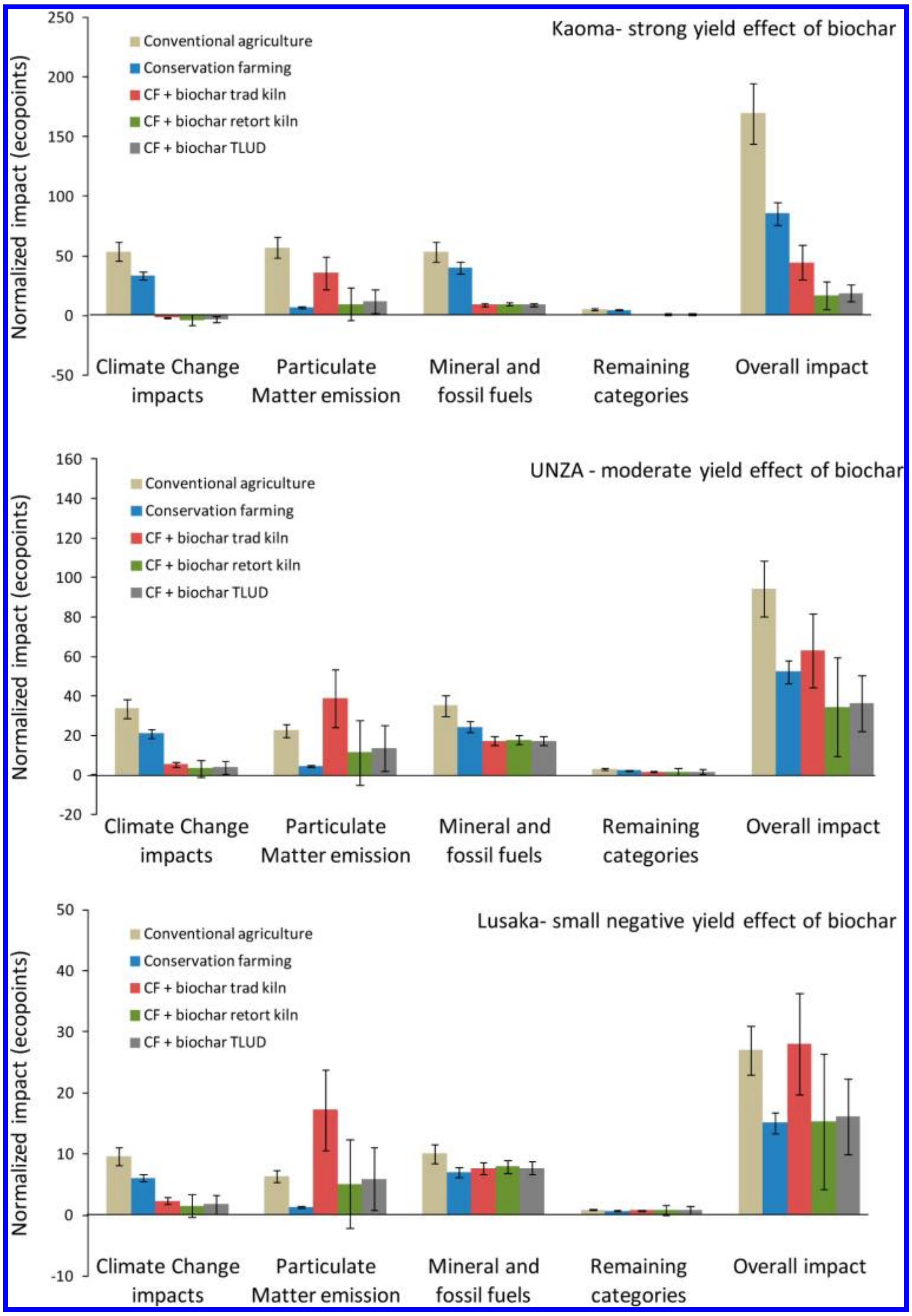

Figure 2. Normalized impacts (ecopoints) per ton of annual maize production for the different sites. Note the variation in the numerical ecopoint values on the vertical axes. Aggregation of impact categories are based on equal weighing of individual categories. Negative values mean reduction of impact, that is, an improvement. The standard deviation (SD) for the cases was calculated based on Monte Carlo simulations using the predefined SD for the single inventory processes.

in sandy soils,[28] thus requiring an annual addition of 0.5 ton biochar to maintain carbon concentrations stable over time. Instead of a single biochar addition we have therefore conservatively credited repetitive annual additions of one ton/ha in the carbon balance for the LCA.

Third, secondary positive effects of biochar production were not included in the analysis. Both retort kilns and TLUD stoves are designed to utilize the pyrolysis gases for beneficiary purposes (cooking, baking). This may introduce marginal positive effects by the decreased use of inefficient cooking methods accompanied by potential negative health effects as well as by reduction of the use of wood as fuel, which may reduce deforestation.[29] However, these positive effects depend on a spontaneous adoption of stoves for cooking purposes which cannot (yet) be properly quantified for the study sites. These effects were therefore considered to be outside the system boundaries of the present analysis.

Uncertainties. Ecoinvent addresses uncertainties by determining the standard deviation of each inventory value through a mathematical aggregation of individual uncertainty sources (Pedigree method).[30] Uncertainties in project specific inventories, as in Table 3, are estimated with the same methodology. The combined standard deviation for the cases was then calculated based on Monte Carlo simulations varying each data point across their corresponding uncertainty range. A total of 1000 simulations were used in this study, which yielded sufficient stability in results for further analysis. The combined standard deviations are presented as error bars in Figure 2 in the Results section.

Impact Assessment Methods. Impact assessment is an important step in the LCA to be able to evaluate the significance of potential environmental impacts based on the inventory values. In this study we utilized the ReCipe impact model which incorporates both climate aspects and airborne emissions of particulate matter, in addition to several other impact categories such as acidification, eutrophication, toxic effects and resource depletion.[31] An end point method with normalization and weighing was used as the primary impact assessment in order to achieve maximal agreement with the objectives of the study, which was to compare different life cycle indicators for a holistic evaluation of the impacts of biochar implementation in rural agriculture.

End point indicators describe the integrated damage of the components from the inventory, in contrast to midpoint indicators which address effects only. For global warming, a typical example midpoint indicator would be the effect of radiative forcing (global warming potential), whereas the end point approach would assess the human and environmental damage based on radiative effects. ReCipe operates with three different end point indicator units: (i) Disability-adjusted life years (DALY) for human effects; (ii) species × years, for a time integrated value of ecological effects, and (iii) U.S. dollars for the monetary valuation of resource impacts. The use of end point indicators facilitates the interpretation of results for management purposes and allows enhanced integration of results. However, end point indicators are expected to have a higher degree of uncertainty compared to midpoint indicators.[32] In order to address this uncertainty, ReCipe operates with different scenarios with respect to effects and possibilities for mitigations. In this study we selected a common decision maker's perspective (hierarchist). This means, for example, addressing climate gases in a 100 years perspective, assuming a degree of adaptation to health effects as given by World Health Organization (WHO) predictions.[33,34]

In addition, each end point indicator was normalized to a dimensionless index (ecopoint), thus allowing a comparison between impact categories directly. In this case external normalization was applied. The annual global contaminant releases for each corresponding impact category during the year 2000 was used as the external reference.[35] This method facilitates comparison of results across categories since normalized data can be added and subtracted without changing the results, even though this also assumes that the external normalization scenario is representative for the study data, both spatially and in time.[36] Even though this procedure intends to reflect a global perspective, most emission data originate from the U.S. and Europe. The use of different impact methods and subsequent normalization methods has been intensely debated, since results may differ depending on assumptions.[37−39] It is therefore important to complement the use of LCA for decision making in biochar projects with extensive monitoring and verification.[40]

Weighing may be applied in addition to normalization to be able to summarize damage effects into single score indicators. This study has weighted the different effect categories using default weights: ecosystem 40%, human health 40% and resource use 20%. The weighing is another assumption which has been addressed in the sensitivity analysis.

Due to the uncertainties associated with the use of the end point methodology, normalization, and weighing, calculations were for comparative reasons also performed using a ReCipe midpoint impact model. This model addresses impacts from a hierarchic decision maker's perspective as the end point model but limits the impact assessment to observable effects instead of aggregating impacts to potential damages.

RESULTS AND DISCUSSION

Life Cycle Impacts. ReCipe operates with in total 17 different end point categories to describe the outcome of the LCA. In this study the total normalized end point impacts values of the different cases were dominated by three different categories (Figure 2): *climate change impacts* which is the aggregated potential damage of greenhouse gases including human and ecosystem effects; *emissions of particulate matter* which refers to human effects from inhalation of fine particulate matter, and *mineral and fossil fuels* which are connected to the cost of extracting minerals and fossil fuels. This category refers to the point that the extraction of today's resources is assumed not only to lead to climatic effects, but also to increased marginal extraction costs in the future. The other end point impact categories in the LCA were lumped into *remaining categories*.

A complete picture of all end point impact category results and subsequent normalized values can be found in SI Tables S17−S22. SI Tables S23−S25 presents in addition results obtained using midpoint indicators.

Due to the objectives of the present study to evaluate the impact of biochar as an agricultural soil fertility enhancer, all results in Figure 2 and in the SI are presented as annual figures per ton of maize harvest. High yield due to biochar addition, as is the case for Kaoma, will thus lead to a relative decrease in the negative impacts from biochar production, whereas low or negative yield seen for UNZA and Lusaka will emphasize the impacts of biochar production. This can be observed in Figure 2 as a declining benefit of biochar use compared to CF alone, which again is correlated with decreased yield effects from biochar addition.

When exclusively considering carbon sequestration and climate change effects, the use of biochar with conservation farming was, as seen in Figure 2 and supported by the midpoint analysis results (SI Tables S23−S25, category climate change), climatically beneficial compared to conservation farming alone independent of production methodology and maize yield. This was still true in the case of earth-mound kilns, since the negative effects of introducing greenhouse gas emissions and especially methane, did not completely nullify the positive effect of carbon sequestration. However, due to the effects of particulate matter (PM) formation, the total impact from the use of biochar produced in earth-mound kilns became, in general, inferior to conservation farming without biochar use. Even though this is supported by the results in the midpoint category particulate matter formation (SI Tables S23−S25), it should be noted that the uncertainties are large due to the

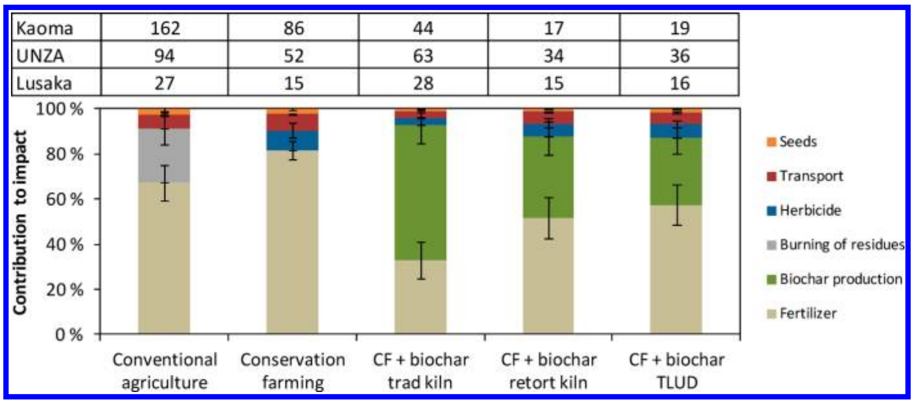

Figure 3. Mean contribution of the major processes including standard deviation for the three sites presented for the different cases. The processes included here are responsible for more than 99% of the total impact. The number above each bar indicates the absolute overall impact in ecopoints for each case.

limited number of reliable emission data for this category. The effect of PM was here associated to respiratory health effects of fine particulate materials distributed through long-range air transport, and not to specific situations relating to direct exposure in confined spaces (kitchens or similar). For such a specific scenario, the negative effect of PM, in addition to the toxic effect of gaseous emissions as carbon monoxide, may result in even larger health impacts than predicted by the LCA.[41]

The potential negative climate effect of atmospheric particulate material is another debated topic currently not addressed in the ReCipe impact model. The effect is regional and much more short-lived than other greenhouse gases and therefore difficult to quantify in terms of a 100 year global warming potential setting.[42,43] It is however plausible to assume that particulate material emissions from biochar production in some form will negatively affect the climate, emphasizing the negative impact of PM release.

This quantified effect of PM, and its potential for an even greater influence on the LCA outcome is interesting. Spontaneous adoption of biochar utilization in tropical rural areas will most likely be through traditional production methods due to their widespread use and the farmers' familiarity with them.[11] This impression was confirmed at the field sites where spontaneous adopters exclusively used traditional methods (either earth-mound kilns or simply holes in the ground) to prepare their biochar.

The results confirmed that the overall impact of conventional agriculture exceeded that of conservation farming. In the present study this was caused by higher yields reducing the impact per produced ton of maize, as well as from avoidance of agricultural waste burning and more efficient use of fertilizer in conservation farming. This is further emphasized by the results presented in Figure 3, where we present the mean contribution for the three sites of major processes for the different cases.

Fertilizer impacts, in addition to biochar production, turned out to be the most important contributors, responsible for over 80% of the total impact of conservation farming. Fertilizer impacts originate from ammonia production in which natural gas is catalytically split into hydrogen and subsequently reacts with nitrogen to produce ammonia. This process emits carbon dioxide and consumes nonrenewable resources.[44]

In contrast, herbicide use and transportation impacts were only identified as minor contributors to life cycle impact in the study.

Finally, it should be noted that the differences between the three case sites in Figure 2 was caused by the variance in harvest results from the three field sites. If biochar had been used only for carbon mitigating purposes this comparison would then be less relevant since the same rate of biochar was applied at all sites. However, if biochar is primarily used for crop productivity enhancement, as it was here, comparison on a yield basis is important and biochar will be most beneficial at sites where the highest productivity increase is achieved. In practice, for biochar to be used in rural tropical agriculture it is plausible to assume that increased yield compared to traditional methods would be a prerequisite for its adoption.[1,9]

Sensitivity Analysis. The present study assumed 37% yield difference between conventional agriculture and conservation farming substantiated by field data results (SI Table S16).[22] A smaller difference in harvest yield between conventional agriculture and CF (with or without biochar addition) would decrease the environmental benefits of CF and increased differences would lead to the opposite effect. Nevertheless, even if crop yields for conventional farming and CF were assumed to be equal, the total impact from CF was 16.5 ± 4.9% (mean value for the three case sites, see SI Table S26) lower than that of conventional agriculture due to the avoidance of open vegetation burning. This is important since the effectiveness of CF practices on a general basis has been questioned.[27]

The second important assumption in the present study was the amendment dose of biochar. Maximized addition would be beneficial from a climate change mitigation perspective, whereas the present results indicate that biochar production may have net negative overall impacts if it is carried out in earth-mound kilns. Figure 4 presents normalized impacts for different application (and therefore production) dosages of biochar using different production technologies for the Kaoma site (the case site where biochar application was most beneficial for crop yield). Results for up to three times higher addition dosages than actually applied in the Kaoma field site are presented. The results emphasize the necessity of focusing on production impacts in addition to soil effects when evaluating biochar amendment. Larger additions of biochar produced by retort kilns and TLUD stoves to the soil reduced the overall impacts due to a larger carbon sequestration effect than the negative impact originating from air emissions, whereas the addition of biochar produced by traditional kilns gave the opposite effect.

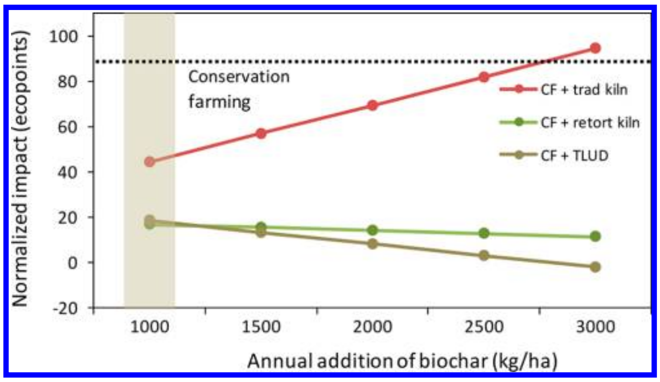

Figure 4. Sensitivity analysis for biochar production and use, showing normalized total impact for the three cases of biochar production at the Kaoma site. The base case scenario of annual additions of 1000 kg per ha is marked in the figure (i.e., additions in the course of 4 years are 4 times as large). The corresponding value for conservation farming is also indicated.

Finally, the study restricted the system boundaries of biochar production to the pyrolysis process itself. Introduction of TLUD stoves replacing traditional three-stone fires in confined spaces allows for more positive secondary health effects than those included in this study.[29,41] In addition, introducing TLUDs may reduce the need for firewood which is positive for reducing deforestation. Inclusion of these factors by expanding the system boundaries for the study would therefore increase the differences shown in Figure 4.

Methodologically, the absolute normalized impact values will change in case of alternative weighing sets as compared to the common decision makers' perspective of 40/40/20, see SI Figure S3. However, the relative rank order between cases were observed to remain unchanged to alterations in decision perspectives. Only in one case, UNZA farm using a 100% health weighing scenario, a distinct shift in rank order between CF alone and CF with biochar produced in traditional kilns was observed.

Implications for Management. The benefits of biochar use in tropical small scale agriculture were found to be sensitive to environmental/climate, health and social impacts, emphasizing the need to consider the use of biochar in agricultural systems from more than just a climate mitigation perspective.[45] First, beneficial use of biochar in agricultural systems requires a positive effect on harvest growth in order to be sustainable when yield is used as the functional unit. The full spectrum LCA showed additionally that the air emissions from biochar production can become so important that negative health effects from the traditional earth-mound kiln technologies can nullify the positive climatic benefits of biochar amendment.

It should however be noted that this study used one specific life cycle impact methodology and therefore is sensitive to uncertainties and assumptions as discussed in the sensitivity analysis. For decision purposes with regard to implementation it is important to reduce uncertainties, for example by the use of site-specific emission measurements. In addition, LCA results achieved by use of general normalization and weighing methods should be used with care since they may be contradictive to public values.[46]

Independent of methodological limitations, the results of the LCA study (also when looking at the midpoint results alone) emphasize the importance of introducing improved pyrolysis technologies for future large-scale applications of biochar in rural areas. This will both improve the climatic effect of biochar amendment and reduce the health effects of biochar production.

When introducing these biochar generation technologies, social and economic aspects have to be evaluated in addition to life cycle impacts. Modern pyrolysis equipment may be far too costly and complicated to maintain in a rural situation, and therefore probably would not provide a viable alternative. The use of small-scale biochar producing gasifier stoves requires significant individual effort to produce sufficient amounts of biochar and would have to be well-integrated in the local society to be effective. For example, it is estimated that an average household in Zambia would need to use a TLUD stove continually for several years in order to produce enough biochar for just one hectare of farming land. At the same time, TLUD gasifiers represent a true local solution with potential secondary benefits for both households and farmers.[7] Retort kilns provide larger production capacities than TLUD equipment and can be used for small-scale business development by dedicated professionals. On the other hand, larger-scale production requires more investments that would have to be compensated for by increased effectiveness and decreased environmental and health impacts.

Thus the optimal solution for biochar production and use will in the end depend on local conditions. Based on the results of the present study, it will require an increased focus on resource use and measurement as well as the control of airborne emissions. Improved technologies are warranted. However, they can be challenging to implement in a rural tropical setting.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

More detailed information about the LCA assumptions, detailed inventory results as well as detailed results from the impact analysis are found in the Supporting Information for this paper. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

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